MOTT MACDONALD

Bahamas Building Code

Coastal Infrastructure Design Guidance

July 2023

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Bahamas Building Code

Coastal Infrastructure Design Guidance

July 2023

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Issue and Revision Record

Revision	Date	Originator	Checker	Approver	Description
P01	28/07/23	P. Henderson A. Douglas	A. Douglas V. Deakin M. Di Leo N. Clarke G. Wallace	A. Burton	First issue

Document reference: 100101522 | 100101522-MMD-CO-ZZ-RP-C-0002 | P01 | S3

Information class: Standard

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List of abbreviations

ADCP	Acoustic Doppler Current Profiler
ALWC	Accelerated Low Water Corrosion
ASCE	American Society of Civil Engineers
BS	British Standards
CEM	The Coastal Engineering Manual
CFD	Computational Fluid Dynamics
CIRIA	Construction Industry Research and Information Association
COSHH	Control of Substances Hazardous to Health
DHEMR	Design Hazard Elimination and Management Record
DEM	Digital Elevation Model
DEPP	Department of Environmental Protection and Planning
DSM	Digital Surface Model
DTM	Digital Terrain Model
ECI	Early Contractor Involvement
EIA	Environmental Impact Assessment
FEMA	Federal Emergency Management Agency
FIDIC	The International Federation of Consulting Engineers
FRA	Flood Risk Assessment
GCP	Ground Control Point
H&S	Health and Safety
HSRA	Health and Safety Risk Assessment
IHO	International Hydrographic Organization
IPCC	Intergovernmental Panel on Climate Change
MIC	Microbially Induced Corrosion
NOAA	National Oceanic and Atmospheric Administration
NMBAQC	NE Atlantic Marine Biological Analytical Quality Control
PAH	Polyaromatic Hydrocarbon
PIANC	Permanent International Association of Navigation Congresses
PSA	Particle Size Analysis
SHE boxes	Safety Health and Environmental boxes
SIDS	Small Island Developing States
SoP	Standard of Protection
USACE	US Army Corps of Engineers
VOC	Volatile Organic Compounds

1 Introduction to the Guidelines

1.1 Background

This document has been developed to support and complement the 2023 update to the Bahamas Building Code. A gap has been identified in the Code concerning design requirements, and definition of best practice, when commissioning and controlling the design process of coastal infrastructure.

1.2 Purpose and objectives

Purpose This guidance document provides guidance on what constitutes best practice throughout the complete lifecycle of coastal infrastructure assets in The Bahamas.

Objective To recommend acceptable design practice for coastal infrastructure and increase the confidence of various parties to critically assess the process of coastal design.

Clarifications This guidance document should be read alongside the latest version of the Bahamas Building Code. However, the reader should be aware that this is not a building code but rather a guidance document to allow various stakeholders to make informed decisions for a variety of purposes: it does not prescribe design practice, but instead provides guidance on what performance criteria should look like.

Given the significant degree of complexity and variability associated with the coastal environment, general standardisation of recommendations and best practice is not possible. This document should therefore be read in consideration of the specific use-case that may allow for identification of unique efficiencies, opportunities, and risks.

1.3 Scope of document

This document considers the complete lifecycle of coastal infrastructure assets including preliminary studies such as flood and erosion risk assessments, data collection and surveys, design, construction, maintenance, and demolition. Guidance for the development of strategy-level studies such as Strategic Flood Risk Assessments and Coastal Zone Management Plans is not included.

This guidance relates specifically to **coastal** infrastructure. For the purposes of this document *coastal infrastructure* includes structures or assets with a function or providing a service specific to the coastal environment. Such services primarily include coastal protection (from flooding and erosion) and maritime activities. Guidance on designing assets that perform general functions but require unique considerations due to their placement in the coastal zone is also provided (Refer to Sections 5.8.3 and 5.8.4). This guidance does not include dwellings or commercial properties that lie within the coastal zone. Design guidance for these structures can be found within the appropriate building code.

Two examples to illustrate this point are provided below:

1. A residential property in the coastal environment will need to adhere to the building code; this guidance will not repeat standard design processes or requirements but will instead identify additional concerns that should be considered when such a structure is intended for the coastal zone. For instance, this could include restrictions on habitable floor levels or the

need for emergency access. It would not cover items outside the influence of the coastal zone such as internal accessibility needs or wind loading.

2. Services such as electrical systems or pavements may often be developed in accordance with generic designs or specifications. While this may be an appropriate and efficient approach in the terrestrial environment, its intended coastal location may likely lead to additional requirements to ensure its resilience to considerations such as regular inundation, wave loading, and salt exposure.

Dedicated guidance is provided for specific structure types under various categories of coastal infrastructure including:

- Flood/erosion protection assets
- Maritime infrastructure
- Outfalls
- Reclamation
- Infrastructure such as highways, promenades, and services within the coastal zone

While dedicated guidance is provided only for conventional structures, innovation is not precluded where the developer can demonstrate that their proposed design is appropriate and conforms with the underlying principles described in this document, especially as it pertains to reliability and risk.

1.4 Target audience and applicability

It is assumed that users of this guidance will have the minimum level of competency for their project and intended interest. For instance:

- users reading this for general and background information may have a very limited technical understanding of coastal processes,
- reviewers and implementers of the document should have a basic understanding of coastal processes and coastal engineering principles.

A selection of potential users and their anticipated uses are listed below.

- Governmental Authorities including:
  - Flood risk officers, environmental protection officers, and other planners: to facilitate review of proposed developments in the coastal zone.
  - Buildings control officers: to facilitate the implementation of planning conditions and eventual controls on the development and its construction.
- Developers: to facilitate conception, procurement, due diligence, and management of coastal projects.
- Designers and Engineers: for use as a guidance, but not as a design tool.
- The public: to support review of publicly av8(n)8(d)ogs backgroT/2(p)8(38(a)8(ma)8(t))8(.)]TJETQq0.000008873 0 595

information may be equally acceptable. Further documents are referenced throughout this guidance.

Table 1.1: Common technical design standards and guidance documents

Document title	Author/Issuer	Purpose	Relevance
The Coastal Engineering Manual (CEM)	(U.S. Army Corps of Engineers, 2006)	"The CEM provides a standard for the formulation, design, and expected performance of a broad variety of coastal projects." (2006 issue, Section I-1-1)	General
Shore Protection Manual	(U.S. Army Corps of Engineers, 1984)	Essentially the predecessor to the CEM. However, some useful information not included in the CEM may be useful for reference.	General
CIRIA Beach Management Manual (Second edition) (C685B)	(CIRIA, 2010)	Guidance for practitioners on beach management as a whole.	General
ASCE/SEI 24-14 Flood Resistant Design and Construction	(ASCE, 2014)	"This standard provides minimum requirements for flood resistant design and construction of structures that are subject to building code requirements and that are located, in whole or in part, in Flood Hazard Areas." (2015 issue, Section 1.1)	Management of risk and reliability, design practice
FEMA P-499 Home Builder's Guide to Coastal Construction – Technical Fact Sheet Series	(FEMA, 2010)	"The fact sheets present information aimed at improving the performance of buildings subject to flood and wind forces in coastal environments." (2010 issue, Introduction)	Design
BS 6349-1-1: 2013 Maritime works – General – Code of practice for planning and design for operations	(BSI, 2013)	"This part of BS 6349 gives recommendations and guidance on general criteria relevant to the planning, design, construction and maintenance of structures and facilities set in the maritime environment." (2013 issue, Section 1.1)	Data collection
BS 6349-1-2: 2016+A1:2017 Maritime works – General – Code of practice for assessment of actions	(BSI, 2017)	"This part of BS 6349 gives recommendations for the assessment of actions for the planning and design of maritime works." (2016 issue, Section 1.1)	Data collection and risk
EN 1990-0:2002 Eurocode – Basis of structural design	(BSI, 2002)	EN 1990 establishes Principles and requirements for the safety, serviceability, and durability of structures, describes the basis for their design and verification and gives guidelines for related aspects of structural reliability. (2002 issue, Section 1.1 (1))	Design
The Rock Manual. The use of rock in hydraulic engineering	(CIRIA, CUR, CETMEF, 2007)	"[…] presents current good practice for the design and construction of rock structures." (2007 issue, Section 1.2)	Materials and design
EurOtop Manual on wave overtopping of sea defence and related structures	(Van der Meer, 2018)	"The manual has been intended to assist an engineer analyse the overtopping performance of any type of sea defence or related shoreline structure found around the world." (2018 issue, Section 1.2)	Design
Advice to Inform Development of Guidance on Marine, Coastal and Estuarine Physical Processes Numerical Modelling Assessments	(Natural Resources Wales, 2017)	"[…] to review existing guidance on modelling approaches including requirements for establishing an adequate baseline understanding to support modelling assessments, including model set up,	Modelling

Document title	Author/Issuer	Purpose	Relevance
		calibration, validation and model run scenarios." "to review and summarise key information on model type, applicability, set up, and limitations, for available models which can be applied to the assessment of effects on the hydrodynamic and sediment transport regime in marine, coastal and estuarine environments."	
Guidance on Setup, Calibration, and Validation of Hydrodynamic, Wave, and Sediment Models for Shelf Seas and Estuaries	(Williams & Esteves, 2017)	"It addresses the common problems associated with data availability, errors, and uncertainty and examines the model build process, including calibration and validation." (2017 issue, Preamble)	Modelling
Manual on Hydrography	(International Hydrographic Organization, 2020)	"[…] a professional guide for hydrographic surveyors" (2005 issue, Preface)	Data collection – Bathymetric surveys
1110-1-1005 Control and Topographic Surveying	(U.S. Army Corps of Engineers, 2007)	"[…] guidance on performing detailed site surveys of military installation facilities and civil works projects."	Data collection – Topographic survey
National Standard Contract and Specification for Surveying Services	(Environment Agency, 2013)	"[…] standard specifications for the surveys most commonly commissioned by the Environment Agency"	Data collection – Topographic & bathymetric surveys
International Guidelines on Natural and Nature-Based Features for Flood Risk Management	(U.S. Army Engineer Research and Development Centre, 2021)	"Presenting a rational approach to the classification, evaluation, planning, design, operation, management (including repairing and upgrading), and construction of NNBF for coastal and riverine shoreline erosion, coastal and fluvial flooding, and flood risk mitigation"	Design – Nature-based solutions

Note: Readers should be aware of, and make use of, the latest version of external reference documents.

1.6 Document structure

The structure of the current document is driven by the various phases in the project lifecycle and is outlined in Table 1.2.

Table 1.2: Document structure

Section No.	Title	Description
1	Introduction to the Guidelines	Introduces the document and its purpose.
2	Risk, Resilience, and Reliability	Provides guidance around the management of risk, design life, and design events.
3	Coastal Zone Environmental Parameters	Provides guidance on appropriate data requirements. Includes guidance on modelling.
4	Coastal Flooding and Erosion Risk Assessment	Provides guidance on requirements around risk assessments including flooding, erosion, and environmental impacts.
5	Design and Appraisal	Provides guidance on possible design approaches and the suitability of various solutions.
6	Construction	Provides guidance on key considerations arising from the location of works in the marine environment.
7	Management, Maintenance, and Demolition	Provides guidance on key considerations from completion of construction up to and including demolition of coastal infrastructure.

2 Risk, Resilience, and Reliability

2.1 Risk tolerance and definition of minimum Standard of Protection

The objective of any design should always be to optimise the reliability[1] and resilience[2] of a coastal infrastructure project. However, an increase in reliability typically corresponds to an increase in capital costs (while also acknowledging possible negative impacts on the environmental sustainability of the development). This can lead to potentially conflicting priorities between developers and planners. The current section aims to standardise minimum expectations and provides guidance on:

- What may qualify as an appropriate risk tolerance depending on the severity of consequence in the event of failure (categorised by consequence class).
- The interpretation of typical measures of risk; mainly the relationship between the Annual Exceedance Probability (AEP)[3] of a storm event and the probability that the design conditions are exceeded over an asset's design life.

The levels of tolerable risk are driven by consequence of failure in terms of human life, economics, social considerations, and the environment. This will generally align with the priorities of the planners and control officers. However, a key priority for developers will include reduction of financial risk which may call for more onerous design requirements. As the developer is exceeding minimum requirements, this approach should be considered acceptable by planners and enforcers in terms of risk.

To illustrate this point, consider design of a private dock facilitating day excursions for visitors. While the low consequence of failure would require a relatively modest Standard of Protection[4] (SoP) (i.e., a relatively significant tolerable risk), the financial consequences may be significant due to the resulting disruption to operations. As such, the developer may desire greater reliability and therefore choose to design to a less frequent storm event than that required by the planning authority.

Guidance on what should be considered tolerable levels of risk for each consequence class are provided in Table 2.1.

Table 2.1: Definition of Consequence Classes

Consequence class	Description	Examples	Minimum Standard of Protection
• C3 (Most critical)	• **High** consequence for loss of human life, • or;	• Maritime infrastructure critical for delivery of	0.5% AEP or;

1 Reliability: As it pertains to design, the probability of failure.

2 Resilience: The capacity of a system or asset to withstand or recover quickly from a variety of external and internal stressors, to continuously perform as required now and in the future.

3 Annual Exceedance Probability (AEP): The probability that an event will, on average, be met or exceeded in any given year.
Return Period: The average time, in years, between occurrence or exceedance of a particular event.
While the Return Period and AEP are numerical inverses of each other, the perception of the two commonly differs; the term Return Period is commonly misinterpreted and should be used with care. This document primarily uses AEP.

4 Standard of Protection: The most severe event, defined by Annual Return Period or Annual Exceedance Probability, for which a defence should effectively fulfil its function.

Consequence class		Description	Examples	Minimum Standard of Protection
		• **Very high** economic, social, or environmental consequences.	emergency supplies following disaster events. • Coastal defences protecting critical energy infrastructure such as large-scale power stations and water treatment plants. • Critical coastal defences protecting population centres. • Critical coastal defences protecting key economic hubs	the %AEP corresponding to the event with a Return Period equal to the design life[5], whichever the less frequent
C2	• C2.A	• **Medium** consequence for loss of human life, • or; • **High** economic, social, or environmental consequences.	• Coastal defences protecting important energy infrastructure such as small-scale power stations and water treatment plants • Beach control structures/systems for beaches of particular economic or social importance. • Coastal defences protecting important roadways. • Large hotels • Large residential developments (many properties). • Large commercial developments (unless specified otherwise).	1% AEP or; the %AEP corresponding to the event with a Return Period equal to the design life, whichever the less frequent
	• C2.B.1[6]		• Residential developments (single to few properties). • Structures that are not in class C3 or C1.	
	• CS.B.2		• Small to medium scale commercial properties. • Access routes of moderate importance such as those serving a significant number of non-critical developments or those not required for essential connectivity, but key to efficient traffic management.	2% AEP or; the %AEP corresponding to the event with a Return Period equal to the design life, whichever the less frequent
•	C1 (Least critical)	• **Low** consequence for loss of human life, • and;	• Coastal defences protecting minor access roads and	10% AEP or;

[5] Design life: The life expectancy of a development or structure. This does not necessarily need to correspond to the SoP.

[6] Sub-classes of C2 have been developed to align with Flood Risk Assessment considerations as per Section 4.2.

Consequence class	Description	Examples	Minimum Standard of Protection
	• **Low or negligible** economic, social, or environmental consequences.	other infrastructure of low importance. • Access routes serving developments that, during the design event, are sure to be absent of people and that will not require access during or shortly after storm events. • Temporary structures.	the %AEP corresponding to the event with a Return Period equal to the design life, whichever the less frequent

Source: Adapted from Table B1, Eurocode EN 1990:2002 (BSI, 2002)

2.2 Interpretation of risk and reliability

It is important to consider the AEP in relation to the design life of the structure. A useful way to view this is by considering the *Encounter Probability*[8]. This may be calculated using the following equation.

$$p_L = 1 - \left(1 - \frac{1}{RP}\right)^L \qquad \textit{where:}$$

p_L *is the probability of exceedance for a useful lifetime of* L

L *is the useful lifetime of the structure being considered*

RP *is the return period, in years, corresponding to the AEP of the event being considered*

For example, the encounter probability of a 1% AEP event for a structure with a design life of 50 years is approx. 39%.

Further information may be found in Section 15 of BS 6349-1-2:2016 (BSI, 2017)

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2.3 Definition of the design event

2.3.1 Typical process to define the design event

Understanding of the design event is critical for the design processes as it will have direct implications on the achieved reliability. The typical process is outlined in Table 2.2.

Table 2.2: Typical process to establish design conditions

Step	Description
1 Decide the intended reliability of the structure.	The objective of this step is to agree the desired reliability of the development, as discussed in Section 2.1. This is normally accomplished via agreement of the event (defined by its AEP) to which the development will be designed. Design conditions should consider future impacts due to climate change. Refer to Section 3.13.
2 Translate AEP to environmental conditions.	The objective of this step is to understand what conditions the required AEP event corresponds to. For instance, this step would define the 100-year wave height in terms of absolute values in metres/feet. Depending on the development, this process may need to

[8] Encounter Probability: The probability that the return period event will be encountered at least once within the useful lifetime of the structure.

Step	Description
	be carried out for several parameters depending on the anticipated failure scenarios that will need to be assessed. For this reason, some iteration between this step and step #3 will normally be required. Associating AEP to design parameter conditions is typically accomplished via an Extreme Value Analysis (EVA)[9]. EVAs will normally require continuous historic datasets for as long term as possible. For further information on the EVA process, refer to the World Meteorological Organization/JCOMM's technical report, Extreme value analysis: wave data (World Meteorological Organization & JCOMM, 2011) .
3 Understand the conditions corresponding to the critical design events.	The objective of this step is to identify the scenarios corresponding to potential failure scenarios that will need to be assessed. *Scenario* refers to a combination of environmental conditions. Multiple scenarios will normally need to be assessed so that various failure mechanisms can be designed for. For instance, design of a rock revetment may require undertaking EVAs on wave height, period, and direction; storm duration; and surge such that the structure may be adequately designed against failures such as toe instability and excessive overtopping. Assuming design to the 2% AEP event (i.e. 50-year design return period), it is important to note that the 50-year design scenario is not necessarily the combination of the 50-year wave height, wave period, storm duration, surge height, etc. as these will not necessarily occur at the same time or represent the critical scenario.

2.3.2 Implications of hurricanes on the process to define the design event

The Extreme Value Analysis (EVA) process as indicated in Step #2 is limited in the context of The Bahamas by:

- Its reliance on long term historic datasets which will often not be available.
- The implications of design conditions being driven by hurricane events.

The current discussion is around the latter point pertaining to hurricanes. The availability of historic datasets is discussed in Section 2.3.1 and throughout Section 3.

The typical EVA process based only on measured datasets will normally be under-conservative due the partial randomness in hurricane tracks. Given the discrete and relatively localised nature of hurricane impacts, storm tracks can significantly influence the conditions experienced at a site, the probability of which will not normally be adequately captured in the subsequent EVA. Therefore, it is recommended to modify the EVA process towards a bottom-up approach whereby hurricane tracks are separated by their intensities and managed almost independently. Two possible approaches, in order of increasing complexity but also reliability, are described in Table 2.3.

Table 2.3: Potential approaches to reliably design to hurricane conditions

Approach	Description
1 Hybrid approach	Carry out a typical EVA to identify a suitable design storm corresponding to the required AEP. This will provide the design storm based on intensity and actual historic storm tracks. However, the track of this storm should then be artificially varied such to represent worst case conditions at the site of interest. This approach will generally be appropriate for most developments, assuming the availability of suitable historic datasets on which to carry the initial EVA. This may be best accomplished using numerical modelling but may also be adequately carried out to a lower level of detail via more manual techniques.
2 Synthetic hurricanes	To get around the limitation of uncomprehensive datasets, an alternative approach is to make use of numerical modelling tools to run hundreds to thousands of simulated, or synthetic hurricanes. In this way, an artificial long-term dataset can be extracted at the site that is appropriate to feed into a conventional EVA process. While this represents the most comprehensive approach, it is also the most onerous and requires a high level of modelling expertise.

[9] Extreme Value Analysis: A statistical technique to associate Annual Exceedance Probabilities to environmental parameters.

3 Coastal Zone Environmental Parameters

3.1 Section purpose and structure

This section discusses data requirements for coastal design processes, providing guidance on:

1. Minimum levels of data reliability recommended for various project types.
2. Key considerations and clarifications pertaining to the use and commissioning of that data type
3. Key considerations when collecting data through surveys or similar.

Key questions this section intends to support include:

- What is the minimum level of information that should be gathered such that the design is adequately reliable within the geographical situation?
- Will dedicated surveys be required or is it instead appropriate to make use of existing/historical information or assumptions?
- Assuming dedicated surveys and similar are required, what information should be captured and are there any complications or challenges to be managed?

This section is structured as shown in Table 3.1.

Table 3.1: Section structure breakdown

Sub-section	Heading	Description
3.2	Minimum levels of data reliability by project category	Definition of minimum levels of data reliability by project type in addition to associated notes and considerations.
3.3	Additional data considerations	Further considerations relating to the collection and use of data.
3.4 to 3.12	Wind to Extreme temperatures	For each data type: ● Requirements: General context around the relevance of that data to coastal design and how to achieve the various levels of data reliability. ● Key considerations: Such as common pitfalls or opportunities in addition to clarifications associated with that data type. ● Data collection: Assuming such activities are required, provides guidance on the commissioning and assessment of surveys, data collection exercises, and modelling including how to acquire reliable and useable data while highlighting common constraints and limitations. The guidance focuses on considerations specifically in relation to the coastal zone.
3.13	Climate change	Recommended approach to account for future conditions in consideration of climate change.
3.14	Modelling	Guidance on the use and procurement of physical and numerical modelling.

3.2 Minimum levels of data reliability by project category

The coastal environment is a variable and complex environment. Therefore, the acquisition of accurate and reliable data is essential to understand the site conditions and design requirements. However, the sensitivity of a project's design process to different input data will vary; certain input parameters may be adequately captured using high level data while others may require maximum accuracy captured via dedicated site-specific surveys. Essentially, the

level of data reliability informing a design should be proportionate to the project in terms of both successful project delivery and management of risk.

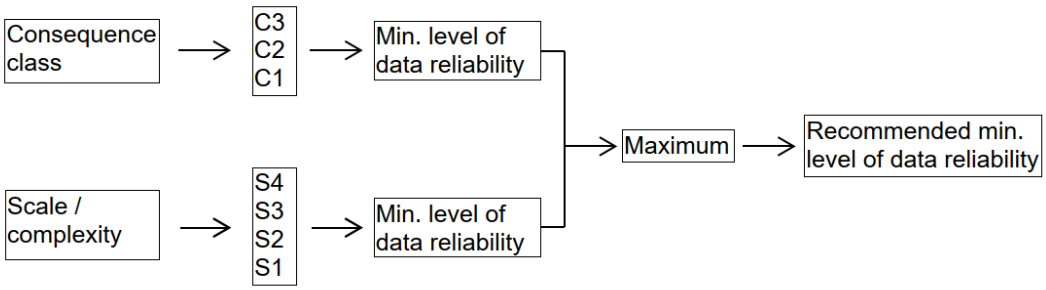
The objective of this section is to provide guidance as to what may constitute *proportionate*, taking into account typical sensitivities of designs to certain data types thereby facilitating an efficient, yet reliable, design process.

Data requirements are described in terms of *level of data reliability*. This term should be understood as a reflection of the accuracy, precision, and confidence of the data which will in turn feed into the reliability of the design. Recommended minimum levels of data reliability have been developed as functions of:

1. Project criticality in terms of consequence of failure, and;
2. Project scale and/or complexity.

Projects should be assessed using under both criteria with the final minimum level being the maximum of the two results. This process is illustrated via a flow diagram as in Figure 3.1 and developed further in Sections 3.2.1 to 3.2.3.

Figure 3.1: Flow chart of process to define the recommended minimum level of data reliability



While a single minimum level of detail is assigned for all data for a project, requirements can vary by data type depending on the sensitivities of the design to that data type and practical considerations. However, the decision to use information of lesser reliability for any data type should be fully justified by the developer and subsequently reviewed by planners and enforcers in a holistic manner.

Key considerations such as common pitfalls or opportunities associated with each data type will also be highlighted to provide context around the acquisition of reliable and appropriate data for the project needs. The parameters discussed in this Section are those most commonly of particular importance in the design of coastal infrastructure and should therefore not be regarded as an exhaustive list.

3.2.1 Data reliability by Consequence Class

Minimum recommended levels of detail as a function of the project criticality, categorised using Consequence Classes (defined in Section 2.1/Table 2.1) are presented in Table 3.2.

Table 3.2: Minimum level of data reliability by Consequence Class

Consequence class	Min. level of data reliability
C3 (Most critical)	3 (High)
C2	2 (Medium)
C1 (Least critical)	1 (Low)

Note: The recommended minimum level of data reliability should apply to all data types unless the developer can demonstrate otherwise.

3.2.2 Data reliability by project scale/complexity

Minimum recommended levels of detail as a function of the project scale or complexity are presented in Table 3.3.

Table 3.3: Minimum level of data reliability by project scale and complexity

Project scale/complexity	Min. level of data reliability	Examples
S4 (Very large or highly complex)	3 (High)+	Commercial ports; Large private marinas (indicatively >100 berths); critical breakwaters; groyne series; rubble mound structures in exposed environments; outfalls; large beach recharge schemes (indicatively >15,000,000ft^3 (~400,000m^3) of sediment); large dredged pockets/channels (indicatively > 500,000ft^2 (~50,000m^2)).
S3 (Large or of medium complexity)	3 (High)	Medium sized private marinas (indicatively 25 to 99 berths); medium sized beach recharge schemes (indicatively 50,000 to 500,000 m^3 of sediment); medium sized dredged pockets/channels (indicatively 50,000ft^2 (50,000m^2) in plan)
S2 (Medium and of low complexity)	2 (Medium)	Private docks for medium sized vessels (indicatively 40-60ft (12-18m)); private marinas and associated small breakwaters; seawalls and revetments in exposed environments; small dredging works. Also local flood and erosion risk assessments.
S1 (Small and of low complexity)	1 (Low)	Private docks for small vessels (indicatively <40ft (12m)); seawalls of limited lengths in sheltered environments; pedestrian boardwalks, less important beach access structures, temporary structures Also high level or strategic designs such as concept design, feasibility studies, master planning, and strategic flood an erosion risk assessments. However, such studies are not typically subject to planning or other regulatory bodies.

Notes: Structures with high degrees of interaction with sediment transport and hydrodynamics should generally be considered highly complex.
+ Data collection and manipulation should be rigorous and of the highest reliability.
The recommended minimum level of data reliability should apply to all data types unless the developer can demonstrate otherwise.

3.2.3 Definition of Level of data reliability categories

Categories of *level of data reliability* are indicated in Table 3.4. These are indicated in greater detail for specific data types in the subsequent sub-sections.

Table 3.4: Description of levels of data reliability

Level of data reliability	Description	Common data collection approaches
3 (High)	Measured data for the specific site	• Dedicated data collection activities such as topographic/bathymetric surveys, installation of temporary or permanent weather stations, tide gauges, and wave buoys or acoustic doppler current profiler instruments. • Use of measured data from a strongly comparable site for that data type.
2 (Medium)	Measured data from comparable or nearby locations extrapolated or modified to reflect local site conditions.	• Acquisition of measured data from a nearby or comparable site and transformed to the local site. • Inference of offshore conditions based on design hurricane conditions and transformed to site.

Level of data reliability	Description	Common data collection approaches
	Alternatively, measured data collected to reduced but acceptable reliability (in terms of time, accuracies, precision, transparency of collection process, etc.)	● Assumption of expected surge levels based on experience of historic storms comparable to the design scenario. ● Acquisition of out-of-date data for the site. ● Inferred/extrapolated from measured data from similar locations using empirical and analytical formulae.
1 (Low)	Typical / expected conditions	● Data collection generally limited to acquisition of existing information, assessed critically for reliability and suitability, and applied critically using best engineering judgement. ● Assumed site conditions based on high level concepts and/or local knowledge/experience. For instance: – Conservative design to the maximum unbroken wave based on approximate local bathymetry. – Assumption of expected surge levels based on experience of historic storms comparable to the design scenario.

3.3 Additional data considerations

3.3.1 Note on temporal data requirements

Measured data represents a snapshot in time of certain conditions. This may be appropriate, depending on the intended use of that data. However, partly due to the dynamic nature of the marine environment, design processes of coastal infrastructure are typically driven by risk management – this requires adequate understanding, and quantification of site conditions and event probabilities which is normally only achievable with an historical dataset of sufficient duration, continuity, and reliability.

3.3.2 Note on Health and Safety

Given collection of marine data will typically require operations either in or above water, such activities will typically be associated with increased safety risks. Any required surveying or data collection activities should be undertaken by suitably experienced and qualified personnel only. Health and Safety (H&S) risks should typically lie with, and be actively managed by, the party leading the activity. Best practice is to develop and adhere to a bespoke Health and Safety Risk Assessment (HSRA) prior to any in-field activity.

3.3.3 Note on reference systems

Collection of elevations, such as seabed, land, and water levels, should always be undertaken against a known, standard reference system both horizontally and vertically. The choice of reference system should be driven by its appropriateness to the location (for instance in consideration of projections), its compatibility with other surveys to enable different datasets to be related to each other if needed, and any practical constraints.

While coastal design is commonly undertaken relative to current and future mean sea level, construction will typically require absolute elevations in the local vertical datum. Therefore, the relationship between the two needs to be clearly and reliably understood. This understanding will also be critical to relate topography with water levels, especially in relation to flood risk and structure tie-in requirements.

Construction to relative levels may, at times, be appropriate. For instance, for design of repairs to an existing structure, it would normally be acceptable to refer to relative levels from a fixed relative point such as the crest height or a bedrock level.

The intricacies of this process are strongly dependent on specific project requirements and context and should normally be managed by the designer; the focus for developers and governmental authorities should be to have confidence that the final designs are buildable, will be constructed to the actual levels intended, and have adequately considered the proposed design in relation to existing structures and assets.

3.3.4 Note on instrument calibration, and installation

It is generally advisable to ensure instruments deployed for data collection activities are calibrated and installed directly by the manufacturer given their expertise with that specific equipment. Servicing and maintenance should be carried out by a competent party, which usually requires a form of training if to be done in-house.

3.3.5 Note on proprietary restrictions

Developers should be aware that proprietary restrictions may apply when attempting to acquire existing datasets. This common challenge should also be appreciated by planners and enforcers. For instance, wind data acquired at publicly owned locations such as airports typically lies with the Department of Meteorology who is under no obligation to share wind data records. It is recommended that efforts be made to encourage the sharing of data as far as possible by those in a position to do so.

3.3.6 Note on data availability

The need for data collection activities should be understood as early on in the procurement and design process as possible due to the potential for significant impact on project timelines.

Reliable and efficient design processes often call for historical robust, long-term datasets. Examples of common tasks that inherently rely on such data include:

- Extreme Value Analysis[10] of winds, waves, etc. – frequently needed when defining design conditions to meet the required performance criteria.
- Assessment of historical erosion rates – typically an early step when understanding erosion risk.
- Identification of lowest credible beach levels – a common design parameter for structures such as seawalls (e.g. to design against undermining) or access points (to ensure continuous safe access).

The lack of such data is anticipated to be a recurring theme for reliable design of future coastal infrastructure projects given the limited number of formalised public data collection schemes at present (2023). Much of the information believed to exist is understood to be inhibited by proprietary restrictions (See Section 3.3.5). Even should owners be willing to share information, the awareness of what information exists and where to find it remains limited.

As a result, it will often not be possible to take the preferred design process forward. Furthermore, a reduced reliability in the underlying data will typically lead to reduced reliability in the final design. Designers will need to actively manage this risk by adopting a conservative design philosophy, making additional allowances as needed, and communicating risks to developers. Developers should support designers if they are able, for instance by making the most of connections or past projects to facilitate the sharing of existing information. Planners

[10] Refer to Section 2.3.1.

Level of data reliability	Description	Common data collection approaches
2 (Medium)	Measured data of reduced reliability for the site.	Obtain the existing wind records from the nearest available location. At this level of reliability, greater allowance can be made for data: ● Measured at a significant distance from the site. ● Measured at lower frequencies and precision. ● Collected historically but lacking recent years. ● Lacking transparency around the data collection methods. While it may be difficult to assess the level of reliability of existing data, sense checks and cross-references against other data sources should be undertaken as a minimum to ensure the data is suitable for the intended use. Alternatively, wind inputs may be based on wind maps or similar developed under existing strategic studies. Performance criteria should be driven by a risk management process, captured by design events defined by their Annual Exceedance Probability (AEP). However, should it be accepted that a design is to be carried out to an X-category hurricane event, wind speeds may simply be assumed to correspond to the intended design event as per the definition of hurricane categories.
1 (Low)	Typical conditions or high-level datasets	For very simple, low consequence designs, it may be appropriate to design according to a specific hurricane event without a complete understanding of the associated probabilities of occurrence. In such an instance, wind speeds may simply be assumed to correspond to the intended design event as per the definition of hurricane categories. Alternatively, wind speeds may be extracted from regional, coarse datasets that are normally based off of high level numerical models.

Note: The use of existing data should always be assessed for reliability prior to use.

3.4.2 Data collection

3.4.2.1 Data sources

Typical sources of wind data and associated commentary are provided below.

- Airports – existing data very likely. However, ownership of wind data acquired at public establishments such as airports typically lies with the Department of Meteorology who is under no obligation to share wind data records.
- Ports – existing data moderately likely for large ports. Otherwise, ports may acquire wind data from instruments on board vessels such as tugs and larger cruise or cargo ships. However, this data is likely to be discontinuous and should be associated with a reduced confidence.
- Regional datasets, typically the results of large-scale modelling, should be regarded as low reliability not suitable for most design processes but acceptable for use in providing developing large scale numerical models. These datasets are not typically open source.
- Depending on the design event and level of data reliability required, wind speeds may simply depend on the design hurricane conditions.

3.4.2.2 Key considerations

Items of particular importance when acquiring wind data are highlighted in Table 3.6. The recommendations apply whether collecting data via dedicated wind stations – in which case there is full control – but can also be useful in understanding the reliability of existing datasets.

Wind data can typically be obtained in two parts:

3. Long-term wind records from established wind stations or regional datasets, depending on reliability requirements.
4. Shorter-term wind records, most commonly to be obtained through dedicated, temporary wind stations and used to calibrate longer term datasets to local site conditions if required.

Table 3.6: Key considerations – Wind

Parameter	Recommendation	Comments
Key information to capture	Wind speed, wind direction, and atmospheric pressures	The capture of atmospheric pressures is also recommended to facilitate an understanding of surge heights and storm event intensities.
Temporal interval	<30min	Critical wind speeds typically occur during storm events. However, should wind speeds be recorded at large intervals (indicatively >30min), peak wind speeds are likely to be missed; if this is suspected to be the case the uncertainty should be accounted for in the design.
Record duration and period	>3months if to be calibrated against a long-term dataset, any season.	However, if wind records are captured for summer only without the occurrence of tropical storm events, consideration should be made to extend the monitoring period into winter months to capture a greater range of wind speeds.
Elevation at which wind speeds are captured	Well above ground levels, clearly recorded (a common standard is 30ft (~10m))	Wind is significantly affected by friction and obstacles at ground level.
Obstructions	Situated in a location clear of large obstacles such as tall buildings or hills	Data should avoid irrelevant localised variations in wind behaviour as far as possible to ensure validity across the site.
Security	Anti-tampering measures should be considered	The security of the equipment is best managed by careful selection of its location – equipment should be set up such that is remains inaccessible to the general public. The installation should also be able to withstand and remain operable under severe storms within reason.

3.5 Waves

3.5.1 Requirements

An understanding of waves and their interaction with the environment and structures is critical for the attainment of a reliable design. Any sea state will consist of a spectrum of waves, varying by height, length/period, and direction. Some design approaches, normally those using numerical modelling techniques, may run individual waves within this spectrum. Others, such as standard deterministic approaches that use empirical formulae may make use of a single representative wave – most commonly the significant wave height (H_s), which corresponds approximately to the limit of the upper third of wave heights.

While the maximum wave heights are generally the driving design parameters – as wave energy is proportional to the square of its height, the highest waves are therefore typically the most destructive (though there are exceptions). Other failure mechanisms may be induced by maximum waves at lower water levels or long period waves despite reduced heights. Long-term sediment transport is typically driven by the general wave climate and local current behaviour.

To allow data to remain relevant to a wider area, long term wave data is typically captured at deep water – such that the influence of the seabed is negligible for most wave heights. A key activity for the designer, therefore, is the transformation of offshore sea states to the nearshore. This transformation may be accomplished via numerical modelling. However, where the shoreline and nearshore are relatively uniform such that conventional transformation theories

remain relevant, dedicated numerical modelling will likely be excessive unless required in support of other project activities.

Table 3.7: Level of data reliability – Waves

Level of data reliability	Description	Common data collection approaches	Typical use cases
3 (High)	Measured data appropriate to the site.	Obtain measured long term, offshore wave data captured at an appropriate location. Appropriate locations would typically be offshore with suitable sites to make use of it being those that would experience comparable sea states, considering influencing factors such as islands, reefs, cays, and other areas of shallow water. Data collection will normally involve offshore wave buoys but alternative systems may also be appropriate. In the absence of suitable measured wave records, long term data from regional models may be purchased but should normally be supported by dedicated temporary instalments near the site. In the former or latter case, even greater reliability may be obtained by supporting the transformation from deep to shallow water waves with temporary instruments in the nearshore. However, this would normally only be done at site with particularly complex hydrodynamics.	Numerical modelling, especially for sites subject to complex hydrodynamics. It may be appropriate to transform offshore waves to nearshore conditions via non-modelling methods where the coastline and bathymetry is relatively uniform such that conventional transformation theories remain relevant.
2 (Medium)	Measured data of reduced reliability for the site.	As level 3 but based on data captured at locations less suitable for the site – however, sea states should still be comparable to the site. At this level of reliability, deployment of dedicated temporary instruments will generally not be required.	Data to normally be acquired for offshore conditions to be transformed to the nearshore using well-established relationships (as opposed to numerical modelling which would typically not be undertaken at this level of reliability).
1 (Low)	Typical conditions or regional datasets	Assumed conditions based on high level information. For instance, this may include design waves taken as the maximum unbroken waves based on local bathymetry – though local bathymetry would preferably be at a medium level of reliability. This should be estimated in consideration of the design water level (e.g. allowing for surge). Alternatively, design waves may be taken from previous studies of reduced but reasonable reliability.	Data to be used to guide assumptions. Engineering judgement and clear tracking of assumptions will be particularly important. Associated risks should be well-communicated and managed through conservative design as a minimum.

3.5.2 Data collection

3.5.2.1 Data sources

Typical sources of primary and secondary wave data are listed below.

- Dedicated instruments such as wave buoys and Acoustic Doppler Current Profilers (ADCPs). Wave buoys are commonly installed and maintained at offshore locations. These must then typically be transformed to represent nearshore conditions via:
  - Numerical modelling.

  - The application of hydrodynamic principles and empirical formulas such as Goda wave theory.
  - The theoretically maximum unbroken wave based on nearshore bathymetry.
  - Care should be taken around the design water level which will affect waves in shallow and intermediate water depths[11].
- Offshore waves may also be estimated via a fetch analysis[12] to estimate waves induced by sustained wind over a distance of open water.
- Regional, high-level datasets for offshore waves developed by high-level modelling based on measured data. However, these are typically used as boundary condition inputs to local hydrodynamic models.

3.5.2.2 Key considerations

This section will describe key considerations when obtaining primary wave data. Secondary wave data via modelling is addressed in Section 3.14 though the information provided here may also support an understanding of the reliability of existing data. For secondary wave data via analytical and empirical approaches, refer to standard coastal theories. A good starting point would be the Coastal Engineering Manual (U.S. Army Corps of Engineers, 2006) that should be familiar to competent designers. Developers and enforcers should have at least a high-level understanding of such theories to allow for effective understanding of design processes.

When acquiring wave data, the factors outlined in Table 3.8 are of particular importance.

Table 3.8: Key considerations – Waves

Table Item	Recommendation	Comments
Key information to capture	Wave heights and wave periods as a minimum. Depending on project requirements and the type of instrument to be deployed, additional useful data may also be captured.	Most stations will be suitable for inclusion of additional instruments to measure parameters such as air and sea temperature, current speed and direction, physio-chemical parameters, turbidity,
Typical data collection techniques	Wave buoys (typically existing e.g. NOAA-operated) ADCP instruments (typically commissioned) and similar Alternative methods such as those using radar or satellite or those inferring wave conditions from secondary data.	Quality of data captured is typically comparable across techniques. Selected technique is typically determined by practical considerations such as availability and deployment methods. Wave buoys: Preferred for long term offshore datasets due to ease of maintenance. However, increased risk of vandalism. ADCP and other submerged instruments: Potentially suitable for use in heavily trafficked locations and reduced risk of vandalism or damage due to collisions or storms. However, increased maintenance costs. Alternative methods: May be applicable when low resolutions are required or when aimed at capturing long term data to inform on wave climate as opposed to capturing detailed timeseries of storm events.
Maintenance requirements	To be considered prior to purchase or deployment of any instrument.	Maintenance will be required to ensure moorings remain secure and the instrument remains in good condition. Key activities, aside from inspection, will include removal of biofouling, and battery and component replacements.

[11] Under Linear Wave Theory, shallow, intermediate, and deep water are defined by the ratio of water depth (d) to wavelength (L) as follows. Shallow water where d/L < 0.05. Intermediate water where 0.05 < d/L < 0.5. Deep water where d/L > 0.5.

[12] Fetch Analysis: A technique to predict wave generation based on distances of open water and wind speeds.

Table Item	Recommendation	Comments
		Efforts – including careful selection of the instrument type, location, and visibility – should be carefully considered especially in relation to risks of storm impacts, vandalism, and vessel collisions which are often significant. Real-time remote communications should be set up to immediately identify equipment loss/malfunction and trigger a pre-determined recovery plan.
Location	Waves recorded in deep water offshore of the site. Ideally a second instrument capturing transformed, nearshore waves impacting the site.	Shallow water waves will be significantly affected by complex interactions with bathymetry and any nearshore objects or bed conditions. The capture of offshore waves allows for better association of waves with storm events and their corresponding AEP as well as improving the relevance of the information for the wider site and beyond. Location is also important for mitigating risks of equipment vandalism or loss.
Record duration and period	>3months if to be calibrated against a long-term dataset, any season.	However, if records are captured for summer only without the occurrence of tropical storm events, consideration should be made to extend the monitoring period into winter months where average sea states are more energetic.
Vertical reference system	With known relationship to topographic data	Data capture is typically reliant on remote satellite connections. The vertical datums in which data is typically recorded is therefore distinct from the local systems typically used onshore. The separation between them should therefore be understood in order to associate water levels with the topographic and construction elevations.

3.6 Tides

3.6.1 Requirements

Tides are highly predictable variations in water levels, driven by movements of the sun and moon (technically referred to as ‘astronomical tide’), and should be understood due to their relevance in affecting waves, ability to drive and impact currents, role in the wetting and drying of structures, and their influence on ecology. The tidal range in The Bahamas is limited and will therefore often be a relatively less important design factor than in schemes elsewhere in the world; nevertheless its consideration remains important.

Local variations in tidal height and behaviours may arise where the ingress/egress of water is constrained. Common instances would include canal and mangrove systems and harbours with restricted access channels/entrances. However, this will generally not be significant especially in relation to surge heights, sea level rise in time, and the associated uncertainties with each.

When considering water levels, components are best managed and communicated separately; this facilitates easy application of additional uplifts if needed (normally to account for uncertainty). The most important contributions to the overall water level include:

- Tide states
- Contribution to surge of low atmospheric pressures
- Contribution to surge of sustained winds
- Wave set-up
- Sea level rise (Refer to Section 3.13)

Table 3.9: Level of data reliability – Tides

Level of data reliability	Description	Common data collection approaches	Typical use cases
3 (High)	Known tidal levels for the island of the site, or for an island near the site.	Obtain tidal levels for the island at which the site is situated (or near to) as communicated by the Department of Meteorology or another reputable source. Deploy temporary ADCP or similar equipment to record wave heights and water levels and acquire tidal levels via a harmonic analysis exercise or similar. Deployment of instruments exclusively for this purpose would not typically be expected. In the absence of reliable data for the site, design will normally be able to progress without dedicated data collection efforts. However, efforts should be made to reduce the uncertainty by cross-checking against multiple sources such as regional models, historic projects, and interpolating between available records for other locations if appropriate.	Most design activities.
2 (Medium)	As 3 (High)	As 3 (High)	As 3 (High)
1 (Low)	Known tidal levels as per the nearest available dataset.	-	High level studies such as feasibility assessments, concept design, and flood and erosion risk assessments.

3.6.2 Data collection

3.6.2.1 Data sources

Historic and predicted tide levels should generally be recorded and published by the relevant authorities. However, in the absence of reliable existing records, it is normally the responsibility of the designer to manage the associated uncertainty in a proportional manner.

Typical sources of tidal data and associated commentary are provided below.

- Department of meteorology – based on historic tide gauges and subsequent extrapolation across the archipelago. The reliability of this data may be limited by the low number of available tide gauges and the historic extrapolation techniques adopted to date.
- NOAA (the American National Oceanic and Atmospheric Administration) – similar to the above case, tide predictions appear to be based on a limited number of permanent tide gauges.
- Published navigation charts – these give levels to Chart Datum which is the typically the lowest tide level. Where the data is available the relation between Chart Datum and the local and levelling datum will usually be stated.
- Various online sources typically advertised in connection to water sports or fishing activities – such sources are generally not intended or appropriate to support design.

3.6.2.2 Key considerations

Tide levels can be extracted through the processing of water levels gained from installation of a shore-based tide gauge, using harmonic analysis processes or similar. This is normally the most cost-effective method of collecting such information given the relative simplicity of the instrument itself and most importantly its shore-based location allowing for easy installation and

maintenance in addition to greater control against risks such as storm impacts, vessel collisions, and vandalism.

It is also possible to collect water level information using alternative systems such as those described in Section 3.8.2.

Table 3.10: Key considerations – Tides

Item	Recommendation	Comments
Key information to capture	Water levels from which tide heights and surge can be extracted.	The following tide levels should be identified: – Highest astronomical tide (HAT) – Mean high water springs – Mean high water neaps – Mean still water – Mean low water neaps – Mean low water springs – Lowest astronomical tide
Instrument types	Either above-water or below-water installations.	Tide gauges are available suitable for installation above-water or below-water. Above-water installation will typically make use of radar or ultrasonic measurement systems while below-water systems normally take the form of pressure sensors. Above-water systems will allow for easier inspection and maintenance and benefit from reduced biofouling. However, their presence on the surface may present an access constraint or take up valuable space and may be more susceptible to storm damage. Below-water systems will be less conspicuous and may be safer during storms but are associated with greater, but still relatively low, maintenance requirements.
Installation location of tide gauge	Such to ensure a continuous and reliable dataset.	Siting of the gauge is important and the following factors should be considered[1]: a. The gauge should be in sufficiently deep water to avoid drying out (note that this would not apply in the case of 'top-down' sensor systems that are placed above water); b. It should be sheltered as far as possible from the effect of sea and swell; c. It should not be in a position where water is impounded as the tide drops; d. It should be reasonably close to a national or local land levelling datum reference point; e. It should be sheltered from accidental damage by vessels; f. It should not be mounted or fixed on members that are subject to settlement.
Record duration and period	Greater than 2-3 months for basic tidal analysis but reliability of the resulting estimates of mean tidal levels will increase in time.	A minimum of 1 month of continuous water level data is likely sufficient for a basic understanding of tidal behaviour. However, an understanding of mean tidal states and lowest and highest astronomical tides will require longer-term records (at least several years, a full astronomical tidal sequence is 18.6 years).
Temporal interval	Typically a sample duration of 60 seconds every 5 minutes.	Data normally subsequently undergoes time-averaging processes.

[1]Source: adapted from British Standards 6349-1:2013, pp. 28 (BSI, 2013, p. 28)

3.7 Currents

3.7.1 Requirements

Currents refer to the physical movement of water – as opposed to waves, for instance, which mainly refer to a transmission of energy. Currents are typically complex yet need to be understood for their role in:

- Loadings on structures
- Influence on ship movements
- Sediment movement
- Diffusion of suspended and dissolved substances
- Transport of floating or suspended objects and particles

Currents can be induced in a number of ways as outlined in Table 3.11.

Table 3.11: External drivers with potential to induce currents

Inducing factors	Comments
Regional to global variations in solar energy, water levels, and other environmental conditions	These drivers will typically correspond to permanent or seasonal ocean currents.
Tides Driven by gravitational effects of moon and sun.	Tidally-induced currents are commonly the driving design parameter for coastal design and long-term sediment transport in particular. Tidal currents are periodic and cyclical, though not always symmetrical, with daily and lunar monthly periods.
Waves including those undergoing diffraction or refraction and those induced by radiation stresses	Wave-induced currents are often those most readily acted on via coastal infrastructure works; for instance, nearshore breakwaters locally influence currents to encourage sediment accumulation.
Interactions with nearshore processes including wave breaking and set-up	Undertow is a seaward-directed current resulting from the incidence of waves on the shore. It is particularly relevant during storm events as it is the driver of offshore sediment transport. However, such currents are normally only considered in an indirect way through assessment of the associated sediment movement. Instruments are rarely placed within the breaking zone so such current are not normally observed directly.
	Certain nearshore bathymetry can prevent undertow from occurring uniformly along a frontage. Such a scenario can lead to rapid, locally concentrated currents known as riptides – a hazard to swimmers. Instruments are rarely placed within the breaking zone so such current are not normally directly observed.
Breaking waves on structures	The interaction of waves and structures can lead to local hydrodynamic variations including changes in current velocities. One such example is when waves incident on structures lead to currents directed vertically downwards towards the structure toe – with potential to induce scour and subsequent undermining. Instruments are rarely placed within the breaking zone so such current are not normally directly observed.
Vessel movements and propellor/jet action	Currents generated by propellor and jet systems can be significant and particularly relevant for berthing structures which should be designed against undermining. Instruments are rarely placed within actively navigated areas so such currents are not normally directly observed.

Typically acceptable data collection approaches by Level of data reliability are outlined in Table 3.12.

Table 3.12: Level of data reliability - Currents

Level of data reliability	Description	Common data collection approaches	Typical use cases
3 (High)	Measured data appropriate to the site.	Obtain measured long-term data captured at an appropriate location. Where the data is intended to describe the wider site, an appropriate location will generally be one where local effects are limited. Where current information is intended for a more focused application, it may be most appropriate to collect data as close as possible to the area of interest. Current gauges are commonly installed with other instruments such as those to measure water levels; as such, the deployment location may be driven by the need to capture other parameters. However, the impact of this limited flexibility can normally be adequately managed.	Numerical hydrodynamic and sediment modelling including those supporting flushing studies.
2 (Medium)	Measured data of reduced reliability for the site.	At this level of reliability, deployment of dedicated temporary instruments will generally not be required. As level 3 but the following flexibilities may be taken advantage of: If currents are to be observed directly, a lower number of instruments may be deployed or data from a less-than-ideally location may be used. Currents may be estimated based on data from similar sites or calculated based on offshore conditions and the nearshore geometry. Estimated currents from existing studies may be used.	Understanding of structural or operational requirements which require a reliable understanding of current velocities. Numerical modelling of the currents would generally not be undertaken.
1 (Low)	Typical conditions or regional datasets	Assumed conditions based on high level information. For instance, this may include conservative estimates based engineering judgement and an understanding of similar sites.	Associated risks should be well-communicated and managed through conservative design as a minimum.

3.7.2 Data collection

3.7.2.1 Data sources

Local current data is generally not widely available. However, some potential sources of tidal current data and associated commentary are provided below.

- Certain proprietary high-level models – these may provide high level estimates of current speeds alongside other modelled conditions such as tidal variations.
- Existing studies especially those pertaining to sediment transport, flushing/dispersion, or vessel navigability.
- Various online sources typically advertised in connection to water sports or fishing activities – such sources are generally not intended or appropriate to inform reliable design.

3.7.2.2 Key considerations

The current sub-section relates to capture of currents via installation of dedicated instruments. Table 3.13 outlines key guidance on appropriate methods for the measurement of current data.

Table 3.13: Key considerations - Currents

Item	Recommendation	Comments
Key information to capture	Current velocities (i.e. speeds and directions) by depth	The complete current profile should be understood i.e. current velocities at varying depths.
Typical data collection techniques	In order of reliability: – Acoustic Doppler Current Profilers (ADCP) & Recording current meters – Direct reading current meters – Float tracking	The most appropriate data collection method will depend on a number of variables such as: – The required reliability – The required data such as a complete current profile or currents at a specific level – Site constraints such as vessel traffic that may limit the use of instruments deployed on the surface – Maintenance requirements
Installation location of instruments	Driven by safety and such to avoid localised effects.	Common drivers include: – Navigation; risks of vessel collisions should be minimised – Avoidance of localised effects; unless the devices are intended to capture such effects specifically, irregular bathymetric features, significant propellor action, among other considerations, can locally influence current behaviour and inhibit a reliable understanding of the wider site.
Record duration and period	Generally 2-3 months or greater. Timed to capture currents of significant magnitude to increase robustness of dataset (generally winter months will be preferred).	A minimum of 1 month of continuous current data is likely sufficient for a basic understanding of general current patterns at a site. Calibration of numerical models would typically require 2-3 months of data. Timing may need to balance storm and hurricane risks, project schedule constraints, and other constraints.
Temporal interval	Typically a sample every 10 minutes.	Frequency of sampling will depend on the scale of the phenomenon being investigated.

3.8 Storm surge

3.8.1 Requirements

Storm surge is the contribution of low atmospheric pressures and sustained winds leading to a temporary increase in water levels. Surge can be significant and can lead to direct flooding due to increased water levels while also increasing potential wave heights incident on structures or the nearshore. The design storm surge should be that associated with the design event. However, a bottom-up approach is needed as surge heights are strongly influenced by local conditions – bathymetry in particular. In other words, storm surge measurements captured under an historical storm equivalent to the design event will likely not be appropriate for use at a different site. Therefore, surge heights should be developed, either through modelling or analytical methods, considering winds of the design event and local bathymetry. Refer to Section 2.3.2 for a discussion on the association of Annual Exceedance Probabilities to hurricane events.

Surge estimates should consider the contribution of both sustained winds and low atmospheric pressures.

Surge heights, driven by sustained winds, can increase significantly at locations fronted by an extensive area (in the order of miles/kilometres) of shallow water[13]. As a result, surge heights

[13] For example, surge heights on Grand Bahama during Hurricane Dorian were estimated to have been in excess of 20ft (6m). (Assessment of the Effects and Impacts of Hurricane Dorian in The Bahamas (Inter-American Development Bank, 2020)).

can vary significantly between storms and locations. This potential for variability should therefore be considered particularly when referencing historical surge data.

Table 3.14: Level of data reliability – Storm surge

Level of data reliability	Description	Common data collection approaches
3 (High)	Developed via numerical modelling or manual analytical methods based on wind and bathymetric data in addition to atmospheric pressures.	It will generally not be appropriate to directly apply measured surge data due to the sensitivity of surge to local conditions (bathymetry in particular) and specific storm characteristics (wind speeds, storm tracks, wind directions, atmospheric pressure). This information may be best used to support calibration exercises. Data used to support surge estimates should be of a comparable level of reliability. However, less reliable datasets may be appropriate where the sensitivity of the adopted estimation methods is limited to that data type; this will generally mean that bathymetric data, and at times wind data, may be of Level 2 reliability. Generally, the accuracy of surge predictions will be driven by the assumed design event as opposed to the precision of the input data. Common approaches to estimate surge (both wind- and atmospheric pressure- driven contributions) include numerical modelling and other, more manual methods using known relationships.
2 (Medium)	Developed via manual analytical methods based on wind and bathymetric data in addition to atmospheric pressures.	As above though numerical modelling would not typically be undertaken at this level of reliability.
1 (Low)	Assumed surge values	Assumed surge values may be based on previous projects (that undertook surge assessment at higher levels of reliability), historical surge information relatively near to the site or at comparable locations, or if information is completely lacking then a conservative estimate based on best engineering judgement.

3.8.2 Data collection

3.8.2.1 Data sources

The availability of preliminary estimates of surge heights in the form of surge maps for should be investigated as these can serve as useful tools in the preliminary or final designs, depending on project requirements. Otherwise, existing information on surge heights will generally be limited though previous studies near the site may be available.

3.8.2.2 Key considerations

Measured surge information is not generally obtained to support specific developments. Therefore, design processes will normally rely on existing records and analytical predictions. As such, techniques to collect primary surge data are not discussed further although several key considerations are highlighted in Table 3.15 below.

Table 3.15: Key considerations - Storm surge

Parameter	Recommendation	Comments
Key information to capture	Surge height and its associated AEP. Surge duration	The key parameter to capture will normally be surge heights. However, surge duration can be useful to support an

Parameter	Recommendation	Comments
		understanding of flood durations which influence the level of damage and risk to life during an event.
Wind (input information)	To be of an appropriate level of reliability. Data required for sustained winds, as opposed to gusts. Wind direction is important.	Normally Level 2 or greater. It may be appropriate to assess surge heights based on real hurricane measurements but varying its track to a worst-case scenario. Refer to Section 2.3.2.
Bathymetry (input data)	Required for large areas. It may be appropriate to reduce the level of reliability required.	Surge is a large-scale phenomenon, generated over distances I the order of kilometres/miles. Therefore, large areas of bathymetry will be required. However, it is not feasible nor required to capture small scale features as they will not be considered in the empirical or analytical relationships, nor will they notably influence model results.

3.9 Geotechnical

3.9.1 Requirements

3.9.1.1 Guidance scope

Geotechnical information as it pertains to design of coastal infrastructure is typically required from several perspectives. These, and their discussion in this guidance is outlined in Table 3.16. While the intended use of the various kinds of geotechnical data can vary, their collection is normally most efficiently accomplished via a coordinated data collection exercise which may include several survey types. However, making use of this opportunity for efficiency and cost savings typically requires effective planning and communication across teams. The current discussion on geotechnical data pertains to investigations and conditions in both above and below water environments.

Table 3.16: Geotechnical information uses and discussion in this guidance

Geotechnical information	Typical use cases	Comments and extent of discussion in this guidance.
Ground competency.	Structural and geotechnical stability assessments.	Such considerations do not generally differ significantly between coastal and terrestrial design and will therefore not be discussed extensively in this guidance. For further information refer to ● Eurocode 7: Geotechnical design, BS EN 1997-1:2004 (BSI, 2004) and; ● Code of practice for ground investigations, BS 5930:2015 (BSI, 2015).
Sediment grain size distributions in addition to physical parameters such as grain density, bulk density, and organic content.	Understanding sediment transport processes.	Such information is key to many kinds of coastal design and will be discussed further. For further information refer to external guidance documents on best practice such as that from the NE Atlantic Marine Biological Analytical Quality Control (NMBAQC): NMBAQC's Best Practice Guidance. Particle Size Analysis (PSA) for Supporting Biological Analysis.
Physio-chemical information such as the presence of heavy metals, hydrocarbons, volatile organic compounds, other hazardous or foreign	Contamination studies and eco/environmental considerations such as establishment of natural	This guidance will not explore such considerations in significant detail as this is typically captured in the well-established Environmental Impact Assessment (EIA)

Geotechnical information	Typical use cases	Comments and extent of discussion in this guidance.
substances, as well as organic content.	systems such as mangroves and coral habitats.	process. Nevertheless, refer to Section 4.4 for high-level guidance.
Geophysical information such as bed rock levels, sand/silt thicknesses, and the presence of buried objects.	Material requirements and design levels, scour and erosion assessments, and indication on fracturing and variations in ground conditions and composition.	While many of the standard survey methods are consistent with their terrestrial counterparts, additional considerations are relevant to their use in the coastal and marine environment and are discussed further in this Section. For further information refer to BS 6349-5 (BSI, 2016).

Note: Geotechnical considerations for oil and gas exploration, sub-sea cables and pipelines, sub-sea tunnelling, and other specialised, less common works are not discussed in this guidance.

3.9.1.2 Note on relevance of sediment characteristics to transport processes

In addition to wave action and currents, sediment characteristics are also important to understand and predict transport behaviour. As any natural sediment will comprise a range of grain sizes, sediments are often represented by a single value, commonly the median nominal diameter, D_{n50}. Generally, fine sediment (silts and clays) and coarser sediment (such as pebbles/shingle) have the greatest thresholds of motion – i.e. greater energy (or rather bed shear stress) is required to trigger their mobilisation. Sands generally are most readily mobilised due to their smaller grain size relative to the larger pebbles and their lack of cohesive forces that benefit the finer sediments.

While such information is important, it should also be appreciated that the prediction of sediment transport rates is an inherently uncertain field. Therefore, the highest confidence in sediment characteristics will generally not directly correspond to high confidence in predicted behaviour. Confidence will often be inversely driven instead by the complexity of the site; common reasons that may lead to increased uncertainty include non-uniform or irregular shorelines and bathymetry, exposure to a multitude of wave directions, and sensitivity of the frontage to both longshore and offshore processes.

3.9.1.3 Data requirements

Table 3.17: Level of data reliability - Geotechnical

Level of data reliability	Description	Common data collection approaches
3 (High)	Sediment grain size distributions and associated information	
	Measured data at multiple points distributed across the site.	Data collection will generally require dedicated intrusive surveys and subsequent analysis of samples in an accredited laboratory. Information should be captured at multiple locations to understand any spatial variability is sediment characteristics. This is important as it can provide an indication of sediment transport behaviours while also allowing such variations to be captured in any modelling or analysis. The use of existing information will generally be suitable if available. However, this may not be appropriate should the site have undergone recent external changes such as dredging, recharge, significant widespread erosion, or changes in the sediment supply. Generally, activities dedicated to understanding wider sediment transport behaviour of a littoral cell[14] will require data in both the nearshore and offshore as the characteristics at each can vary significantly. Physical parameters other than grain sizes, such as grain density, bulk density, and organic content should be determined in a laboratory.

[14] Refer to Section 4.3.1.

Level of data reliability	Description	Common data collection approaches
		However, an appropriate number and distribution of samples taken for this purpose will normally be less than that recommended for grain size distribution analysis. Depending on the project, dedicated testing may not be proportional especially in cases where the sediment source (e.g. calcification, coral debris, eroded shorelines) is well understood. The responsibility to justify such an approach, however, lies with the developer.
	Geophysical information	
	Measured data at multiple points distributed across the site.	Data collection will generally require dedicated surveys. Normally, the most efficient approach is a combination of approaches such as wider seismic refraction surveys supported by less frequent boreholes to validate findings. Generally, this information is relevant in proximity to the location of intended works as opposed to the wider site. As in the case described above, the use of existing information will generally be suitable if available.
2 (Medium)	Sediment grain size distributions and associated information	
	Visual categorisation based on experienced judgement.	Sediment categorisation (e.g. shingle/pebbles, granular, coarse sand, fine sand, coarse silt, etc.) may be carried out to a reasonable reliability based on a visual inspection by an experienced person on site. This practice should be supported by readily available charts whereby samples may be cross-checked against scaled images. In order to avoid overly onerous requirements considering the constraints on access, it will generally be appropriate to make assumptions on offshore conditions based on nearshore observations. For guidance pertaining to associated physical parameters, see recommendations for reliability Level 1.
	Geophysical information	
	Measured data, less comprehensive than Level 1 (High) and potentially captured via less formal techniques.	Data will normally not be required to the same level of detail as compared with Level 1. For instance, critical information may include bedrock level and sand thickness only, as opposed to comprehensive information on fracturing, indications of density, etc. Data may typically only be collected in the immediate area of interest – most commonly the location of the intended works. Less formal data collection techniques such as trial pits may be appropriate.
1 (Low)	Sediment grain size distributions and associated information	
	Assumptions based on typical sediment characteristics for known site conditions.	General sediment characteristics at the site should be understood at a high level, such as whether the site is characterised by sand, silt, exposed rock, etc. Given the generally homogenous geological conditions in the country, it will normally be appropriate to assume typical information based on the wider site. For instance, a sandy beach could be assumed to consist of carbonate sediment assuming typical distributions and grain densities. Offshore conditions, if required, may be assumed, based on current knowledge of the site and supported by sound engineering judgement.
	Geophysical information	
	Assumptions based on typical ground conditions for known site conditions.	General assumptions around ground composition may be made, based on current knowledge of the site and expected conditions supported by sound engineering judgement.

Notes: Geotechnical data requirements pertaining to ground competency and physio-chemical information are not considered as per Table 3.16.

3.9.2 Data collection

3.9.2.1 Data sources

Sediment characteristics may be collected under established monitoring or larger-scale data collection regimes. In the absence of such schemes, existing data is likely to be limited to that collected through surveys under previous developments. Much of this information may be readily accessible through publicly available EIA documents.

3.9.2.2 Key considerations

Health and safety considerations become especially relevant during geotechnical data collection works due to the probable inclusion of excavation or boring activities and the associated risk of contact with buried infrastructure including potentially high voltage cables. As such, geotechnical investigations should be undertaken by suitably qualified and experienced contractors who should be competent at managing such risks. An especially important exercise that should be undertaken prior to any boring or similar is identification of existing assets such as buried cables and pipes or water mains. Refer to Section 3.3.1 for general notes on Health and Safety relevant to coastal developments.

Ground investigations, of varying kinds, are often intended to validate and quantify assumed conditions on which early designs will normally have been based. Therefore, significant deviations from the expected conditions will normally have an impact on design and should be communicated to the design team without delay i.e. communications should occur without waiting for the issue of formal testing and reporting. This is good practice in the spirit of effective collaboration. *Deviations from expected conditions* may include the presence of buried objects, harder than expected rock which may impact driving activities, and any observations indicating immediate Health and Safety risks.

Factors of particular importance when acquiring geotechnical data are outlined in Table 3.18. A useful external reference providing guidance on geotechnical design and data collection is Eurocode 7: Geotechnical design (BSI, 2004).

Table 3.18: Key considerations - Geotechnical

Item	Recommendation	Comments
Sediment grain size distributions and associated information		
Key information to capture	Sediment grain size distribution, grain density, bulk density (more commonly for fine sediment), organic content.	Sediment grain size is typically presented in a plot of cumulative mass against grain size which facilitates an estimate of D_{n10}, D_{n50}, and D_{n90}.
Typical data collection techniques	Sampling via grabbing or coring. Samples then to be sent to a laboratory for analysis.	Sampling via grabbing is generally the simpler of the two approaches and can usually be carried out without the need of divers. Various instruments may be used to achieve this such as Day grabs and Van Veen grabs. Formal instruments should be used particularly so that finer content is not lost during the procedure. The technique should be selected in consideration of the anticipated sediment characteristics. Sampling via coring preserves the vertical composition of the material and is therefore the preferred approach if practicable. Core lengths can vary from extensive boreholes (in the order to several to tens of feet/metres) to manual push tubes which will only capture the upper layers of mobile sediment (in the order of one foot). Whether sampling by machine or by divers, efforts should be made to reduce the disturbance of the bed for instance by working from the downstream up. Once collected, samples should remain undisturbed and stored in a controlled manner for delivery to the

Item	Recommendation	Comments
		laboratory. If the sampling activity is to also inform on ecological parameters, temperature control may also become important.
Spatial distribution of sampling	Such that the site and its spatial variability may be adequately described.	The number and distribution of samples will strongly depend on the level of detail to which the site needs to be captured. The following considerations should apply: ● 3No. samples is generally the minimum to allow for some spatial variability to be identified and to provide contingency for any erroneous samples. ● The cost of additional samples is often small as compared to the initial mobilisation costs. Therefore, the opportunity to capture as many samples as practicable should be made use of. ● The less homogenous the site, and the more relevant sediment transport to the project, the greater the number and distribution of samples to be acquired. ● Sample locations should be distributed to coincide with areas of the site with potential varying characteristics such as the dry beach, nearshore, deep water, and dredged areas.
Geophysical information		
Key information to capture	Vertical ground composition, such as bedrock levels and sand thicknesses, as inferred from an understanding of vertical variations in ground properties; various ground properties (depending on the technique used); and the presence of buried objects.	Geophysical surveys are generally non-intrusive surveys that acquire information on surface and subsurface conditions through secondary means. For instance, the seismic refraction technique involves artificial generation of vibration (normally using minor explosives or impacts) and a series of sensors. Based on the detected vibrations and sensor position, ground conditions can be inferred thanks to varying properties of different ground conditions (ground type such as sand or consolidated rock, the presence of fractures, rock density etc.).
Typical data collection techniques	Indirect surveys incl. seismic refraction (most typical for marine environments). Direct surveys incl. boreholes, jet probes, and trial pits.	Indirect surveys Many techniques are available and can be based on seismic, electrical, radar, or magnetic information. The suitability of each will depend on the site context and desired information. Further guidance may be found in BS: 5930:2015 (BSI, 2015). Direct surveys Direct surveys vis boreholes should normally be used to support and validate the results of indirect surveys. The use of boreholes will be widely consistent with their terrestrial counterparts. Where the desired information is limited to thicknesses of mobile sediment and when this thickness is limited, jet probes may be appropriate. Where the extent of the required information is limited, trial pits may be appropriate and can generally be done by unspecialised contractors.
Spatial distribution of testing	Such that the site and its spatial variability may be adequately described.	The number and distribution of the data collection locations should follow the same principles as those discussed above in relation to sediment sampling. Generally, indirect surveys will be carried out in transects which should be set out and accurately described in an established reference system prior to undertaking of the survey. These should capture any areas of anticipated variability as well as those areas of particular importance for the planned works.

3.10 Topography, bathymetry, and aerial imagery

3.10.1 Requirements

Surface ground levels on land and under water are essential for coastal design projects. Elevation information will feed into elements such as:

- Development of designs and an understanding of material requirements.
- An understanding of hydrodynamics whether through modelling or manual approaches.
- An understanding of sediment transport processes.
- An understanding of existing features to facilitate structural tie-ins and transitions.
- An understanding of navigation constraints and hazards.
- An understanding or flood risk.

Given the wide range of uses for such data, what may constitute an appropriate data collection approach will vary depending on its intended purpose. This will normally be evident. However, where a development calls for wider use of this information (for instance where topographic data is to be used in support of flood risk assessments as well as detailed design), the most efficient approach is normally to combine survey activities whose specifications should be driven by the most onerous use cases (in this example design as opposed to flood risk assessments). The relationship between appropriate survey technique and use case is normally obvious and is therefore not made explicit in this guidance. However, given an intended data collection approach, guidance on typically important considerations is provided.

Table 3.19: Level of data reliability – Topography, bathymetry, and aerial imagery

Level of data reliability	Description	Common data collection approaches
3 (High)	Measured data captured via dedicated surveys.	In the absence of existing survey results (whose reliability should be thoroughly assessed prior to use), dedicated survey activities will normally need to be carried out. As topographic, bathymetric, and aerial imagery information are normally used in combination with each other, coordination between surveys is needed to ensure compatibility between them and to ensure that, once combined, the resulting output remains representative of the site – for instance such that the site has not undergone significant variations between surveys.
2 (Medium)	Measured data of reduced reliability for the site.	Given the importance of understanding site levels, dedicated surveys will normally be required even at this level of reliability. However, it may be appropriate to make greater use of efficiencies and reduce the onerousness of the surveys, for instance by reducing resolution requirements or adopting a less-than-ideal method. The risks associated with such an approach should be well understood by both designers, developers, and regulators.
1 (Low)	High level information and assumptions based on extrapolation/inference from measured data.	Assumed typical conditions (bedrock capacity, beach sediment grain size distributions etc.) based on site conditions.

3.10.2 Data collection

3.10.2.1 Data sources

National (or as extensive as practicable) topographic, bathymetric, and aerial imagery datasets may be collected under formalised public data collection schemes. However, such data is not generally available. Therefore, existing data is likely to be limited to:

- Data collected under previous developments with associated access challenges as noted in Section 3.3.5.
- Publicly available satellite imagery such as the Google Maps, Bing Maps, and Esri or Maxar imagery, noting any proprietary/copyright/trademark restrictions on the use of imagery in addition to the lack of control or understanding of its collection process. Resolutions are generally limited.
- Various data types possibly requiring purchase from various sources such as NOAA, the United States Geological Survey's EarthExplorer, and NASA's Landsat Gallery. However, while some information is likely to be available, it is generally not comprehensive or extensive across The Bahamas.
- Historic photographs are likely to be available for certain sites (such as those with an historic value). However, identifying where they are held is normally difficult as they are not usually digitised and may be hidden in private collections. Nevertheless, if found, they can provide useful information on historic beach conditions, storm impacts, and historic assets lacking records.
- Ports may carry out regular bathymetric surveys to facilitate safe vessel movements. This information will generally be owned by the port but may be available on request.
- Publicly available bathymetric data, possibly requiring purchase, may be found in Admiralty charts or various online sources often intended to support fishing activities. Resolutions and accuracies will normally be limited.

To reiterate, the use of any existing information should be assessed for reliability and suitability prior to use. Given the lack of control over existing data, its adoption for a project should be accompanied by an understanding of the associated risks and uncertainties which will need to be managed and mitigated as far as possible.

3.10.2.2 Key considerations

Further guidance on typical or appropriate specification-related considerations is provided in Table 3.20.

Table 3.20: Key considerations - Topography, bathymetry, and aerial imagery

Parameter	Recommendation	Comments
Coastal topographic surveys		
Extent	Varies widely; as required by the design.	Generally, when assessing wider flood risk implications, the survey should capture the complete extent of possible flooding. As this will be unknown at the time of the survey, the survey should extend to the maximum reasonable flood extent as informed by early desk-based studies and existing knowledge of the area. The seawards extent will be limited by the sea and will normally need to be ties into the bathymetric model.
Timing	At low water, preferable low water springs or lower and during periods of calm water.	Topographic surveys are typically unable to penetrate water.
Weather	Clear, calm conditions as per equipment requirements and safe operations.	Requirements may vary depending on the capabilities of the equipment being used and will typically be driven by wind speeds and visibility.
Min. horizontal resolutions	~30x30ft (10x10m): not generally suitable for the coastal zone.	Resolution requirements will strongly depend on the intended use of the data as well as the nature of the site; homogeneous sites with only gradual elevation changes may make use of more coarse datasets. Where topography is
	~15x15ft (5x5m): not typically suitable for the coastal zone. May be appropriate for national-scale high level studies or for representation of	

Parameter	Recommendation	Comments
	less important land areas for modelling and contextual purposes.	intended to identify structures or similar features, resolution requirements need to be considered against the scale of these features. Note that detailed design requiring tie-in to existing structures will typically require standard topographic surveys to reliably capture edges and near-vertical faces in particular.
	~6.5 x 6.5ft (2 x 2m) to ~3 x 3ft (1 x 1m): generally appropriate to inform high level sediment transport studies, erosion assessments, flood risk studies, and overtopping assessments.	
	~1.5 x 1.5ft (0.5 x 0.5m): Generally appropriate for outline and concept design, site-specific detailed erosion or flood assessments, and detailed design (i) provided tie-ins are not required or, (ii) for construction of assets such as rubble mound structures that are more limited by accuracies of construction techniques than by the resolution of survey outputs.	
Horizontal accuracy	>1.5ft (0.5m): not typically suitable for the coastal zone. May be appropriate for national-scale high level studies or for representation of less important land areas for modelling and contextual purposes.	-
	±1.5ft (0.5m): Generally appropriate for high level designs and studies or where construction of the assets is driven primarily by relative positions during construction, such as for rubble mound structures.	
	±1ft (0.3m): Generally appropriate for detailed design where tie-ins are not required and where accurate definition of vertical faces is not a priority.	
Vertical accuracy	±8in (20cm): Generally appropriate for outline and concept design, site-specific detailed erosion or flood assessments, and detailed design (i) provided tie-ins are not required or where design is driven by relative heights during construction and (ii) for construction of assets such as rubble mound structures that are limited by accuracies of construction techniques.	-
	±2in (5cm): Generally appropriate for detailed design provided tie-ins are not required and where accurate definition of vertical faces is not a priority.	
Verification of accuracies	Ground control points (GCPs) and independent check points should be used.	Surveys undertaken using drones or similar require GCPs to develop the digital elevation models (DEM). However, accuracies should be verified via the use of additional GCPs, distinct from those used to develop the model.
Model type	Objects can be removed during post-processing to transform a Digital Surface Model (DSM) into a Digital Elevation Model (DEM), the latter of which represents bed levels following removal of objects such as vegetation.	Requirement will vary by intended use. However, the use of DSMs to represent exposed foreshores and beaches will often be appropriate. DEM's should be used in vegetated areas or where features such as cars and other assets should be captured.
Bathymetric surveys		
Extent	To be driven by project requirements. The vessel used to carry out the survey should be carefully selected. Given the limited tidal range in the country, there will normally be an area in the nearshore than can neither be captured by an aerial topographic	Generally, the typical challenge will be the capture of shallow areas due to the need to ensure sufficient under keel clearance of the survey vessel. Suitable vessels for survey of deeper and exposed areas will generally need to be more stable and therefore larger – therefore the same vessel may not be suitable

Parameter	Recommendation	Comments
	survey nor a conventional bathymetric survey. Therefore, bed levels in this area may need to be estimated via an interpolation between DEMs or captured via a dedicated survey using handheld equipment.	for survey of the shallower or more constrained areas.
Timing	At high water for nearshore areas, preferably high-water springs or greater and during periods of calm water.	-
Weather	Clear, calm conditions as per equipment requirements and safe operations.	Requirements may vary depending on the capabilities of the equipment being used and will typically be driven by wave heights and visibility.
Resolutions and accuracies	As per the International Hydrographic Organization Standards for Hydrographic Surveys (International Hydrographic Organization, 2020).	The referenced IHO standard establish minimum requirements depending on the intended use of the bathymetric data and can be regarded as best practice.
Aerial imagery		
General	Typically captured at the same time as topographic data. A typical resolution is 1.5ft x 1.5ft (0.5m x 0.5m). Requirements will be driven by project objectives.	Free, recent satellite imagery is generally available for the entire country at low resolutions. Aerial imagery is typically used when greater resolution and/or when the most up-to-date information is needed.

3.11 Water and sediment quality

3.11.1 Requirements

Water and sediment quality is important primarily from the perspective of environmental impacts and protection. However, the management of environmental impacts as outlined in Section 4.4 should be considered from the onset of design. Therefore, while data requirements of this kind are well-established in guidance and legislation pertaining to the Environmental Impact Assessment process, some key considerations are also outlined on this Section. Water and sediment quality are discussed together despite the differing collection techniques required due to the similar testing requirements and the normal correlation between the two.

Generally, contaminated sediment is an indication of long-term or historic pollution as it implies the contaminants have had the opportunity to settle. While never desirable, contaminated sediment is generally most important in relation to coastal developments when:

- There is a potential for mobilisation of contaminants due to natural (such as wave action) or anthropogenic (such as dredging) activities.
- There is potential for contact with humans.
- There is potential for contaminants are to enter the food chain – the concept of bioaccumulation is important here.

Generally, the presence of contaminants in the water is an indication that these have already been mobilised with a resulting wider potential area of impact. Signs of recent pollution events will normally be visible in water quality testing but may not be evident in the corresponding testing of sediment.

Indicative descriptions of what kind of data corresponds to the various levels of data reliability are outline in Table 3.21: Level of data reliability – Water and sediment quality .

Table 3.21: Level of data reliability – Water and sediment quality

Level of data reliability	Description	Common data collection approaches
3 (High)	Measured data local to the site.	Contamination is generally important in terms of concentrations; the further from the source of contamination, the lower the expected concentration of contaminant. Therefore, it is normally not appropriate to infer information from anywhere but the site of interest itself. At this level of reliability, testing will normally be required for a greater range of contaminants. However, even at this level of reliability, fully comprehensive testing will not always be required. However, any exclusions should be justified by the designer.
2 (Medium)	Measured data of reduced reliability for the site.	Dedicated testing will normally be required at the site itself. However, in contrast with level 3, less comprehensive testing will often be appropriate, limiting the exercise to those contaminants expected to be relevant based on known site conditions. It will likely be appropriate to adopt historic test results if available for the site, assuming no significant change in site conditions or use.
1 (Low)	Inferred conditions from known site activities and supported by testing of comparable sites.	Testing will usually not be required; contamination risks may be managed based on expected conditions. To support the understanding of *expected conditions*, it may be useful to acquire existing records for comparable sites.

3.11.2 Data collection

3.11.2.1 Data sources

Existing data, if available, can normally be found in publicly accessible documents developed in compliance with the Environmental Impact Assessment process held by the Department of Environmental Protection and Planning (DEPP). Bathing water quality records for key sites may be held by the Department of Health or associated departments.

3.11.2.2 Key considerations

As recommended in relation to other data types, the most efficient approach is generally to coordinate sampling exercises such that the number of in-field activities is limited. This approach will normally reduce mobilisation and management costs and lead to reduced schedule requirements.

Table 3.22: Key considerations – Water and sediment quality

Parameter	Recommendation	Comments
Key information to capture	Various physio-chemical parameters. However, it will normally be appropriate to develop a directed testing regime to target relevant parameters only.	Common physio-chemical parameters to be tested for include: ● Total Organic Carbon ● Total Organic Matter ● Metals such as As, Cd, Cr, Cu, Pb, Mn, Ni, V, Zn, Hg, Al, Ba, Fe, Li ● Total Hydrocarbon Content ● Polyaromatic Hydrocarbons (PAHs) (DTI 2-6 Ring aromatics + EPA 16) ● Other volatile organic compounds (VOCs) ● Turbidity ● Total Dissolved Solids ● Conductivity

Parameter	Recommendation	Comments
		• Salinity • pH • Temperature • Dissolved Oxygen
Typical data collection techniques	Formal equipment should be used. Samples should be stored and recorded appropriately to be sent to an accredited laboratory.	Sediment sampling techniques will normally coincide with those described in Table 3.18: Key considerations - Geotechnical.
Temporal requirements	Varies; As required for the project.	Repeated testing is generally not required to establish baseline conditions but will be needed when assessing ongoing impacts (such as during construction) and the effectiveness of any mitigation measures.
Depth at which data is captured	Water quality: at multiple levels throughout the water column Sediment quality: grab sample should extend to sufficient depth.	-

3.12 Extreme temperatures

3.12.1 Requirements

Extreme temperatures are expected to become increasingly important due to climate change. In the case of The Bahamas, the higher extremes are expected to be relevant. Health and Safety considerations should be front of mind; working during extreme temperatures should generally be avoided. Otherwise, the most significant impacts of extreme temperatures in relation to design and construction of coastal infrastructure pertain to materials such as potentially reduced performance of paving and complications when preparing and setting concrete.

Designers should understand whether extreme temperatures are important for their designs and manage the risk accordingly using the acceptable allowances described in Section 3.13. Impacts are generally consistent with typical terrestrial designs and are therefore not explored further in this guidance.

Increases in average temperatures will also be important and are expected to lead to wider impacts especially in terms of storms and wave climates. Such considerations are captured in Section 3.13.2.2.

3.13 Climate change

3.13.1 Requirements

Design will need to consider the complete lifetime of the development and will therefore require consideration of future conditions. In this consideration, the impacts of climate change will need to be captured; most commonly through application of uplifts on parameters as outlined in Table 3.23. Requirements are not presented against levels of data reliability as climate change allowances should be included anytime the design process calls for application of environmental conditions (whether directly or indirectly) in future scenarios.

Recommended uplifts are presented in Table 3.23. If a parameter is derived from its forcing parameter (e.g. waves estimated based on wind speeds), then any uplift should be applied on only one of these to avoid double counting. Percentage values are from the base year of 2025 conditions. For design lives between or beyond those presented, linear interpolation or extrapolation should be considered acceptable.

Table 3.23: Recommended uplifts in consideration of climate change

Date at end of design life	2025 (base date)	2050	2075	2125	2225
Wind (%)	0	1.5	4	10	22
Waves (%)[2]	0	1.5	4	10	22
Water level increase[1] (m)	0	0.23	0.56	1.43	3.1
Storm surge[2,3] (%)	0	1.5	4	10	22
Geotechnical (%)	None, though more energetic wave climates may lead to increased coarseness of mobile sediment.				
Topography/bathymetry	None, though variations in sea states will influence bathymetry and coastal topography e.g. likely accelerating erosion				
Water and sediment quality	None though this may be impacted by impacts such as increased runoff due to changes in precipitation.				
Extreme temperatures (°C, (°F))	± 0 (0)	± 1 (1.8)	± 2 (3.6)	± 4 (7.2)	± 9 (16.2)

Notes: 1 Sea level rise accounted for here. Values based on 2022 IPCC projections for the RCP 8.5 scenario, 95% confidence band. Assumption of RCP 4.5 scenarios may be appropriate where a greater degree of risk may be tolerated. This should be justified by the developer.

2 Where waves and surge are modelled as driven by the wind speed only the wind speed input to the model need be increased.

3 % increase on surge element only, not on overall water level.

Where a scheme undertakes a climate change assessment that establishes cautious estimates of future design values based on best practice at that time, those may be used.

3.13.2 Data collection

3.13.2.1 Data sources

Insight into the impacts of climate change on extreme events may be found in the external reference, *Impacts of Climate Change on Extreme Events in the Coastal and Marine Environments of Caribbean Small Island Developing States (SIDS)* (Stephenson & Jones, 2017).

Planners, developers, and designers should be aware that studies with a regional or national focus may exist or be made available following the publication of the current guidance which may provide useful insight into anticipated impacts for The Bahamas specifically. As with any publication, consideration should be made on the reputability of the source and read with a critical eye.

Sources for information relating to climate change are predominantly academic in nature. The leading source for climate change projections are documents produced by the Intergovernmental Panel on Climate Change (IPCC). While these are not intended for design, in the absence of more reliable sources their use to guide coastal design is recommended. As previously noted, all should be aware of updates and new information as this is a highly active field of research.

3.13.2.2 Key considerations

It should be noted that climate change projections are inherently uncertain. It is intended that the recommended factors in Table 3.23 account for this uncertainty as far as practicable. However, recommendations should be updated regularly to capture the latest state of knowledge.

Developments will often comprise multiple components with varying design lives; for instance, paving is rarely designed with a design life of greater than 25 years while the structures they may be providing access to could be designed for 50 years or more. It is generally more appropriate, in terms of adaptability and cost and carbon savings, that the individual components of the development be designed to the conditions at the time of its intended decommissioning to avoid an excessive design. For instance, an access road may be designed with predicted sea levels in the year construction+25-years despite the wider development being designed to sea levels for the year construction+50-years. However, the capacity for the component to be replaced for future conditions should be considered, for instance taking into account spatial constraints and potential interfaces with adjacent ground and structures.

While Table 3.23 has considered the most common environmental parameters used in the design of coastal infrastructure, direct, indirect, and induced climate change impacts extend beyond just these parameters. However, consideration of these factors is generally more challenging but may still need to be assessed depending on the scheme. Possible additional impacts include:

- Variations in patterns and/or intensities of precipitation
- Variations in storm tracks and frequencies
- Directional and/or intensity variations in ocean currents and trade winds
- Sediment characteristics
- Water temperature and acidification
- Saltwater intrusion
- Pollution due to impacts on drainage systems or changing land use
- Ecosystem displacement and loss
- Biodiversity loss
- Wider impacts on property, infrastructure, industry, and socioeconomics

3.14 Modelling

3.14.1 General

This section provides guidance on the use of modelling to support coastal design, strategic studies, and Environmental Impact Assessments (EIA), among other relevant activities. Both physical and numerical modelling are be considered. While modelling aims to recreate physical processes, there will always be some degree of compromise and interpretation between the model representation of reality with the actual behaviour of the system being modelled.

Unfortunately, model outputs are commonly read and used without a proper understanding of the underlying uncertainties and model limitations. This guidance aims to provide clarity on where these uncertainties commonly lie and thereby where particular efforts should be focused for model planning, review, and implementation.

The complexity of a modelling approach demands decisions be made by experienced coastal scientists/engineers. Furthermore, there will not necessarily be a single solution to arrive at the desired outcome. Therefore, developers and regulators should generally avoid prescription of model approaches including the need for modelling in the first place, model types to be used, or other details. They should, however, communicate to the designer reliability requirements and the intended use of the outputs. This may include prescription of required accuracies or the format of certain deliverables to ensure clear demonstration of impacts. Such an approach allows greater efficiency in the design process by providing greater flexibility to the designer while allowing the designer to select a model for which they have the specific expertise and licensing.

When used appropriately, models are useful tools to support the design and review process of coastal infrastructure. Common advantages of modelling as compared to the conventional

approach (i.e. use of typically 1-dimensional analytical, empirical, or semi-empirical formulae) include:

- Improved representation of complex systems
- Standard relationships are normally inadequate for investigation of scenarios in which 3-dimensional effects or increased interactions between phenomena become important. Modelling can identify non-linear behaviour, feedback mechanisms, and other behaviour that may not be apparent through conventional approaches. This is typically the factor driving the need for modelling.
- Increased range of applicability
- Analytical and empirical relationships should only be applied within their range of applicability which commonly derive from the underlying assumptions as well as, for empirical relationships, by the range of test scenarios on which they were developed. Modelling can facilitate investigations of specific situations or configurations, or capture phenomenon not considered in standard methods. The latter consideration is especially true in relation to physical modelling.
- Manipulation of time
- Models can readily investigate future scenarios and accelerate time. The latter consideration is especially relevant for numerical sediment transport models.
- Cost and time efficiencies
- Modelling is often the most efficient method to support a design.
- Replicability
- Once a baseline model has been developed and validated, it can often be used to investigate multiple iterations of the same design, to allow optimisation, support further studies, or carry out sensitivity testing.

Useful external references on include:

- Guidance on the Environmental Clearance (EC) Requirements for Development, Infrastructure and Industrial Projects in the Emirate of Dubai, Annex 4 Part 2 (Dubai Municipality, 2021)
- Guidance on Setup, Calibration, and Validation of Hydrodynamic, Wave, and Sediment Models for Shelf Seas and Estuaries (Williams & Esteves, 2017)
- Guide to Wave Analysis and Forecasting (World Meteorological Organization, 2018)

3.14.2 Physical modelling

Physical modelling involves constructing scaled replicas of coastal systems and testing their performance under various hydrodynamic conditions. It is most commonly used to validate and optimise the design of coastal structures but may also be used to investigate sediment transport processes.

Physical modelling offers several significant advantages over numerical models and as such remains a key design tool. Key advantages include the ability to:

- Investigate physical processes without the need for underlying assumptions. As such it allows for identification of phenomena whose representation in numerical models may be poor or absent altogether.
- Reliably investigate small scale effects and structure interactions – the only alternative being the use of the less widespread Computational Fluid Dynamics (CFD) which also may require calibration.
- Provide visual feedback.

Physical modelling can be either 2D or 3D, carried out in wave flumes or wave basins, respectively. Wave flumes are long, narrow tanks of various scales that are essentially limited to studying the cross section of a structure under perpendicular wave attack. Wave basins are larger, wider tanks that allow for investigation of irregular shoreline or non-perpendicular alignments or entire structure geometries and may include current flows as well as waves.

The primary challenge in physical modelling pertains to scaling. While dimensions and material densities can be scaled, other parameters such as gravity or fluid viscosity, cannot be scaled. Furthermore, excessive scaling can induce certain small-scale phenomenon resulting in a fluid or sediment that does not behave as intended. Therefore, a decision has to be made to as to which parameters to scale as desired and on which a compromise can be tolerated. This decision is best made by the laboratory experts in conversation with the designer.

Further limitations of physical modelling include:

- High cost and time requirements.
- Laboratory constraints – laboratories have fixed facilities such as flume sizes and often require completion of testing within a predefined timeframe.
- Replicability – accurate reproduction of the site can sometimes be challenged, especially the fronting foreshore in fixed-bed flumes and basins.
- Limited ability to reliably examine all phenomena – for instance, while movement of revetment armour units can be observed, the scaling of surface wear and fracture damage to armour units cannot be replicated; therefore, unit breaking due to settlement, excessive contact pressures, or rocking (fatigue) cannot be investigated.

While physical modelling can be a valuable tool to increase confidence in design, it is an expensive design step. The decision to undertake physical modelling should be led by a number of factors:

- Where the consequence of failure would lead to significant loss of life or loss of assets with an economic value significantly greater than the cost of the coastal structure.
- Where the meeting of operational performance criteria (overtopping/wave attenuation) to a high level of confidence is critical to the success of the project.
- Where the performance or reliability of the design cannot be demonstrated by use of existing standards or empirical formulae. This may include:
  - Structures whose geometries are at, or outside, of the validity of existing formulae.
  - Innovative designs.
  - Structures with a complex geometry.
  - Structures (or groups of structures) that have complex interactions or transitions with one another, existing structures, or landfall.
  - Where integrity is anticipated to be driven by the stability of the toe – an area of the structure for which design remains predominantly led by high level design rules and the experience of the designer.
- Where performance is expected to be driven by 3D phenomena such as at roundheads of rubble mound breakwaters or at structures with complex geometries. Such an instance would require 3D modelling.

3.14.3 Numerical modelling

3.14.3.1 Model types and selection

A large variety of models exist, each with different strengths and limitations that lend themselves to different use cases. The selection of the appropriate model is therefore a key design decision

that should be afforded the appropriate attention; this decision will need to be made early in the process but should be made with adequate understanding of the available information and the required outputs.

As with physical modelling numerical models can be 2D or 3D (though 1D sediment transport models also exist). 3D models are not necessarily more accurate than a 2D model, but they are more complex to setup, calibrate, and interpret. The decision on when 3D numerical models are required should be based on the consideration of the processes which are important to the outcome of the study.

While this guidance will discuss model types on an individual basis, users of this guidance should be aware that different models are commonly used in combination with each other. For instance, sediment models are typically based on an underlying wave model, or water quality models require an underlying hydrodynamic model.

Table 3.24 outlines typical modelling requirements by project scope.

Table 3.24: Modelling requirements by project scope

Project type	Hydrodynamics	Waves	Sediment transport / Morphology	Plume dispersion	Water quality	Navigability	Mooring / Berthing
Dedicated flood risk assessments.	☑	☑					
Erosion risk assessments and shoreline change studies	☑	☑	☑				
Design of most structures on the beach or nearshore including groynes, breakwaters, seawalls, and revetments. Also large scale nature-based solutions.	☑	☑	☑	✓	✓		
Beach recharge and recycling	☑	☑	☑	☑			
Reclamation	☑	☑	☑	☑	✓		
Dredging works (e.g. for source material)	✓	✓	✓	✓	✓		
Approach channel	✓	✓	✓	☑	✓	✓	
New port or marina development	✓	✓	✓	✓	☑	✓	✓
Change of use of existing maritime facilities such as upgrades to accommodate larger vessels						✓	✓
Intakes and outfalls	✓	✓		✓			✓

Source: Adapted from Table 4-2, Guidance on the Environmental Clearance (EC) Requirements for Development, Infrastructure and Industrial Projects in the Emirate of Dubai (Dubai Municipality, 2021)

Notes: ☑ Likely required
✓ Likely if impact expected or if particularly complex

An overview of model types and key considerations for each is provided in Table 3.25: Model types and key considerations.

Table 3.25: Model types and key considerations

Model type	Processes to be modelled	Key considerations
Hydrodynamics	To model: – Tides – Wind induced currents and water levels – Atmospheric pressure where this may induce water level changes – Wave effects such as radiation stresses, if required. – Density / salinity if required in shallower water areas (e.g. estuaries/ embayments).	Hydrodynamic models are used to understand the impacts of water levels and currents. Outputs may be required to illustrate time independent maxima, or pre and post development differences. Calibrated hydrodynamic models may also be required to underpin other model types.
Waves	Spectral wave models may be suited best to large areas, and will include wave processes including growth (driven by wind), decay due to bed roughness, and transformation of waves (height and direction caused by refraction). Boussinesq type models are required where diffraction, reflection and wave-wave interactions are important (e.g. mooring studies)	Outputs include wave parameters such as wave height, period, direction. Outputs may be required for a range of quasi-timesteps driven by singular water level, wave and wind combinations. For sediment transport a range of typical conditions and storm conditions may be required, while for structure design typically extreme conditions based on water level / wave combinations will be required.
Sediment transport / morphology	Sediment movement in time. To understand net and gross movements and changes of shoreline geometry in time. Timeframes depend on period of time being considered (e.g. storm response to decadal changes to even longer term morphological trends).	These models are typically developed on the basis of hydrodynamic and/or wave models. Various types of sediment transport and morphology models are available. They are commonly either 1D or 2D. Outputs can include changes to beach profiles / shoreline planforms, sediment budgets, and difference plots (to identify areas of erosion/deposition). Calibration and validation can be limited by a lack of data. In such instances, efforts should still be made to make use of the information available. Additional effort should also be placed on sensitivity analysis.
Dredge plume dispersion	Short term transport of suspended sediment.	Strongly dependent on sediment characteristics. Outputs can include time independent maximum water column

Model type	Processes to be modelled	Key considerations
	To understand time for settlement/dispersion and direction of movement.	load, total bed deposition (in. or mm) / deposition rate (in. or mm/day). Particularly relevant when monitoring construction impacts. Therefore, the model needs to be appropriate to capture short term behaviours.
Water quality (Including conservative tracer / flushing studies)	Dispersion of discharges, turnover of water within embayments or channels, diffusion of contaminants and bacterial loading/decay. Models can be near field, localised to the point of discharge to investigate how well contaminants are initially mixed, or far field to look at wider impact of discharge flows.	The type of water quality model will be driven by the type of discharge and the proximity of sensitive receptors. Conservative tracer or flushing models are most common however these look at the dispersion of contaminants without the complex processes of decay caused by UV, salinity/temperature. These typically provide an indication of 'good' water quality based on tracer residency times within defined areas. Agreement on the areas to be assessed and the criteria to be achieved should be made prior to commencement of the modelling Specialist water quality models exist to undertake initial dilution analysis, full water quality including bacterial decay due to UV / salinity / temperature, and eutrophication, as well as oil spill impact assessments.
Navigability	Vessel traffic densities and safe clearances from hazards including other vessels. To understand choke points and high-risk areas/scenarios.	-
Mooring / berthing	Vessel movements in consideration of hydrodynamic and wave conditions. To understand berthing scenarios as well as to predict loads on mooring lines and fenders.	-

Source: Adapted from Table 4-2, Guidance on the Environmental Clearance (EC) Requirements for Development, Infrastructure and Industrial Projects in the Emirate of Dubai (Dubai Municipality, 2021)

3.14.3.2 Calibration and validation

For in depth guidance on model set up, calibration, and validation, refer to the paper, Guidance on Setup, Calibration, and Validation of Hydrodynamic, Wave, and Sediment Models for Shelf Seas and Estuaries (Williams & Esteves, 2017). As per the same, "(a) calibration is a process which requires the adjustment of certain model parameters to achieve the best performance of the model for specific locations and applications; (b) verification ascertains if the model implements correctly the assumptions made; and (c) validation seeks to establish the agreement between the predictions and the observations." Calibration and validation should be based on two separate datasets (a similar concept to the use of Ground Control Points and Check Points when developing Digital Terrain Models, refer to Section 3.10).

Given the reliance of the model's development on checks against observed data, a common adage in the modelling community is: *'Garbage in, garbage out.'* Essentially, a model will never be more reliable than the data on which is it based. Therefore, the importance of recording high

quality measured data to support modelling activities should be appreciated by all. This includes developers and designers affording appropriate resources, in terms of both budget and schedule, to this data collection phase; other stakeholders and owners of existing data making long term datasets available where possible; and regulators permitting deployment and import of the required instruments.

Model outputs should be assessed both qualitatively and quantitatively. Under the former, simple plots of both predicted and measured parameters can readily identify shortcomings in the model and identify any obvious trends, for example a consistent under or overprediction of wave heights. Following the qualitative or visual assessment, outputs can be assessed against measured data in a quantitative way and the resulting statistics compared to various tolerances. Statistical guidelines to establish calibration standards for a minimum level of performance for coastal hydrodynamic and sediment models are presented in Table 3.26.

Table 3.26: Minimum calibration standards for coastal hydrodynamic and sediment models

Model predictions	RMSE	Bias	R	SI
Bathymetry	± 2.5% of the mean water depth.	< 0.10	> 0.95	< 10%
Water level (coast)	± 0.1m or 10% of the measured level (Spring tide); ± 15% (Neap tide).	< 0.10	> 0.95	< 10%
Water level phase (coast)	± 15 minutes	< 0.20	> 0.90	< 20%
Average current speed	± 0.1m/s or ±10% to 20% of the measured speed.	< 0.10	> 0.95	< 10%
Peak current speed	Within <0.05m/s (very good), <0.1m/s (good); <0.2m/s (moderate) & < 0.3m/s (poor) of the measured peak speed.	< 0.15	> 0.90	< 15%
Current direction (coastal)	± 10° of the measured direction.	< 0.25	> 0.90	< 20%
Bed shear stress	± 10% N/m^2 of the measured mean stress.	< 0.10	> 0.95	< 10%
Wave height	± 10% of the measured mean observed height.	< 0.15	> 0.95	< 10%
Wave period	± 20% of the measured mean observed period.	< 0.20	> 0.90	< 20%
Wave direction	± 30% of the measured mean observed direction	< 0.25	> 0.90	< 25%
Mean SPM concentration	± 20% of the mean measured SPM concentration	< 0.20	> 0.90	< 20%
Accretion based on dredge volumes	± 50% of the measured dredge volume	N/A	N/A	N/A
Temperature	± 0.5° ± 1 psu			

Source: Based in part on the recommendations from (Evans, 1993) and (Bartlett, J M, 1998).

3.14.3.3 Other considerations

Further key considerations when developing and interpreting numerical models are outlined in Table 3.27.

Table 3.27: Further considerations for the development of numerical models

Consideration	Comments
Grid set up	Grid dimensions should be suitable for the desired accuracy and precision. Common practice is to use a coarser grid in areas where less variability is expected, such as offshore areas; and a finer grid in areas of greater interest. This is deemed an efficient approach. The resolution of the model should be considered and its impacts on the results understood. As a minimum all channels/flow paths should be a minimum of 3 elements wide, with a desire to be 5 minimum to avoid artificially restricting flow due to the grid resolution.
Boundary conditions	Boundary conditions i.e. the conditions at the 'edge' of the resolved model, are important and a potential source of model instability. For further detail refer to (Williams & Esteves, 2017).
Model domain	The model domain should cover the complete project site and extend sufficiently from the site such that boundary conditions do not adversely affect the point of interest. The domain is likely to extend offshore to coincide with the data available for use as boundary conditions.
Sensitivity analysis	Sensitivity tests should always be undertaken on key parameters to ensure that small changes in input values do not result in large changes in output values. This is particularly true where input values are assumed, e.g. bed roughness for wave models.
Physical structures	The representation of physical structures should be carefully considered so that relevant interactions may be accurately modelled. Common concerns include predicting the degree of wave reflections and transmission. It should be noted that modelling future scenarios with increased water levels may represent a significant change from the present-day situation. Structures should be represented such that they remain relevant under such scenarios.

4 Coastal Flooding and Erosion Risk Assessment

4.1 General

This section provides guidance on the assessments as described in Table 4.1.

Table 4.1: Overview of the approach to guidance on flood, erosion, and environmental impact risks

Assessment	Clarifications	Guidance approach
Flood risk	This guidance refers to long-term flood risk (i.e. risk on the basis of average probabilities of occurrence etc.). This guidance refers exclusively to flood risk from the sea; other flood risk from other sources should still be assessed. Combined effects from multiple sources should also be considered. Other sources of flood risk can include groundwater, sewers and water mains, surface water, and reservoirs.	Guidance will be provided from the perspective of an individual development – strategic-level studies such as Strategic Flood Risk Assessments and Coastal Zone Management Plans are not considered and will be assumed to exist. Should they not exist, it is assumed that strategic decisions will be agreed through discussions between the relevant authorities and developers.
Erosion risk	This guidance relates to long-term erosion risk.	
Environmental impacts	This guidance pertains to coastal infrastructure works in the marine environment only.	The Environmental Impact Assessment (EIA) process is well established in the legislation which should be adhered to. The current guidance is intended to highlight key considerations relevant to coastal infrastructure developments specifically.

4.2 Flood risk

4.2.1 Principles and approach to flood risk management

4.2.1.1 Flood risk bands

A Flood Risk Assessment (FRA) should be completed for every development requiring planning permission. However, the level of information and detail of the required FRA will vary in line with the vulnerability, impact, and scale of the proposed development. A FRA should be carried out alongside an Erosion Risk Assessment as erosive shorelines will normally drive an increase of flood risk in time.

A useful external reference relating to management of flood risk in the coastal zone is provided in ASCE 24-14 Flood Resistant Design and Construction (ASCE, 2014). However, this document has not been adopted by The Bahamas and should therefore be read for information only.

Flood risk bands are defined in Table 4.2. A development should demonstrate in which band it is located. If the development is unable to demonstrate the risk band in which it is found, it should be assumed to be at high risk. While the concept of flood risk bands will generally not apply to coastal defences and assets intended to be regularly inundated, such developments should demonstrate they do not increase flood risk elsewhere.

Table 4.2: Definition of flood risk bands

Flood risk band	Events to which the site is exposed			
	Annual Exceedance Probability (AEP)			Return Period (years)
FR1 Low		AEP	≤ 0.1%	Less frequent than 1 in 1000 years
FR2 Medium	0.1% >	AEP	≤ 0.5%	More frequent than 1 in 1000 years and less frequent than 1 in 200 years
FR3 High	0.5% <	AEP		More frequent than 1 in 200 years

Note: Refer to Section 4.2.3 for a discussion on the reliance on coastal defences when assessing the flood risk to a site.
If available, a development's Flood Risk Band may be defined using Flood Hazard Maps approved for use by the government. If such maps are used, no further demonstration of the development's Flood Risk Band is necessary. However, the final flood risk of a development should still be demonstrated.

4.2.1.2 Minimum FRA requirements

All developments going through the planning process should undertake an FRA. However, the level of detail required will depend on the project context and, in the simplest cases will be high-level, while in the most complex cases, dedicated studies undertaken by specialists will be required. The current section provides guidance on minimum FRA requirements for a particular project type.

FRA requirements will be driven by:

1. The flood risk band of the site.
2. Consequence class of the development as described in Section 2.1 which in turn relates to the severity of the impacts in the event of failure. In the context of flood risk, *failure* refers to flooding of the development.

The final objective of the FRA is to demonstrate that flood risk has been adequately considered and mitigated. The manner in which this is achieved for an at-risk site is by reducing the vulnerability of the development to flood events i.e. the capacity of a site to endure the design flood event without unacceptable damage or harm to people or the environment.

The recommended level of detail to which a development's FRA should be carried out, depending on its assigned Flood risk band and Consequence class, are categorised in terms of *FRA requirement levels*. These are defined in Table 4.3 and Table 4.4.

Table 4.3: Descriptions of FRA requirement levels

FRA requirement level	Description
FRA3 (Comprehensive)	Most comprehensive requirements
FRA2 (Moderate)	Moderately comprehensive requirements
FRA1 (Limited)	Least comprehensive requirements

Table 4.4: FRA requirement level by Flood risk band and Consequence class

Flood risk band	Consequence class			
	C1 (Least critical)	C2.B	C2.A	C3 (Most critical)
Low	**FRA1**	**FRA1**	**FRA1**	**FRA2**
Medium	**FRA1**	**FRA2**	**FRA2**	**FRA3**
High	**FRA2**	**FRA2**	**FRA3**	**FRA3**

Source: FRA requirement level as defined in Table 4.3.
Flood risk bands as defined in Table 4.2.
Consequence class otherwise as defined in Table 2.1. C2-B refers to both C2.B.1 & C2.B.2

4.2.2 FRA expectations

Guidance on what level of information may be expected per FRA requirement level is outlined in Table 4.5.

Table 4.5: FRA expectations by requirement level

Item	FRA requirement level		
	FRA3 (Comprehensive)	**FRA2 (Moderate)**	**FRA1 (Limited)**
General information such that the existing site and proposed development may be adequately understood.	Descriptive text and preliminary plans including: ● Location plans including the red line boundary of the site at an appropriate scale such that the site extent and location may be understood. ● Description of the existing site including descriptive text and drawings/sketches as appropriate. ● Description of the proposed development including descriptive text and drawings/sketches as appropriate, such that the nature and scale of the proposed changes may be adequately understood. Important details to be communicated include: ● Development scale. ● Key vulnerabilities such as sensitive receptors to impacts. ● Ground and finish levels. ● Proposed materials. ● Design performance criteria such as design lives, design events, and Standards of Protection (if applicable).		As for FRA3 and FRA2 but to less detail. Information can generally be limited to that required for planners to make an informed decision whether to accept the assumed Flood risk band and Consequence class. Nevertheless, as a minimum, the following should be provided: ● Location plans. ● Description of the existing site. ● Description of the proposed development.
Understanding of: ● Existing flood risk to the site (in the absence of approved flood hazard maps) ● Future flood risk to the proposed development	Risk should typically be demonstrated using a bottom-up approach via appropriate calculations and modelling (if appropriate) based on data of at least medium reliability (as per Section 3). Where relevant, overtopping assessments should be carried out in addition to assessment of anticipated flood depths and flow velocities (See Section 4.2.3.1). Information on historic flooding at and near the site should also be provided.	Risk should typically be demonstrated using a mostly bottom-up approach. However, as compared with FRA3, higher level calculations and increased reliance on reasonable assumptions should be expected. For instance, numerical modelling will normally not be required. Data should normally be of medium reliability (as per Section 3). Information on historic flooding at and near the site should also be provided.	Risk may be demonstrated based on higher level information such that planners may make an informed decision whether to accept the assumed Flood risk band. This may often be limited to as assessment of site levels against anticipated surge heights. It will normally be appropriate to base the assessment on data of low reliability (as per Section 3).
Management of flood risk to the development	Flood risk is expected to be a primary design driver and should therefore be at the forefront of high-level to detailed design phases. Controls will be required to ensure protection from, and resilience to, flooding and will require formal design. A combination of structural and non-structural measures will normally be required.	Flood risk is not expected to significantly drive design but will nevertheless need to be explicitly considered. Controls will normally include a combination of structural and non-structural measures, but the reliability of structural measures for flood prevention purposes may be reduced. For instance, walls designed for non-flood related purposes may be assumed to fulfil a flood protection role despite not	Flood risk is not expected to drive design. Controls may be limited to measures ensuring resilience, which may be limited to non-structural measures such as sign-up to flood warning alerts.

		necessarily being designed for such scenarios.	
Management of wider flood risk impacts	The FRA should demonstrate that the development does not contribute to any increase in flood risk beyond the site, for instance due to the introduction of structures that may impede flood water escape routes. Dedicated studies may be required should this risk be significant. This will normally be the primary focus for FRAs for coastal protection or beach control solutions given the limited relevance of flood risk to the developments themselves.	Wider flood impacts should be considered but demonstration of negligible impact will normally be appropriate via a brief, high level justification.	Wider flood impacts will not normally need to be considered.

Note: Comments apply to coastal flooding only.
Demonstration via calculations do not generally need to include detailed calculation sheets; it will normally be sufficient to provide the primary findings although key design assumptions should be communicated.

4.2.3 Assessment of flood risk

4.2.3.1 Flood mechanisms and parameters

Flooding via all feasible and relevant mechanisms should be considered. The most important flooding will normally be that due to increased water levels due to the combination of tides, surge, wave set-up, and sea level rise. However, flooding via overtopping may also be relevant in terms of rates and/or volumes. Flooding can also occur via indirect flow paths, sometimes referred to as backdoor flooding[15], the potential for which should be considered.

The flood risk band of a site should be defined based on the worst-case mechanism of flooding, or their worst-case combination.

The impact of flooding has been found to be strongly linked with flow velocities in addition to flood depths and duration. Therefore, most FRAs carried out under the FRA3 requirement level should consider all such variables of flood events. The additional consideration of flow velocities, as opposed to consideration of depths and duration only, represents an increase in onerousness but also reliability of the FRA. Therefore, while this represents best practice and should be encouraged and increasingly enforced, planners should acknowledge the additional cost and effort implications of this requirement and avoid overly stringent and disproportional requirements.

4.2.3.2 Climate change and erosion

Flood risk assessments should consider the complete lifetime of the proposed development and account for climate change impacts (refer to Section 3.13), including sea level rise and potential increases in wave energies.

4.2.3.3 FRA for coastal defences

The concept of flood risk for coastal defences and other structures intended to be regularly inundated will differ; assessments of such developments do not normally need to protect the assets themselves against flooding but should demonstrate that they will not result in

[15] Backdoor flooding: Where inundation occurs not due to flooding along the length of coast directly fronting the affected area but rather due to flooding of an adjacent length of frontage and the subsequent flows of the flood waters.

unacceptable increases in flood risk elsewhere. Wider impacts due to the proposed works should also be considered (refer for instance to Section 5.6.1.6) such as impacts on sediment movement.

4.2.3.4 Reliance on existing coastal defences

A development benefiting from the protection of flood defences may assume its flood risk corresponds to the Standard of Protection (SoP) offered by those defences. However, the proposed development should account for residual hazards such as overtopping allowed for in the defence's design event. Considerations should take into account the intended lifetime of the development and the residual lifetime of the defences; the latter of which should be communicated by the relevant authorities. If unknown, estimating the SoP of a defence will normally be the responsibility of the developer. However, as these are typically public assets, the owner of the defences should make efforts to support this assessment, for instance by sharing design and construction records if available.

4.2.3.5 Emergency access

Emergency access needs to be explicitly considered in the design. Required emergency access will typically depend on the occupancy intent; where there is a possibility that developments remain occupied during storm events (whether by residents, workers, or visitors), the design should allow for access by emergency services.

Appropriate emergency access may take the form of access structures or land routes sufficiently protected from, and/or elevated above, design flood levels; or, as a minimum when such an approach is deemed impractical, balcony or roof access to facilitate emergency evacuation by air or sea.

Roads and other access routes do not generally need to be useable during storm events unless they serve to connect people or critical infrastructure with safe areas. For instance, an access road connecting a ferry terminal or port to the mainland will not normally need to be useable during a storm as operations will have ceased during the event and a full evacuation of the site should have taken place. However, and particularly when such facilities may be important for post storm recovery, such access routes should be resilient so that operations may resume following passing of the storm.

4.2.4 Flood risk protection and resilience

4.2.4.1 Flood risk resilience

Coastal developments should be resilient by design. A resilient design is one where that damage is limited in the event of flooding.

Useful external references providing guidance on designing flood resilient structures include:

- ASCE/SEI 24-14 Flood Resistant Design and Construction (ASCE, 2014)
- Home Builder's Guide to Coastal Construction, Technical Fact Sheet Series, (FEMA, 2010)

Resilience can be provided via *dry* or *wet flood proofing*. These are sometimes referred to as *flood proof* and *flood resilient* design, respectively. ASCE/SEI 24-14 (Flood Resistant Design and Construction, SEI 24-14, 2014) imposes one of the two approaches on developments depending on the flood risk of the site and the intended use of the development. This requirement is not adopted as a recommendation in the current guidance; the preferred approach is left to the developer to allow them greater flexibility to design for the project needs. However, guidance around the implementation of each strategy remains relevant.

Dry Floodproofing – A combination of measures that results in a structure, including the attendant utilities and equipment, being watertight with all elements substantially impermeable and with structural components having the capacity to resist flood loads.

Wet Floodproofing – Floodproofing method that relies on the use of flood damage-resistant materials and construction techniques in areas of a structure that are below flood level.

Common measures to increase resilience to coastal flooding include:

Structural measures

- Raised threshold and floor levels
- Raised electrical sockets
- Proper material selection
- Falling levels directing flood waters away from critical portions of a development
- Removeable flood barriers
- Incorporation of flood resistant planting and landscaping, especially to protect from scour

Non-structural measures

- Establishment and sign-up to flood warning alerts
- Education to communicate good practice such as the need to remove outdoor debris before storms
- Emergency response plans – at all levels including plans for individual properties, neighbourhoods, islands, and the nation.

Further considerations are provided below:

- The most effective way of improving resilience to coastal flooding is to firstly site developments appropriately, avoiding high hazard areas.
- Flood risk assessment should explicitly consider climate change and future scenarios, such as the longer-term impact of erosion. Refer to Section 3.13.

4.3 Erosion risk

4.3.1 Principles of erosion risk management

Shoreline positions are not fixed in space or time but are affected in multiple time scales. Shorelines can accrete, erode, or remain stable and this categorisation can vary depending on the timescale it is being assessed in. Erosion processes also differ significantly depending on the composition of the shoreline in question. Shorelines can be composed of:

- Consolidated sediment i.e. rock – in the Bahamian context this generally refers to cliffs and rocky shores.
- Unconsolidated sediment – this generally refers to muddy, sandy, and shingle/pebble shores (the latter of which does not naturally occur in The Bahamas).

Shorelines can also be formed of artificial structures such as seawalls and wharves. While these are assumed fixed, they can be susceptible to issues of scour and also play a role in erosion of the fronting beach as described in Section 5.6.3.6

Table 4.6: Overview of relationship between shoreline composition and erosion

Sediment composition	Typical shoreline	Typical erosion process	Indicative erosion risk*
Consolidated	Cliffs and rocky shorelines	Generally irreversible although eroded sediment may act as a sediment source or be deposited at the cliff toe if not caried offshore. In the case of cliffs, erosion typically occurs episodically in distinct events of collapse; therefore, erosion trends derived over a limited time scale will likely give a false impression of the long-term trend. Even with	Generally relatively predictable and, due to Bahamian geology, relatively resistant to erosive pressures.

Sediment composition	Typical shoreline	Typical erosion process	Indicative erosion risk*
		toe protection (i.e. assuming a fixed toe position), the cliff will tend to its angle of repose.	
Unconsolidated	Shorelines characterised by clay and silt (mud is captured here) such as mangroves and some tidal flats.	Often irreversible as, once mobilised (refer to Section 3.11.1 or 3.9.1.2), fine sediment is easily transported and deposited offshore. Such shorelines are typically situated in low-energy wave environments and characterised by very shallow bed slopes. Such systems are often characterised by a high portion of biomass generated in-situ. Prediction of erosion at these shorelines is generally the most complex.	Generally situated in low energy environments reducing the erosion risk.
	Sandy shores such as beaches of various granularity	Shoreline behaviour is generally very dynamic with highly mobile sediment that is mostly contained within the littoral cell[16]. Apparent erosion is often temporary as sediment can be displaced from the beach to the nearshore and provide a source for beach recovery. Sandy shorelines undergo seasonal variations, typically leading to steeper, narrower beaches with various berms in the winter and wider, shallower beaches in the summer. These shorelines can also experience rapid changes in response to storms followed by a gradual recovery. Given the dynamic behaviour of sandy shorelines, erosion processes will normally need to consider the complete littoral cell to understand whether observed local erosion corresponds to internal redistributions of sediment or to loss from the system.	Generally highly dynamic and responsive to erosive pressures.
	Pebble/shingle beaches	Pebble/shingle beaches not naturally occurring in The Bahamas and therefore not considered further	

Notes: *As per typical behaviour – the information indicated here should not be used to inform erosion risk of a specific site or development.

Predictions of erosion risk are dependent on the availability of long-term reliable data. In the absence of supporting data, building control lines, and strategic level plans such as Shoreline Management Plans; an early conversation between developers, designers, and regulatory bodies should take place to agree an acceptable approach in terms of managing erosion risk. A useful tool to facilitate these conversations and gain an early appreciation of the local shoreline behaviour is open-source satellite imagery – images should be compared over at least a medium-term period (indicatively 10 years). However, potential changes in shoreline response and sediment transport patterns should be considered, for instance due to recent coastal developments. The result of such a conversation should, taking into account the context and kind of development being proposed, be limited to a high-level preliminary conclusion as outlined in Table 4.7.

[16] Littoral cell: A coastal ‘compartment’ in which coastal sediment transport is isolated from the adjacent lengths of frontage.

Table 4.7: Typical screening criteria to agree erosion risk assessment requirements

Susceptibility of shoreline to change[1]	Typical expectation[2]	Comments
Likely	A dedicated erosion risk assessment is required. However, the required comprehensiveness of the erosion risk assessment may still vary depending on the actual site.	Erosion risk should be quantified and is anticipated to be a key design consideration. Generally, all sandy shorelines should be considered vulnerable.
Uncertain	A dedicated erosion risk assessment is required. For mobile structures (not necessarily temporary), it may be appropriate to manage risk through non-structural measures as discussed in Section 4.3.2.4. Under such an approach, a high level erosion risk assessment may be sufficient although the developer may wish to carry out a more comprehensive assessment to inform financial assessments.	-
Negligible	A high level erosion risk assessment is required to justify the assumed negligible susceptibility.	Erosion risk will normally not need to be quantified. Generally, such shorelines will be: ● rocky in composition or; ● those hardened by artificial structures. However, in this case, the residual life of such structures, and the likelihood that they will be maintained should be understood.

1 Generally the likelihood that the shoreline will experience change over the lifetime of the development.
2 This table is for general guidance only; each development should be considered in its specific context. The required level of erosion risk assessment should be proportionate to the degree of likelihood of erosion and vulnerability of the proposed development.

Key principles that should drive any erosion risk assessment are listed below.

1. Erosion should be considered for the full design life of the development.
2. Forecasted erosion rates will always carry a significant level of uncertainty. Therefore, reporting should also capture the associated uncertainty while designs should adopt a conservative approach when managing erosion risk. The extent to which conservative factors of safety or similar are applied may vary depending on the confidence of the underlying assessment.
3. Impacts of climate change, sea level rise and increased storminess in particular, should be explicitly considered.
4. A suitable buffer should remain between vulnerable portions of the development and the shoreline. The definition of *suitable* will also vary depending on the importance, function, and vulnerability of the development. The definition of *vulnerable portions* will typically include the primary structures and any necessary infrastructure servicing it especially access and evacuation routes. The definition of *shoreline* may vary by local conditions and the context of the development. This could be considered the cliff edge, limit of wave impact, limit of runup, extreme water level, etc..

4.3.2 Assessment of erosion risk

4.3.2.1 General

This sub-section provides guidance on what an acceptable erosion risk assessment would provide in light of the anticipated shoreline response and context of the development. Erosion risk assessments should normally consist of three parts:

5. Understanding and predicting erosion rates.
6. Assessing the resulting erosion risk to the proposed development.
7. Managing and mitigating the risk.

Many forms of coastal infrastructure such as groynes and nearshore breakwaters aim to directly act against erosion. Rather than being used to understand the risk to a development, in these cases the erosion risk assessment process will normally be used to justify and inform the required performance of the works.

4.3.2.2 Understanding and predicting erosion rates.

Erosion processes are the result of complex interactions between the land and the sea. Quantifying erosion (or accretion) rates is usually challenging, and the appropriate level of effort invested to do so will typically be driven by the wider context of the site and development. Nevertheless, some understanding of erosion risk will always be required; some typical approaches to understanding of shoreline movements is provided in Table 4.8 below.

Table 4.8: Typical approaches of shoreline movements

2. Cross-shore surveys	
Description	3. Acquire historical cross-shore beach profiles – these are generally topographic datasets captured along a beach width undertaken at regular intervals along a frontage. Surveys should be repeated at consistent locations to enable comparisons in time. 4. Interpolate or infer to the desired location needed for the project - Survey locations (unless carried out via dedicated surveys for the project) will generally not be situated ideally for the project. However, the use of historical data will normally outweigh any advantage of carrying out only a few dedicated surveys. Therefore, while recent datasets can be utilised to support any inferring or interpolation activities, a common approach is to interpolate between profiles if appropriate. The additional advantage of this method is that it can support an understanding of variability with the beach cell which does not necessarily correspond to a net loss of sediment but rather to temporary beach oscillations or similar. 5. Assess shoreline changes in time, noting seasonal trends, storm impacts, and any impacts due to external activities such as new coastal structures or recharge activities. While the erosion rates should be quantified, they should be accompanied by an understanding of their uncertainty.
Constraints / advantages	● This method will normally provide information along the entire beach width, enabling an understanding of cross-shore processes and modes of beach response. ● The data is relatively low-cost and simple to collect yet provides detailed information suitable for a wide range of purposes. ● Data will typically be captured at a high resolution and provides an opportunity to collect additional information such as sediment types. ● This method relies on existing information which will generally not be available. Collection of this information for a specific project will require repeated surveys and will only provide information in the short term which is insufficient to understand long term erosion trends. However, short term information can be useful to understand beach responses to storm events, provide critical input information to designs, and serve as input to numerical models. ● Interpolation between profiles may not be appropriate in cases of irregular or complex frontages.
Indicative reliability	Provided data is available, this approach is normally a simple and reliable approach for the assessment of historical erosion rates. The primary limitations relate to: ● The need to interpolate between profiles in order to understand longshore beach behaviour. ● Extrapolation into the future remains complex and should consider climate change and other relevant external forcings as well as the potential changes in shoreline response due to the changing beach shape and loss of beach width.
Digital elevation models based on LiDAR, photogrammetry, acoustic (for bathymetry) or similar	
Method description	6. Develop or acquire digital elevation models (DEM) based on elevation information collected via aerial surveys (for e.g. using LiDAR or photogrammetry methods). Multiple surveys will be required in time and at appropriate intervals and timings. 7. Assess shoreline changes in time, noting seasonal trends, storm impacts, and any impacts due to external activities such as new coastal structures or recharge activities. The common

	approach is to develop difference plots which readily provide a visual and quantitative way to show where the beach has accreted, eroded, or undergone little change. While the erosion rates should be quantified, they should be accompanied by an understanding of their uncertainty.
Constraints / advantages	● This method will provide complete elevation information for a length of frontage but for only either above or below the water line depending on the method used. A full description of the nearshore will require use of multiple survey types. ● This method will normally provide information along the entire beach width and length of frontage, enabling an understanding of cross-shore processes and modes of beach response but also of long-shore processes such as temporary oscillations in beach shape related to seasonal trends or temporary wave conditions. ● The data is relatively low-cost and simple to collect when done over a large area yet provides detailed information suitable for a wide range of purposes. ● Data will typically be captured at lower resolutions and accuracies than that captured via cross-shore surveys. Nevertheless, such datasets are generally sufficient for understanding of erosion processes. ● This method relies on existing information which will generally not be available. Collection of this information for a specific project will require repeated surveys (at appropriate intervals and timings) and will only provide information in the short term which is insufficient to understand long term erosion trends. However, short term information can be useful to understand beach responses to storm events, provide critical input information to designs, and serve as input to numerical models.
Indicative reliability	Provided data is available, this is normally a simple and reliable approach for the assessment of historical erosion rates. The primary limitations relate to forecasting based on historical information. Forecasted behaviour should consider climate change and other relevant external forcings as well as the potential changes in shoreline response due to the changing beach shape and loss of beach width.
Satellite and aerial imagery	
Method description	8. Acquire suitable datasets over as long a time period as possible. 9. Normalise the imagery against permanent hard structures to manage distortion or projection variations between datasets and enable a comparative assessment. 10. Using the visuals, determine the shoreline position; this may be defined in a number of ways but should be distinct, representative, and repeatable across datasets. Common examples include: – Cliff crests – generally reliable. However, note that cliff erosion commonly occurs in distinct events as opposed to a gradual recession. – Beach crests – generally difficult to define without elevation data and subject to high variability. – Vegetation lines – useful if continuous and natural, generally easy to define. – Debris (such as seaweed) lines – generally an appropriate approximation of high water though will vary depending on the most recent water levels and/or wave runup. 11. Assess shoreline changes in time, noting seasonal trends, storm impacts, and any impacts due to external activities such as new coastal structures or recharge activities. While the erosion rates should be quantified, they should be accompanied by an understanding of their uncertainty.
Constraints / advantages	● Thanks to the wide, open-source availability of historical satellite imagery, this method will normally be available. ● The primary challenge is typically in reliably and consistently identifying the shoreline position especially. ● While elevation information, if available, can be related to the imagery, outputs will generally only provide information on horizontal recessions from which vertical decreases and changes in slope can only be inferred.
Indicative reliability	Generally reliable for identification of significant, long-term trends to a limited accuracy.

Predicting the impact of climate change is particularly challenging given, firstly the uncertainties in the predictions but also the significant uncertainties in the shoreline response. Where erosion assessments are based on numerical sediment models, this impact can be captured in a relatively straightforward way – normally by running future scenarios increasing water levels and wave energies.

Consideration for climate change may be accomplished via a number of approaches including:

- Application of the Bruun rule[17] or alternatives for sandy shorelines to estimate the impact of sea level rise.
- In the absence of reasonable assumption, application of simple uplifts to include conservativeness in the estimate.

The expected outputs of this process should include:

- Average erosion or accretion rates.
- An indication of the confidence of the reported rates. Ideally, this would take the form of confidence bounds but otherwise this may be captured by reporting of assessment limitations and a description of how this has been accounted for in the assessment.
- Predicted shoreline positions in time at regular and appropriate intervals up to the end of life of the development.
- Identification of any hot spots i.e. localised areas of relatively greater rates of erosion.
- An understanding of the shoreline behaviour for the complete Zone of Influence – not just the length of shoreline directly fronting the development. The Zone of influence will typically correspond to the littoral cell[18].

4.3.2.3 Assessing the erosion risk

The risk of erosion to the development will depend on the predicted erosion at the site and the vulnerability of the proposed development. Generally, consequences of erosion include:

- Increased flood risk.
- Direct undermining of the development and subsequent loss of structures, access roads, and other infrastructure.
- Contamination, for instance should erosion impact landfalls or stores of hazardous substances.
- Loss of beach, generally undesirable but even more so if critical to the services provided by the development, such as hotel complexes.

Erosion risk should be assessed in the context of the proposed development and the degree of tolerable uncertainty and risk.

4.3.2.4 Managing and mitigating the risk.

Generally, the preferred strategy to mitigate risk of erosion impacting a developing is to avoid it altogether by taking the decision to not build at all. Alternatively, adaptive solutions can be found, such as design of mobile, or readily relocatable structures for which erosion risk may be managed via non-structural methods such as the development of action plans. For instance, a trigger level[19] could be defined which would allow the developer to identify the time when the development should be demolished or retreated. However, if such an approach is adopted, commitments by the developer to follow the agreed plan should be formally captured and enforceable including timelines for implementation and monitoring requirements.

Assuming intervention is required, management of the shoreline itself is best undertaken by the public authorities in accordance with the corresponding Shoreline Management Plan if available. Mitigation of erosion risk for individual developers, unless permission is granted to

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17 Bruun rule: A relationship originally published by Per Bruun in 1962 to predict the response of sandy shorelines to sea level rise. This rule should be used in consideration of its limitations and underlying assumptions.

18 Refer to Section 4.3.1.

19 Trigger points identify when critical thresholds are approached for irreversible or damaging impacts and therefore when adaptation strategies should be adjusted.

carry out intervention measures such as beach control structures and recharge, is therefore typically limited to mitigation of its impacts. For instance, developments can increase resilience to flooding and adopt setbacks. However, in the event such an approach is taken forward, it will be the responsibility of the developer to demonstrate that the design and intended use is appropriate and, most importantly, will not result in unacceptable risk to people or the environment.

4.4 Environmental Impact Assessment

The Environmental Impact Assessment (EIA) process is well established in the legislation which should be adhered to. The current sub-section is intended to highlight key considerations relevant to coastal infrastructure developments specifically.

Fundamental principles and best practice in carrying out EIAs continue to apply. In particular, the hierarchy for mitigating impacts as outlined below should be followed.

1. *Avoid* the impact by not taking certain action
2. *Minimise* the impact through, for example:
    a. Changes in the design
    b. Changes to construction techniques and their timing
    c. Implementation of additional controls during construction
    d. Implementation of a maintenance or preservation scheme
3. *Restore/Remedy* the impact by repair or restoration
4. *Compensate* by replacing resources
5. And *Enhance* positive opportunities.

While the ecological habitats are often characterised in terms of plan area, the quality of the habitat is also important and some areas may have statutory protections. Created habitats often are typically less ecologically valuable than those that have developed naturally. A preferable approach is to consider the overall biodiversity net gain; an approach currently considered standard practice elsewhere in the world such as the UK.

Stakeholders in the development of coastal infrastructure should be aware of a variety of potential environmental impacts on sensitive receptors. Compared to a terrestrial environment, impacts in the marine environment can be particularly significant and far-reaching given the connectivity (biological, hydraulic, etc.) and dynamic nature of the coastal zone.

Table 4.9: Environmental risks and considerations for the marine environment

Risk	Special considerations for the marine environment
Water quality	Well developed in existing literature and regulations. The impact of the construction, operation, and demolishing of the proposed development should be investigated. The developer should demonstrate that the proposed development and construction methods have negligible or acceptable impact on water quality. Factors of particular relevance include: ● The potential of a development to reactivate contaminated sediment due to construction activities or dredging. ● The introduction of micro-plastics to the water, due for instance to the deterioration of geotextiles, PVC pipes or coverings, etc. Deterioration of PVC is accelerated by UV radiation, significant in the Bahamian climate. ● Flushing of the site which can help reduce concentrations of pollutants. Refer to Section 3.11 for further information on data collection and survey requirements
Noise and vibrations	Noise and vibrations can propagate underwater, potentially impacting beyond the site in the order of miles/kilometres.

Risk	Special considerations for the marine environment
	During construction, the most significant sources of noise and vibrations will normally be piling activities and heavy machinery. Impacts during operation will often be related to increased human activity and boat traffic. Common mitigation measures during construction include the use of bubble curtains and timing of high impact works in consideration of seasonal and daily movements of marine and coastal fauna. Mitigation measures during operation are generally difficult but can include restrictions on operations during certain temporal windows, such as restricting beach access or vessel movements during key breeding seasons or hours of increased fauna activity. In the likely event such mitigations are insufficient, compensatory habitat may need to be established in addition to the mitigations. Given such difficulties in controlling such impacts, the context of the site and the intended use of the development should be properly considered. Where important habitats are impacted and mitigation measures are insufficient,
Mobilisation of sediment	Marine and coastal works, especially any dredging works, have high potential to mobilise sediment with possible increases in turbidity and remobilisation of contaminated material. Impacts may relate to smothering of sensitive habitats such as corals, reduced quality of bathing waters and subsequent H&S concerns, as well as the re-introduction of harmful substances into the wider ecosystem. For further considerations on contaminated sediment refer to Section 3.11.
Sediment transport	Local modification of a shoreline can have significant impacts on the wider frontage. This is particularly likely to be an issue where structures extend into the nearshore thereby interrupting alongshore sediment transport. Such impacts should be anticipated and considered for the full extent of the potential impact, normally the full littoral cell in which the development is found. Structures parallel to the coast may also impact sediment movement due to increased wave reflection although impacts are more likely to be more local.
Flood risk	Developments should demonstrate that they will not increase flood risk elsewhere nor place the development itself at unacceptable risk, as described in Section 4.2.
Direct habitat loss	This consideration is not unique to coastal developments but will often be particularly important for the marine environment given the high ecological value of such habitats.
Carbon and emissions	The overall sustainability of a development from a carbon (inherent and emitted) and consumption/emissions perspective should be considered for the whole life of the asset. Assessment for coastal developments will generally not require any unique considerations.

Source: The considerations listed are not exhaustive. Relevant legislation on the EIA process should be adhered to.

5 Design and Appraisal

5.1 General

This section is intended to provide guidance to stakeholders on appropriate design processes and decisions in the design of various coastal infrastructure asset types.

A primary aim of this section is to provide developers and planners with the toolset and awareness of key risks, opportunities, and challenges around the design of coastal structures, enabling them to ask the right questions to the designer in particular. This section is also intended for reference by designers and engineers for use as guidance, but not as a design tool.

Asset types have been broadly grouped into the five categories below.

1. Flood and erosion protection measures
2. Maritime structures
3. Land reclamation
4. General infrastructure in the coastal zone (i.e. additional considerations around standard infrastructure required when situated in the coastal zone)
5. Other structures in the coastal zone

Guidance is also provided around the wider design process in relation to client and contractor involvement, the recommended approach, managing safety by design, and design constraints and opportunities that will impact key design decisions.

A useful external reference is Part V Chapter 3 of the Coastal Engineering Manual (U.S. Army Corps of Engineers, 2006) which goes into significant depth on the current state of knowledge and function of shoreline protection assets. Some content in this Section will include similar information though refined for the priorities of the intended audience and made relevant to the Bahamian context.

5.2 Typical procurement approaches

The developer or promoter of a scheme (contractually the client) will choose a procurement route in order to manage their cost and schedule risks. This typically leads to several design phases with the aim of progressively increasing price and schedule certainty. For coastal work the plant available to the contractor and the constraints on construction methodology by the environment and location have an influence on the design.

Useful external guidance includes:

- FIDIC international standard forms of contracts (FIDIC, 1999)

This guidance is focused on the design of schemes, but this should not exclude the important input required from contractors during the design.

There are several typical methods of procurement:

1. Design to construction by client (or their appointed designer)
2. Design to construction by contractor (or their appointed designer) to a performance requirement.
3. Outline design by client (or their appointed designer) and developed with the contractor via an Early Contractor Involvement (ECI) stage

4. Outline design by client (or their appointed designer) with design to construction developed by contractor (or their appointed designer)

Where there are many alternatives of meeting the client's requirements and these can be clearly defined it may be appropriate to appoint a contractor to carry out all phases of the design. However, it will be difficult for the contractor to put a fixed cost on the works without some outline design and option selection. Appointing a contractor on only performance requirements would be more appropriate if there is only one form for the works.

To limit the risk to the contractor in assessing unconstrained options it is typical for the client to produce, or procure, an outline design, probably after an optioneering exercise.

If the client's performance requirements are difficult to define or dependent on the layout or appearance of the scheme, then they will need to retain more control of the design as it develops. However, given the construction constraints in the marine and coastal environment it is appropriate to engage a contractor before the design is finalised in order to effectively manage construction risks and associated costs.

It is appropriate to engage a contractor early if novel and innovative solutions are being investigated, including nature-based solutions.

The choice of procurement route will depend on the nature and location of the scheme and how tolerant the client is to construction risks of cost and delay.

5.3 Safety in design

International good practice is for infrastructure owners and designers to consider the safety of the works during construction, operation/use and afterlife (such as the UK Construction Design and Management Regulations, https://www.hse.gov.uk/construction/cdm/2015/index.htm (HMSO, 2015)).

The designer should consider risks from the works for those:

- carrying out the construction work;
- likely to be affected by the construction work;
- maintaining the works over its functional life;
- using or occupying the works; and,
- demolishing the works.

Following this, the design should then adopt the hierarchy of mitigations to:

- **Eliminate** the hazard by changing the design approach: A radical approach involving providing the clients required performance in a different way.
- **Reduce** the hazard through changes to the design or incorporating, generally passive, safety provisions: for example ensuring appropriate edge protection to falls from height or sight lines at road junctions. This is good design.
- **Inform** the contractor and the end user about the residual hazards: This requires effective communication between the parties but this transfer of information from the designer to the contractor is essential in reducing hazards on site information. Key information concerns design assumptions and measures to ensure the stability and integrity of the works during construction. Where necessary warning signs would be provided to inform the end user of any residual hazards.
- **Control** exposure to the hazardous situations. This includes provision of protective equipment or adopting particular working methods or limiting how the works are used. These active methods of hazard reduction relying on human behaviour only are often ineffective.

For works in the coastal environment it is not possible to eliminate or reduce all hazards and how to manage the residual hazards of working in between tides or during the hurricane season need to be understood – that is communicated to – the contractor and end user.

A useful tool to manage and record such risks is the Design Hazard Elimination and Management Record (DHEMR) document. This may take the form of a single spreadsheet. However, digital records with increased integration with BIM models and similar are becoming more common and should be considered by developers and reviewers alike. The DHEMR captures all assumptions and design decisions that have either a positive or negative impact on hazards in a single place. Recorded hazards should include those affecting all stakeholders (contractors, members of the public, maintenance operators, etc.) at all phases of the project lifetime (construction, operation, and demolition). Hazards unable to be eliminated in the design (i.e. *residual hazards*) should be highlighted and communicated to the contractor and other relevant parties, generally on construction and as-built drawings, so that they may be effectively controlled.

5.4 Adaptive design

Coastal infrastructure should be designed in consideration of present-day and future conditions, as appropriate for the intended design life. Refer to 2.3: Definition of the design event and Section 3.13: Climate change.

Predicting future conditions remains challenging especially when such changes need to be quantified. Given such uncertainty, a cautious approach should always be adopted. However, design to end of life conditions can often lead to highly impactful structures in terms of social impact (e.g., obstruction of sea views), monetary and carbon costs (e.g. larger structures requiring greater material quantities), and others. While this may often be required, an adaptive approach may be a suitable alternative.

Adaptive design refers to a design that intentionally allows for future modification of the structure. Take, for instance, a coastal defence with a 50-year design life providing a 1 in 100-year Standard of Protection (SoP). A conventional approach would be to design such that the required SoP for end-of-life conditions (i.e., including 50-years worth of predicted sea level rise and intensification of storm events), is achieved in the present day. The actual SoP immediately following construction would therefore be greater than 1 in 100-years. Under a potential adaptive approach, the structure may be designed in two phases: such to attain the required SoP for the first 25 years at which point the structure can be modified to improve its performance for the second half of its design life.

Advantages of adopting an adaptive approach include:

- Reduced risk of overdesign as adaptations can benefit on additional years of historic data and improved predictions.
- Distribution of funding.
- Reduced impact.
- Potential to take advantage of improved innovations and technologies.
- Take advantage of known major maintenance or replacement of elements that do not meet the full design life.

Key considerations to be made include:

- Non-replaceable components should be designed for the complete design life.
- The initial design should facilitate future modifications. Common examples include:
  - Initial overdesign of pile capacities and/or ground conditions to allow for enlargement of the structure.

  - Selection of flexible solutions such as preference for multiple layers, randomly placed revetment units as opposed to single layer structures.
- While the initial design will need to consider likely future adaptations, these should not be prescribed at this time but rather through a dedicated design phase once required. The capacity be clear on the 'as built' documentation.
- The developer should understand that the time at which adaptation will be required should be guided by observed trends and materialised risks as opposed to potentially out-of-date predictions carried out under the initial design.
- Design of any modifications or adaptations should consider the impact on the conditions to which the initial solution was designed. For instance, modification of the foreshore could induce breaking waves on the structures itself or lead to actually exacerbate overtopping if not designed appropriately.

Common adaptations include, but are not limited to:

- Modification of the seawards side of the structure for increased wave attenuation such as:
  - Revetments.
  - Beach recharge.
  - Mangroves or other coastal/marine vegetation.
- Modification of structure geometry such as:
  - Increase of crest heights.
  - Inclusion of recurve crest blocks / wave reflectors.
- Addition of further armour unit layers or toe protection to rubble mound structures.

5.5 Materials

5.5.1 Performance of materials

Particular attention needs to be placed on the selection of appropriate construction materials when working in the coastal zone. Key references that provide guidance on acceptable material specifications include:

- BS 6349-1-4 Maritime works Part 1-4: General — Code of practice for materials (BSI, 2021)
- The Rock Manual. The use of rock in hydraulic engineering (CIRIA, CUR, CETMEF, 2007)
- ASCE 24-14 Flood Resistant Design and Construction (Chapter 5) (ASCE, 2014)
- Manual on the use of timber in coastal and river engineering (Thomas Telford and HR Wallingford, 2004)

In particular, The Rock Manual (CIRIA, CUR, CETMEF, 2007) provides detailed guidance on the selection of rock for use in rubble mound structures – particularly important given the limited availability of suitable-grade rock from local sources in the country. BS 6349-1-4 (BSI, 2021) provides useful guidance on appropriate concrete class designations depending on its exposure to saltwater wetting/drying cycles. In addition to the concrete class, the thickness of the concrete cover of the steel reinforcement is critical.

In many instances material on site can be used, recycled or repurposed for any new works. Crushed concrete can be used as a fill material or aggregate for new concrete. Old timber can often be re-used if any damaged or rotten areas are removed.

- Key considerations for the main materials are summarised in Table 5.1: Key considerations - Materials.

Table 5.1: Key considerations - Materials

Consideration	Rock	Steel	Concrete	Timber
Embodied carbon and emissions	Relatively low for material but cost of transport can be high	High	Relatively high but benefits from production on site.	Low in terms of carbon
Sustainability	Good as is a natural material with high reusability. Quarrying depletes natural resource.	Poor and very low reusability but is typically recycled.	Moderate. Low reusability but crushed concrete may be used as aggregate but its use may be restricted if it has a high chloride content.	Good if sustainably sourced. Moderate reusability.
Maintenance and repairability	Material itself is low maintenance with low repairability. However, rubble mound structures are designed to move and suffer damage in extreme events and will therefore occasionally need some repairs.	High maintenance but high performance of repairs. Potentially rapid deterioration if MIC is not anticipated in the design but develops later.	Low but reduced performance of repairs. Major repairs are difficult so regular inspection and, if necessary minor repairs should be the maintenance strategy.	Medium maintenance and repairability. Lower design life than other options. If used as trims to other materials should be designed to be replaceable.
Typical uses	Beach control structures – groynes, breakwaters and revetments Wave control structures – breakwaters and revetments	Structural elements on jetties and quays Sheet pile for bulkheads Piles	Structural elements on jetties and quays Decks of jetties and quays Retaining walls	Structural elements on lightly loaded jetties – marinas. Decking of pedestrian access ways – marinas and beach walks. Rubbing strips Groynes

All materials require careful consideration when used in the coastal environment and specialist advice should be sought. Further considerations include:

- Aluminium is susceptible to corrosion unless the residual copper content is restricted.
- Stainless steel performs better with a high molybdenum content and a high-quality surface preparation is required.
- Many timbers are susceptible to marine borers and careful species selection is required.
- Fibre reinforced plastics (glass – GRP, carbon – CFRP, aramid fibres etc.) are widely used in marine works but need to be stabilised against UV degradation.
- Rubber is used for fendering and rubbing strips and should be from a supplier specialising in marine uses.

5.5.2 Earthworks and dredging

Dredged material can be used in earthworks or as landscaping fill if the physical properties are appropriate and it is not contaminated. It is environmentally preferable to re-use dredged materials rather than dumping it offshore.

Reclamation fills can be general fill materials if the design protects them from tidal and wave action. Where fill is exposed to wave action, armoured or reveted faces are required generally

using rock armour, rip-rap, or concrete armour units. The sequencing of gradings and/or use of geotextile is important to prevent internal erosion.

For further information pertaining to the beneficial use of dredged sediment refer to Section 5.8.2 and 5.8.2.

5.5.3 Corrosion protection

Steel elements require either corrosion protection or a sacrificial layer of steel.

High quality paint systems are required in the intertidal and zones exposed to sea spray. Permanently immersed sections require specialist paint systems.

Cathodic protection can be used in the permanently submerged zone. Either passive anodes or impressed current anodes can be used to induce a protective electric current preventing corrosion. Sacrificial anodes can be vulnerable to damage and have a limited functional life. Impressed current systems require regular specialist maintenance and a continuous electrical supply.

In some locations microbially induced corrosion (MIC, also accelerated low water corrosion, ALWC) is prevalent. This causes very rapid corrosion of steel where sunlight can penetrate the water and can only be controlled with cathodic protection as undamaged paint coatings are not feasible.

5.5.4 Availability and sourcing of materials

Designers should specify minimum performance requirements but should generally avoid prescribing specific materials or suppliers in the interest of maintaining a fair and competitive market; furthermore, this approach will normally increase efficiencies. Designers will need to understand constraints on availability as well as limitations in the working experience of available labour sources.

While innovation should not be precluded, materials or units requiring specialist knowledge and techniques should be avoided wherever possible as this lack of flexibility can reduce the pool of available contractors/suppliers with associated reductions in commercial and technical efficiencies.

Early Contractor Involvement (ECI) may be particularly useful when the anticipated design is likely to require rare materials or those requiring less common construction techniques. Refer to Section 5.2.

5.6 Flood and erosion protection measures

5.6.1 Groynes

5.6.1.1 Overview

Groynes (also *groins*) are beach stabilisation structures intended to retain sediment in order to increase beach widths. They are oriented perpendicular (or close to) to the shoreline and are commonly constructed using timber or rock. Sheet pile and/or concrete may also be used, especially if the structure is intended to fulfil additional functions (such as hosting drainage services or serving as a pier). While typically designed to simply extend seawards in a straight line, groynes may also be L-shaped, Y-shaped (commonly known as fishtail groynes), T-shaped in varying degrees from the perpendicular. The alternative shapes are used for terminal groynes at the downdrift end of the groyne field or where there are several wave directions causing movement of the beach.

5.6.1.2 Function and applicability

Groynes serve to inhibit and trap sediment transport thereby increasing beach widths that may have been reduced by erosion. They also typically to result in differential beach heights either side of the structure. While groynes are intended to increase beach widths, they do not do so uniformly; the modified shoreline generally orients itself parallel to the predominant wave direction, which, due to diffraction patterns around the groyne tips, forms at an angle from the original shoreline. For a groyne field (i.e., a group of multiple groynes spaced along a frontage), this typically results in a saw-shaped shoreline.

The use of groynes will not generally be appropriate for frontages with the following characteristics.

1. A dominant cross-shore (as opposed to longshore) sediment transport.
2. As groynes can only act on sediment transport parallel to the shoreline (alongshore sediment transport), they are not suitable for locations where sediment transport and any resulting erosion is driven by cross-shore transport. As an example, this transport in the onshore-offshore direction is typical behaviour during storm events. Therefore, the use of groynes is unlikely to be effective if erosion is driven by discrete events as opposed to the general wave climate.
3. An excessively wide surf zone.
4. The majority of longshore transport occurs in the surf zone (i.e., from the point at which waves break to the shore). Therefore, if the surf zone is excessively large, such as a frontage exposed to large waves and fronted by an extensive shallow shelf then the use of groynes may not be practical as they will only intercept a small portion of the alongshore drift.

5.6.1.3 Design considerations

The key design parameters to be considered when designing groynes and groyne fields are listed in Table 5.2 which has been adapted from a similar table in the Coastal Engineering Manual (CEM) (U.S. Army Corps of Engineers, 2006).

Table 5.2: Key design considerations – Groynes

Parameter	Relevance
External information	
Wave climate including wave heights, directions, and water levels	Influences net and gross sediment transport rates and patterns while also important for understanding structural requirements for the groynes themselves
Sediment characteristics including. rock type, density, and grain size distributions	Influences the relative permeability of the structure and sediment transport behaviour
Design parameters	
Groyne length	Important for bypassing rates (i.e., rate of sediment transport not trapped by the groyne)
Groyne length to spacing ratio	As above
Groyne permeability and height	As above while also influencing rip current formation and water circulation

Source: Information extracted from Table V-3-8, Part V Chapter 3, CEM, (U.S. Army Corps of Engineers, 2006)

5.6.1.4 Structural failure

The most important loadings for groynes are typically wave loadings and the geotechnical pressures resulting from the differential beach heights either side of the groyne. The most

common mechanisms of structural failure for groynes of various materials are shown in Table 5.3.

Table 5.3: Common mechanisms of structural failure – Groynes

Mechanism of structural failure	Comments
Timber groynes	
Rotting of timber and general deterioration	Timber is typically susceptible to rotting and attack from marine borer etc., which can lead to common defects such as split piles and rotting of planks esp. around connections leading to their detachment from the structure.
Heaving	Due to differential beach heights.
Corrosion of metal connections	Exacerbated when marine grade metals are not used.
Rock armour groynes	
Displacement of rock units	Due to wave action and potentially caused by insufficient rock sizes and/or insufficient interlocking.
Loss of core material	Core is not generally used to allow a degree of permeability. However, if included in the design movement of armour layer units can lead to loss of the finer core material which in turn can lead to settlement of the structure
Sheet pile	
Corrosion	Which can lead to voids in the retained fill and eventual collapse if not maintained or if thickness loss is not adequately accounted for in the design. Reduction in wall thickness and loss of strength or connections leading to structural collapse.
Scour	The impermeable nature of the material can increase the risk of scour of beach material, undermining and instability.
Multiple failure mechanisms	Due to wave loadings.
Concrete	
Scour	The impermeable nature of the material can increase the risk of scour of beach material, undermining and collapse.
Concrete damage	Abrasion of the concrete can lead to loss of integrity and reduction in protection to any reinforcement. Sea water is aggressive to concrete an inappropriate concrete mix will lose strength and integrity For reinforced concrete, the steel will eventually corrode, spalling the concrete and the section will lose strength eventually collapsing.
Multiple failure mechanisms	Due to wave loadings.

5.6.1.5 Functional failure

Common reasons that may describe why a groyne system does not function as intended are outlined in Table 5.4.

Table 5.4: Common reasons for functional failure – Groynes

Functional failure	Possible driving factor	Comments
	Limited understanding of sediment transport.	Particularly if the role of cross-shore transport is underestimated.

Functional failure	Possible driving factor	Comments
Insufficient retention of sediment	Excessive bypass due to excessive permeability or insufficient groyne length.	-
Erosion on the updrift side of groynes	Excessive spacing between groynes.	Excessive spacing may lead to active erosion on the updrift end of groynes for their length and permeability. However, an excessively small spacing is an inefficient solution and can also exacerbate the negative impacts of the groyne field (See Table 5.5).
Erosion downdrift of the terminal groyne	Insufficient sediment supply due to insufficient bypass.	This is a common challenge when selecting groynes as a solution and is discussed further in Table 5.5.

5.6.1.6 Wider implications

The decision to use groynes to increase beach widths should be assessed critically, considering its wider implications, the most common of which are outlined in Table 5.5.

Table 5.5: Typical wider implications – groynes

Wider implication	Comments
Downdrift erosion	As the groyne field can trap a significant quantity of material, this commonly results in starvation of the portion of frontage immediately downdrift of the terminal groyne. Erosion at this point is often more rapid than that experienced prior to the installation of the groynes. This occurrence should be carefully designed out/controlled, potentially via a tapering of groyne lengths/bypass rates, sediment renourishment and recycling, or the creation of hard erosion control structures (least preferred). The groyne field should extend to a natural break in the sediment movement cell, but this could require an extensive groyne field and extend beyond the scope of a scheme.
Access	Access along the frontage can be limited by the structures themselves and by differential beach heights. The installation of groynes effectively leads to a series of pocket beaches as opposed to one continuous frontage. Control is difficult but may be managed via careful design of bypass rates, groyne heights, and active sediment recycling. Groynes may be designed with steps/ramps to allow them to be crossed by beach users.
Characteristics of the frontage	The impact of groynes on a frontage's character can be subjective and unquantifiable. However, the presence of hard structures on a beach is typically aesthetically undesirable while the resulting saw-shape also has a significant effect on the perception of the frontage as a whole.
Risks to vessels	Groynes should be clearly marked or separated from vessel traffic as there is risk of collision especially when they may be completely submerged.
Rip-tide formation	Groynes have been known to encourage the formation of riptides, presenting a risk to swimmers. This may be controlled by careful design of groyne lengths and permeabilities in particular or the use of a T-groyne. However, this phenomenon is not clearly understood so residual risks will remain.

5.6.1.7 Key difficulties

Some key challenges in the design of groynes have already been alluded to. However, these are reiterated in Table 5.6. Insufficient appreciation of such challenges can lead to uncertainties in design and residual risks in the final solution.

Table 5.6: Key design challenges – Groynes

Design challenge	Comments
Lack of confidence in available design tools and relationships	As noted in pp. V-3-67, Part V Chapter 3 of the CEM (U.S. Army Corps of Engineers, 2006), "Although groins have been around a long time and many references exist, most only provide a few rules of thumb. No systematic methods

Design challenge	Comments
	for functional design under a wide range of structural shapes, waves, and sediment transport conditions presently exist." However, the use of numerical modelling which may be used to validate the effectiveness of the proposed design solution can significantly improve confidence in the final solution – though inherent uncertainties in the sediment modelling remain.
Downdrift erosion	Eliminating, or even controlling downdrift erosion to an acceptable degree is commonly very difficult as it is driven by the very intention the design is hoping to achieve (that is, the retention of sediment). The optimal solution is often a balance between retention and bypass which is reliant on quantifying sediment transport rates that is itself an uncertain field.
Sediment recharge and recycling	Groynes are often most advantageous when designed to complement a beach renourishment scheme. However, the presence of the groynes typically restricts access to the frontage especially for the large plant required to transport large volumes of beach material. This may be worked around via the use of vessels. However, this is usually financially impractical especially for smaller schemes and/or limited by insufficient water depths.

5.6.1.8 Opportunities

While the developer will need to demonstrate that negative impacts have been effectively eliminated or controlled, emphasis should also be placed on the exploitation of opportunities. Common opportunities associated with the decision to install groynes as a shore protection solution are outlined in Table 5.7.

Table 5.7: Common opportunities – Groynes

Opportunity	Comments
Multi-functional use	Groynes may be such that they may serve additional functions and add amenity value to the frontage. Examples include use of the groyne as: – a pier with pedestrian access to serve as a viewpoint or fishing area – a dock for small recreational vessels – protective structures for drainage systems or outfalls – a supporting platform for structures
Intertidal habitat creation	In line with the concept of 'greening the grey,' structures in the intertidal zone can be designed to encourage colonisation by marine life. Possible modifications to achieve this can include: – Design of the structure to retain water between tides to function as artificial rock pools – Increasing the micro and macro textures of materials – Provision of cavities and other possible points of shelter for marine life
Reduction of maintenance dredging requirements	When placed updrift of a channel, what was elsewhere a disbenefit – the common phenomenon of downdrift erosion – becomes an advantage as the lack of sediment reduces maintenance dredging requirements.

5.6.2 Breakwaters

5.6.2.1 Overview

Breakwaters are typically shore-parallel, nearshore, or offshore structures that induce wave breaking thereby reducing incident wave energies. The drivers for constructing such structures vary and as such so will the design parameters. Typically termed nearshore breakwaters, detached, shore parallel structures can act on sediment transport to increase beach widths. When constructed offshore or near port facilities, breakwaters may facilitate vessel movements or port operations by attenuating wave energies. Such structures are sometimes integrated with caisson structures to also serve as vessel berths.

Common variations in breakwaters are outlined in Table 5.8.

Table 5.8: Common design variations – breakwaters

Parameter	Typical variations	Common terminology / comments
Material	Rock armour	*Rubble mound breakwaters.*
	Concrete armour units	Many proprietary and non-proprietary shapes are available and is an area of rapid innovation.
	Caisson units (i.e., large concrete blocks which are floating into place)	*Caisson breakwaters* (which refers specifically to designs using large concrete structures which are floating into place).
	Mixed	*Composite breakwaters.*
Crest height	Below low water level	*Submerged breakwaters* (sometime referred to as a sill when it acts to retain beach material at a more gradual slope than would otherwise be achieved).
	Within the tidal range	*Partially submerged breakwaters.*
	Above high water	*Emergent breakwaters.*
	Floating at water level	*Floating breakwaters* (generally uncommon and will therefore not be discussed further in this document).
Permeability	Permeable	Typically structures without a core thereby allowing a degree of wave energy to be transmitted through the structure. The degree of permeability will depend on the design.
	Impermeable	Typically constructed with a core of fine material.

5.6.2.2 Function and applicability

The presence of the structure forces the wave to break due to the reduced water depth, with energy being dissipated primarily by turbulence between armour units. Wave energies are also reflected to varying degrees while diffraction will occur at the breakwater ends. Unattenuated wave energy may also pass through the structure (e.g., due to permeability of the structure and overtopping); this is known as *transmission*.

Detached nearshore breakwaters are typically intended to act on longshore sediment transport processes. The reduction in wave heights and resulting diffraction around the structure ends produces currents that encourage the deposition of sediment behind the breakwater. The initiation of diffraction also serves to extent the sheltering effect beyond the limit of the structure itself. The accumulation of sediment behind the structure is termed a salient or tombolo, the latter term used when the sediment is deposited up to the structure itself. Similar to groynes, nearshore breakwaters are typically repeated along a frontage in a series. This results in an undulating shoreline with the greater beach widths typically situated directly behind the breakwater structures.

Such structures can also provide benefits to cross-shore sediment transport especially if compared to groynes.

When intended to facilitate port or navigation operations only, their primary intention is not to influence sediment transport but to reduce wave energies. The key factors here become energy transmission, diffraction patterns around the structure, and reflections.

5.6.2.3 Design considerations

Key advantages and disadvantages of variations in breakwater structures are outline in Table 5.9.

Table 5.9: Key design considerations – breakwaters

Parameter	Typical variations	Key advantages	Key disadvantages
Material	Rock armour	● Can be comparatively cheaper than other materials. ● Embodied carbon may be less than that of the alternatives. ● Natural material may be more readily colonised by marine life. ● Standard construction. ● Can be more reparable.	● May not be appropriate for deeper waters (as is typically constructed to a 1:2 slope). ● Can be difficult to source rock of suitable type, size, and grading.
	Concrete armour units	● Can be built at a greater slope as compared to rubble mound structures. ● Special units for toe stability or for eco-enhancement are available. ● Is an area of rapid innovation.	● If unit type is specified in design, limited suppliers will be available. Contractors may likely also require proprietary fittings. ● Due to the regular placement of units, damage can propagate more rapidly, and repair can be more challenging than that of rock armour structures.
	Caisson units	● Typically, the most suitable option for deep water. ● More suitable for use as a berth.	● Less energy attenuation and increased reflection. ● Inflexible structure, increasing importance of adequate bed conditions/foundations.
	Mixed	● Structure can be varied along its length/width as needed for performance/site/etc.	● Interfaces may become complicated and likely require modelling.
Crest height	Submerged	● Reduced aesthetic impact. ● Reduced potential for formation of a complete tombolo (which in turn can overly retain sediment and provide public access to the structure).	● Can pose a navigation hazard. ● Hydraulic behaviour can be difficult to predict.
	Partially submerged		
	Emergent	● More predictable performance. ● Visibility can improve public confidence.	● Increased aesthetic impact. ● Greater material requirements with associated carbon and monetary costs.
	Floating	● Suitable for use in very deep water.	● Limited effectiveness for large wave lengths. ● Less conventional solution – risk of reduced effectiveness.
Permeability	Permeable	● Simpler construction. ● Ease of maintenance/repair. ● Can more readily serve as an artificial reef, providing ecological benefits. ● Reduced reflection.	● Reduced attenuation of wave energies. ● Reduced material requirements.
	Impermeable	● Greater attenuation of wave energy. ● Potentially more stable structure.	● Increased material requirements.

Breakwater design needs to be undertaken for all elements of the structure as the critical design parameters will usually vary. Typical elements include the:

- Seawards slope
- Rear slope
- Toe
- Roundhead
- Any interfaces such as to land or between construction types (such as in composite structures)
- Crest and any crown wall

Examples of the typical wave scenarios that are likely to be critical for various functional or structural failure mechanisms are provided in Table 5.10.

Table 5.10: Key failure mechanisms – breakwaters

Failure mechanism	Most relevant structural element	Example of typical critical conditions
Overtopping	Seaward slope and crest	Max. water depth, max. wave
Transmission through a permeable structure	Seawards and slope and core	Max. water depth, max. wave, or; Long period waves
Scour / toe failure	Toe	Low water depth, max. wave
Stability of rock armour units	Complete armour layer incl. at roundhead, slopes, interfaces etc.	Max. water level giving max. wave, or; Max. waves at a 'normal' water level leading to sustained loading on a local area, or; Sustained long period waves typically without surge leading to cumulative damage.

Note: This table is non-exhaustive and is for illustrative purposes only to highlight the importance to consider various design scenarios. Design processes should be driven by the specific project situation.

Design should follow appropriate design standards and internationally accepted guidance documents such as the Rock Manual (CIRIA, CUR, CETMEF, 2007) and EurOtop (Van der Meer, 2018). Key design parameters to be considered when designing breakwaters are listed in Table 5.11.

Table 5.11: Key design parameters – breakwaters

Parameter	Relevance
External information	
Wave climate incl. wave heights, directions, and water levels	Influence net and gross sediment transport rates and patterns while also important for understanding structural and hydraulic performance of the breakwaters themselves.
Sediment characteristics incl. rock type, density, and grain size distributions (for nearshore breakwaters)	Important for understanding of sediment transport behaviour
Design parameters	
Breakwater length to spacing ratio (for series of nearshore breakwaters)	Influences the formation of a tombolo or salient with subsequent impacts on bypass rates, water quality, and desired shoreline shape.
Breakwater permeability and height	As above

5.6.2.4 Structural failure

The most important loadings for breakwaters are typically wave loadings. The most common mechanisms of structural failure for breakwaters of various types are shown in Table 5.12.

Table 5.12: Common mechanisms of structural failure – breakwaters

Mechanism of structural failure	Comments
General	Design waves should be carefully considered and normally differ depending on which element of the structure is being designed. For instance, toe details are typically designed for minimum water levels while slopes should normally be designed to max wave heights, typically corresponding to maximum water levels.
Displacement of units …with subsequent exposure of less protected underlayers and propagation of damage.	Due insufficient rock sizes, insufficient interlocking, or excessive uplifting forces.
Migration of sub-layers	Due to hydraulic gradients inadequately managed by careful variation of layer permeabilities.
Breaking of units	Due to inadequate rock or concrete quality, or inadequate interlocking resulting in 'rocking' of the units.
Loss of core material	Due to movement of armour layer units or degradation of any geotextiles.
Sliding	Due to insufficient toe design or insufficient mass of a gravity structure for the bed conditions.
Slipping	Due to insufficient consideration of ground conditions.
Settlement	Due to insufficient consideration of ground conditions.
Breaking of units	Due to inadequate rock or concrete quality or excessive slopes.
Toe failure (by unit displacement, scour, etc.)	Potentially due to inadequate consideration of down rush from the upper slope.

5.6.2.5 Functional failure

Common reasons that may describe why a breakwater does not function as intended are outlined in Table 5.13.

Table 5.13: Common reasons for functional failure – breakwaters

Functional failure	Possible driving factor	Comments
General	Insufficient understanding of wave climates or sediment transport.	An understanding of the site and the structure's interaction with its surrounding needs to be fully understood, preferably via numerical modelling based on long term, measured data.
Excessive energy transmission or overtopping	Insufficient crest height and/or permeability.	Particularly if surge was not properly estimated or if the design was assessed against an inadequate range of wave periods.
Insufficient retention of sediment	Excessive bypass due to insufficient length/spacing to distance-from-shore ratio.	This relationship is not well understood and can often be a delicate balance between retaining too much and not retaining enough.
	Increased currents between breakwater structures.	High current can form, especially if the spacing between structures is inadequate.
Excessive retention of sediment	Insufficient bypass due to excessive length/spacing to distance-from-shore ratio.	The formation of a tombolo can exacerbate the issue of excessive sediment retention.

5.6.2.6 Wider implications

The decision to use breakwaters, especially. for the use of sediment control, should be assessed critically, considering its wider implications, typical examples of which are outlined in Table 5.14.

Table 5.14: Typical wider implications – breakwaters

Wider implication	Comments
Downdrift erosion	As the field of nearshore breakwaters can trap a significant quantity of material, this commonly results in starvation of the portion of frontage immediately downdrift of the series. Erosion in this area is often more rapid than that experienced prior to the installation of the structures.
Access	The formation of a tombolo can make the structure readily accessible to the public with associated H&S risks.
	Provision of access to offshore breakwaters may provide social and wellbeing benefits. However, any access requires careful control to ensure users are not at risk in consideration of overtopping rates and falls from hight/into water.
Characteristic of the frontage	The impact of nearshore breakwater(s) on a frontage's character can be subjective and unquantifiable. However, the presence of a structure obstructing the horizon can be undesirable. The irregular shape of the shoreline also has a significant effect on the perception of the frontage as a whole.
Risks to vessels	Breakwaters, especially submerged breakwaters, can pose a hazard to vessels. Displaced units may also end up in navigation channels – posing a risk especially in situations of low under keel clearances. The installation of markers such as navigation aids / beacons should be considered.
Rip-tide formation	A series of nearshore breakwaters may result in increased current between structures, presenting a risk to swimmers and potentially increasing cross-shore sediment transport. This may be controlled by careful design of structure lengths, spacings, and distance to shore. However, this phenomenon is not fully understood so residual risks will remain.

5.6.2.7 Key difficulties

Some key challenges in the design of breakwaters have already been mentioned. However, these are reiterated in Table 5.15. Insufficient appreciation of such challenges can lead to uncertainties in design and residual risks in the final solution.

Table 5.15: Key design challenges – breakwaters

Design challenge	Comments
Retaining the desired quantity of sediment	The balance between allowing enough sediment bypass and allowing too much is delicate and is not fully understood.
Downdrift erosion	Eliminating, or even controlling downdrift erosion to an acceptable degree is commonly very difficult as it is driven by the very intention the design is hoping to achieve (that is, the retention of sediment). The optimal solution is often a balance between retention and bypass which is reliant on quantifying sediment transport rates that is itself an uncertain field.
Structural performance	Hydraulic interactions are complex, and the response of the structure cannot always be predicted. Physical models are useful tools to identify unforeseen issues and increase confidence in the design. Modelling of roundheads should normally be undertaken in 3-D while flume models may be sufficient for design of the toe, slopes, and interfaces provided the geometry of the structure and foreshore remains simple.
Toe design	Toe design is often critical and must allow for complex flows due to the sharp gradients associated with the meeting of the structure slope and the typically-shallower foreshore – in addition to any trench created for the toe design. The toe also is critical in supporting and transferring loads from the main body of the armour layer to the ground.
Embodied carbon	Due to the significant quantities of heavy material – which often derives from sources far from the site – design of a low-carbon breakwater solution is difficult. Lower-impact alternatives as well as variation in the design itself should be considered at the optioneering phase.
Construction	The performance of the structure is dependent on proper placement of the units – whether the design calls for random placement (which is more difficult than one

Design challenge	Comments
	may assume) or regular placement (which will vary by the type of unit being installed).
	Breakwaters are inevitably often constructed in high energy wave environments. Consideration should be made for optimal construction windows in light of generally rougher winter conditions and the possibility of summer hurricanes. The temporary or permanent construction of a core rising above water level is often required for the placement of plant which, without the armour layers, is highly susceptible to rapid erosion by waves. Therefore, construction sequencing and the potential need for temporary works should be carefully considered.

5.6.2.8 Opportunities

Common opportunities associated with the decision to install groynes as a shore protection solution are outlined in Table 5.16.

Table 5.16: Common opportunities – breakwaters

Opportunity	Comments
Eco-enhancements	In line with the increasingly encouraged concept of 'greening the grey,' structures in the intertidal zone can be designed to encourage colonisation by marine life. Possible modifications to achieve this can include: – Inclusion of innovative eco-blocks designed with increased roughness – Inclusion of artificial rock pool elements to retain water between tides – Construction of a functional nearshore breakwater in the form of an artificial reef
Adaptability	Randomly placed rubble mound structures in particular are relatively easily adaptable – units can be rearranged driven by the actual performance of the design (assuming damage is limited to the armour layer only; armour units may be reused for similar structures elsewhere; and the structure can be lengthened/modified as needed with limited challenges at tie-ins (unlike harder structures such as concrete walls).

5.6.3 Seawalls and revetments

5.6.3.1 Overview

Seawalls and revetments are common interventions to prevent coastal erosion by *hardening* the coastline. These structures are constructed on land and as such they typically also act as retaining walls.

Seawalls are vertical or near-vertical structures, most commonly constructed in concrete, but also in steel sheet piles or masonry. When their primary function is to act as a retaining wall as opposed to coastal protection, and especially when situated in a maritime context, seawalls are often referred to as *bulkheads*.

Revetments are typically built to carry out similar functions but are constructed with a sloping geometry – these are most commonly of rubble mound or concrete. For rubble-mound revetment structures, refer to the considerations reported in relation to rubble-mound breakwaters in Section 5.6.1.1. Concrete revetments are particularly commonplace when public realm and access considerations become important as they can be easily modified to provide safe access and are generally less aesthetically impactful.

Useful external references include:

- BS EN 1997-1:2004+A1:2013 (BSI, 2004)
- Toe structures management manual, (Environment Agency, 2012)
- The Rock Manual (CIRIA, CUR, CETMEF, 2007)

5.6.3.2 Function and applicability

Seawalls and revetments, being hard structures capable of withstanding wave loading effectively *fix* the shoreline in the position of the structure. These structures do not serve to retain beach material and in fact have the potential to accelerate erosion on the seawards side due to potentially significant reflection of incident wave energies mobilising sediment and transporting it offshore. This is slightly less of a concern for revetments as downward forces may act on the sloped face of the structure instead and as the intended wave run-up results in reduced reflection.

A key consideration driving the design of seawalls and revetments is the tolerance to overtopping behind the crest. This is typically managed through crest level, slope (particularly in the case of revetments), and crest geometry (e.g., recurve units on seawalls and the inclusion of a crown wall on the revetment).

While these structures will not reduce beach widths, they are effective at establishing a landwards boundary of the coastline. However, the wider implications should always be accounted for and the possibility of a manged landwards realignment of the shoreline be considered as a potentially more sustainable (environmentally, financially, and/or politically) alternative.

5.6.3.3 Design considerations

The key design parameters to be considered when designing seawalls and revetments (excl. rubble mound revetments which are similar to considerations highlighted in Section 5.6.1.1 for breakwater structures) are listed in Table 5.17.

Table 5.17: Key design considerations – seawalls and revetments

Parameter	Relevance
External information	
Wave climate incl. wave heights, directions, and water levels	Primary load on the structure driving strength requirements. Also driving overtopping rates and wider implications such as scour.
Sediment characteristics incl. rock type, density, and grain size distributions	Abrasion to structures due to mobile beach material can be significant. A common way to manage this is by ensuring concrete aggregates are harder than the surrounding beach material.
Ground conditions	Relevant for structure foundations, scour, and geotechnical pressures when acting as a retaining wall.
Design parameters	
Crest height	Relevant for the control of overtopping allowing for design water levels and wave conditions.
Crest geometry	Potential inclusion of recurve walls and crown walls (revetments) to control overtopping.
Slope	Seawalls – a seawards-leaning slope of the front face may be considered to increase reflection and reduce overtopping. However, structural implications as well as scour etc. should be considered. However, vertical to landward-leaning slopes generally lend themselves to simpler construction and increased structural stability. Revetments – gradual slopes (at an equivalent crest height) will lend themselves to reduced overtopping and wave reflection loadings, and runup. However, this will be accompanied by increased material and spatial requirements.
Position relative to water line and beach levels	Given the potential implications on fronting beach material, the more seawards the position of the wall, the greater the potential for the structure to contribute to loss of fronting beach material and local scour.
Drainage	Drainage should be included to ensure overtopped water is not retained. Generally, from a flood risk perspective, drainage should be provided to allow

Parameter	Relevance
	evacuation of overtopped water within a period of several hours at most. However, drainage may also be considered during less severe events to ensure operational requirements are met (e.g., continued access to a promenade, avoidance of damage to services due to inundation, etc.)

5.6.3.4 Structural failure

The most important loadings for seawalls and revetments are typically wave loadings and the geotechnical pressures. The most common mechanisms of structural failure are shown in Table 5.18.

Table 5.18: Common mechanisms of structural failure – seawalls and revetments

Mechanism of structural failure	Comments
Geotechnical failure	Similar to standard geotechnical works but with increased importance for consideration of hydraulic forces under various water level scenarios such as tidal lag.
Failure by uplift	When stabilising forces (most notably self-weight) are insufficient to counteract buoyancy forces. Particularly important for gravity structures.
Failure by heave	Due to a head difference potentially due to tidal lags (less relevant due to limited Bahamian tidal range) or undrained overtopping.
Failure by internal erosion	In granular, non-cohesive materials, movement of finer particles through the material under hydraulic gradient and consequent water movements. This can be controlled by constraints on the material grading.
Failure by piping	Localised internal erosion caused by high hydraulic gradients leading to liquefaction of the ground.
Failure by sliding and overturning	Due to differential beach heights and potentially lacking toe/anchorage design.
Settlement	Anticipated to be less common for most sites given structure will be constructed on the generally nationally homogenous, shallow limestone bedrock.
Undermining	Often due to improper consideration of lowest credible beach levels (as beach material is commonly relied upon to ensure coverage of the toe).
Material failures	-
Multiple failure mechanisms of concrete	Abrasion, cracking, spalling, which may be early indications of excessive loadings or structure movements. See Section 5.5 for guidance on materials.
Loss of core material	Potentially relevant to revetments and can be a consequence of unrepaired voids in upper layer or toe.
Corrosion	Of sheet pile elements but also of reinforcement – the latter of which should be avoided via mass concrete designs, sufficient cover, appropriate concrete gradings and additives, and others.
Other failure	
Damage due to impacts from foreign material during storm events.	Storm events can mobilise even large objects such as loose debris on the foreshore, unmoored vessels or vessels that have become unfixed due to waves, and debris from broken structures. These objects can be thrown onto structures and lead to significant damage.

Source: A useful external reference on common geotechnical hydraulic failures can be found in BS EN 1997-1:2004+A1:2013 (BSI, 2004) (or its latest edition), and the Rock Manual (CIRIA, CUR, CETMEF, 2007) for internal stability

5.6.3.5 Functional failure

Given the primary function of these structures is to fix the shoreline position, functional failure to this end is directly related to structural failure. However, common reasons that may describe why a seawall or revetment may not fulfil its other functions are outlined in Table 5.19.

Table 5.19: Common reasons for functional failure – seawalls and revetments

Functional failure	Possible driving factor	Comments
Excessive overtopping or run-up	Foreshore conditions	Foreshore conditions such as bed level may not have been adequately understood, leading to higher-than-expected waves incident on the structure. A common situation would be reduced beach levels. This may be
	Unanticipated hydraulic interactions	Complex wave interactions such as mach stem waves.

5.6.3.6 Wider implications

The decision to harden the shoreline using seawalls and revetments should be assessed critically, considering its wider implications, the most common of which are outlined in Table 5.20.

Table 5.20: Typical wider implications – seawalls and revetments

Wider implication	Comments
Flanking i.e., potentially accelerated erosion at structure ends	Insufficient length of defence or inadequate understanding of erosion processes along the frontage.
Increased erosion and local scour	As discussed in Section 5.6.3.2, the installation of hard seawalls and revetments can accelerate erosion and local scour towards the structure toe. This may be especially prevalent the more seawards-advanced the structure is positioned. The inclusion of softer (i.e., measures with less reflection of energies and more attenuation) at the structure toe may assist to reduce this occurrence and also overtopping.
Access	Access along the frontage can be limited by the structures themselves. Refer to Section 5.8.3 for guidance on coastal access.
Characteristics of the frontage	The impact of such measures on a frontage's character can be subjective and unquantifiable. However, the presence of hard structures on a beach is typically aesthetically undesirable.

5.6.3.7 Key difficulties

Key challenges in the design of seawalls and revetments have already been alluded to. However, these are reiterated below. Insufficient appreciation of such challenges can lead to uncertainties in design and residual risks in the final solution.

Table 5.21: Key design challenges – seawalls and revetments

Design challenge	Comments
Prediction of the impact of wave reflection	Predicting scour and any increased erosion is challenging as these are driven by complex hydraulic interactions that may also vary significantly along the length of the structure. Should this occurrence be a significant risk or should there be potential for the structure to worsen the existing condition then a regular monitoring scheme should be implemented post-construction.
Minimum credible beach level	With sufficient information, this is a relatively straightforward process. In the absence of such data, dedicated surveys may be required to, as a minimum, understand the level of the underlying bedrock.
Interaction with members of public	Human behaviour is difficult to predict and control. Where publicly accessible, design should ensure safe access including consideration of falls from heights, impacts of overtopping flows on pedestrians, vehicles, etc., and trip hazards and lighting. Design should also consider, and design against as far as reasonable, the potential for dangerous behaviour such as climbing over defence structures.

5.6.3.8 Opportunities

While the developer will need to demonstrate that negative impacts have been effectively eliminated or controlled, emphasis should also be placed on the exploitation of opportunities. Common opportunities associated with the decision to construct seawalls or revetments as shore protection solutions are outlined in Table 5.22.

Table 5.22: Common opportunities – seawalls and revetments

Opportunity	Comments
Use as a retaining wall	Structures are typically suitable for the raising of ground levels on the landward side as desired. Structures may also be suitable should the need be to advance the shoreline position seawards.
Intertidal habitat creation	In line with the increasingly encouraged concept of 'greening the grey,' if found in the intertidal zone, these can be designed to encourage colonisation by marine life. Possible modifications to achieve this can include: – Design of the structure to retain water between tides to function as artificial rock pools – Increasing the micro and macro textures of materials – Provision of cavities and other possible points of shelter for marine life
Access	Structures can be readily modified or made suitable to host formal beach access points or provide new viewing and areas and walkways.

5.6.4 Beach recharge and recycling

5.6.4.1 Overview

Beach recharge, also known as nourishment, is the process of importing sand (or other beach sediment) to increase beach widths and or levels. Beach recycling is the similar process whereby beach material is not imported but instead transferred from one part of the frontage to another. This intervention is a *soft* solution (and may be considered a nature-based solution by some) although hard beach stabilisation structures such as groynes and nearshore are commonly used alongside. Common drivers for the increase of beach levels include:

- Flood protection
- Improvements to the public, but also private, realm
- Protection of existing coastal infrastructure – for example to bury exposed toes

Reclamation works, while also involving the movement of sediment to a coastal area, are covered Section 5.8.2 and differ from recharge and recycling in the intended use of the newly created land; reclamation is considered the creation of new, permanent, land area as opposed to the creation or expansion of a functioning beach.

Useful external guidance on the design of recharge and recycling works is provided in Part V Chapter 4, CEM, (U.S. Army Corps of Engineers, 2006) (or its latest edition).

5.6.4.2 Function and applicability

The process of recharge and recycling will require at least two occasions of handling material: firstly, excavation at the source location and secondly unload at the intended destination. The source location will need to provide suitable sediment and be resilient to the planned loss of material in terms of environmental impact and flood implications should this be a coastal source location, among others. The receiving location should be suitable for the designed beach; best practice is to consider historical conditions as to the appropriateness of that location to host such a beach. For instance, a beach created at a location lacking any historical beach is likely to be highly unstable whereas the use of renourishment to supplement an existing beach,

especially when combined with additional stabilisation measures, usually has a greater chance of success.

5.6.4.3 Design considerations

The key design parameters to be considered when designing beach nourishment schemes are listed in Table 5.23 which has been adapted from a similar table in the CEM (U.S. Army Corps of Engineers, 2006).

Table 5.23: Key design considerations – beach recharge and recycling

Parameter	Relevance
External information	
Wave climate incl. wave heights, directions, and water levels	Influences net and gross sediment transport rates and patterns while also important for predicting the response of the design beach. Longshore and cross-shore sediment transport should be considered.
Local and imported sediment characteristics incl. rock type, density, and grain size distributions	Important in sediment transport behaviour and the resilience of the design beach.
Borrow area	The local conditions of the borrow site like depth, exposure, distance from the reclamation site, need to be factored in to identify the most cost-effective solution.
Littoral cells[20] (the length of a frontage whereby net longshore sediment transport is approx. zero – a common example may be a bay constrained by headlands)	Provides an indication of the likely required scale of works and an indicative length of frontage where efforts to understand any wider implications of the scheme can be focused.
Nearshore bathymetry and depth of closure	Loss of material offshore is likely to occur if nearshore bed slopes are steeper than the angle of repose for the new material. If this is the case inclusion of a sill in the nearshore or a reduced design beach width could be considered. Similarly, the potential for offshore sediment losses can be informed by estimated depth of closures (indicatively the depth at which bed levels remain constant in time).
Design parameters	
Design beach profile incl. width, slope, and berm height	While the beach will naturally evolve to its most stable profile under the dominating sea conditions, the initial geometry is important as: – Initial profiles significantly far from its equilibrium state will evolve rapidly, potentially resulting in cliffing with impacts on beach access and safety. – Low berm levels can result in over washing and ponding with resulting impacts on the upper beach or hinterland such as unintended flooding or the accumulation of fine material.
Project longevity	The anticipated longevity of the newly placed sediment should be estimated in consideration of both longshore and cross-shore losses and recoveries in time.
Material grading	Imported material should generally match the existing. Refer to note under External Information on *Local and imported sediment characteristics*.

5.6.4.4 Failure

As artificially recharged beaches will normally lose sediment in time, the term failure used here is to be understood as the unexpectedly rapid loss of sediment whether along the scheme

[20] Refer to Section 4.3.1.

length or local to distinct beach areas. The most common mechanisms of this are shown in Table 5.24.

Table 5.24: Common mechanisms of failure – beach recharge and recycling

Mechanism of failure	Comments
Rapid loss of sediment offshore	Typically occurring at a decreasing rate in time. Due to insufficient understanding of cross-shore processes or the response to storms. Often exacerbated by inappropriate grain sizes of imported sediment. Potentially managed by sills or nearshore breakwaters, or similar.
Formation of 'hot spots' (localised areas within a recharge scheme that experience greater sediment losses as compared to the wider scheme)	Such an occurrence can result in a locally insufficient Standard of Protection, access issues along the frontage, among others. This may be due to insufficient consideration of sediment transport processes along the complete length of the scheme – while it is normally appropriate to represent the frontage as a series of cross-shore transects, these must be spaced and placed depending on local variations in anticipated sediment behaviour, for instance due to irregular nearshore bathymetry. The rectification of hot spots may require additional recycling/recharge or the construction of additional structures – the cost of which would often be unforeseen.
Over washing	Due to insufficient crest height commonly associated with pooling, landwards sediment losses, and deposition of undesirable material such as fines and seaweed. Design crest heights should normally match or exceed natural crest heights but should be designed in consideration of ground/retaining structure elevations (i.e., beach levels should remain below seawall levels to avoid landwards loss of sediment).

5.6.4.5 Wider implications

While the use of a soft solution such as beach recharge and recycling is typically associated with fewer negative impacts, these should still be considered and managed in the design. The most common are outlined in Table 5.25.

Table 5.25: Typical wider implications – beach recharge and recycling

Wider implication	Comments
Deposit in navigational channels or smothering eco habitats	In the event of failure – that is rapid offshore displacement of sediment – there is potential for the displaced sediment to smother sensitive habitats such as coral reefs, increase turbidity of swimming waters, and deposit in navigational channels. These potential impacts should also be considered in the context of the intended lifetime of the scheme, though impacts over the greater length of time should be reduced but may remain relevant to channel dredging maintenance requirements in particular.
Impact on coastal vegetation Recycling leads to loss of fines. No vegetation. Also smothering vegetation.	Coastal vegetation often serves as key habitat that warrants preservation. The sourcing of sediment from a coastal area may result in loss of such habitat, as can the deposition of material on top of existing habitat at the destination location.
Changes to the sediment characteristics	Recycling in particular can result in loss of the fine component of material.
Characteristics of the frontage	While recharge and recycling would generally be accepted as an improvement to a frontage, it will inevitably change the character of the frontage, the impact of which is subjective and unquantifiable.

5.6.4.6 Key difficulties

Some key challenges in the design of recharge and recycling schemes have already been alluded to. However, these are reiterated in Table 5.26. Insufficient appreciation of such challenges can lead to uncertainties in design and residual risks in the final solution.

Table 5.26: Key design challenges – beach recharge and recycling

Design challenge	Comments
Understanding of the expected lifespan and maintenance requirements	Sediment transport is inherently difficult to predict. Furthermore, the actual lifespan of a scheme can be strongly dependent on the unpredictable occurrence and timing of storms.
Access for the works	Transport of the large quantities of beach material required for such schemes is a major challenge – landside access is generally significantly cheaper but may be limited or impossible without permanent or temporary demolition of coastal assets while seawards access is generally expensive and can be limited by shallow waters. Transport by road may also result in significant pressures to road networks as well as increased damage to the infrastructure due to the significant weight of material.
Working against nature	While seen as a soft solution or even a nature-based solution, the desired outcomes of recharge schemes are often at odds with the most energetically stable beach orientation. If a beach has undergone significant erosion, then this will typically continue to occur at an even faster rate following implementation of the scheme. Furthermore, sediment transport behaviour is typically driven by waves and currents which will not be significantly affected by changes to bathymetry in the nearshore only.

5.6.4.7 Opportunities

While the developer will need to demonstrate that negative impacts have been effectively eliminated or controlled, emphasis should also be placed on the exploitation of opportunities. Common opportunities associated with the decision to implement recharge and recycling schemes are outlined in Table 5.27.

Table 5.27: Common opportunities – beach recharge and recycling

Opportunity	Comments
Recreational use	– A wider beach supports greater use for recreational purposes. Increased access to such sites should be considered so as to enhance this opportunity.
Multi-functional performance	– Increasing beach widths and heights can successfully address a range of issues from flood protection, recreational and social benefits, and reduced maintenance of existing assets. While one or two of these may be the underlying drivers of a scheme, the opportunity to capture benefits of other kinds should also be exploited – for instance, a recharge scheme driven by flood protection could also improve access to enhance the recreational value of the beach.
Long term efficiencies	– The level of effort of design will likely be front-loaded during the period of the initial design – future recycling activities can generally follow the original design if informed by the findings of a monitoring activity.

5.6.5 Mangrove, seagrass, and reefs

5.6.5.1 Overview

Mangroves, seagrass, and reefs can play an important role in coastal protection. These are examples of nature-based solutions. A useful external reference around the use and implementation of nature-based solutions is the International Guidelines on Natural and Nature Based Features for Flood Risk Management (U.S. Army Engineer Research and Development Centre, 2021). Mangroves, seagrass, and reefs all contribute to the attenuation of incident wave energy prior as well as the potential stabilisation and even creation of sediment. Mangroves and seagrass schemes typically take the form of restoration activities while the use of coral reefs often includes artificial structures and techniques to accelerate coral growth such as the use of low voltage electric stimulation and coral planting and micro fragmenting.

Key benefits of such systems include:

1. Reduced flood risk due to attenuation of wave energies.
2. Reduced erosion risk due to retention of sediment.
3. Reduced maintenance requirements of existing assets due to attenuation of wave energies as well as the ability of these habitats to grow and self-repair.
4. Provision of ecological services.
5. Can be cheaper than conventional solutions, especially in the longer term.
6. Can naturally adapt to rising sea levels.

A nature-based solution approach can serve as a more sustainable, and cheaper alternative for coastal protection, providing numerous additional services while avoiding some of the well-known drawbacks to hard options such as adverse knock-on effects. However, the reliance on such measures should be accompanied by an informed appreciation of the underlying constraints and limitations.

5.6.5.2 Function and applicability

While mangroves, seagrass, and reefs all work to limit the energy incident on the coastline, they accomplish this in different ways. Mangrove systems have the potential to reduce wave heights thanks to complex root systems, sloping shores, and shallow waters that dissipate wave energy as well as vegetation above the water line that reduces wind velocities or, at increased water depths, also attenuates wave energy. Furthermore, they support the retention of sediment and even increase biomass, thereby raising bed levels.

Seagrass can stabilise material and encourage settlement by decreasing bed velocities and thanks to their root systems. Though to a much lesser degree as compared with other habitats, they can also act to reduce wave heights by increasing the bed friction.

The function of coral reefs in relation to wave breaking is similar to that of offshore breakwaters; coral reefs, especially those forming fringing reefs at shallow waters, induce wave breaking and significant energy dissipation via the resulting turbulence. In addition, all three of these systems provide critical ecological functions with significant benefits and ecological connectivity beyond the extent of that habitat itself.

For the greatest chance of success, preferred locations for the use of mangroves, seagrass, and coral systems are within their historical extent. The use of these natural features for coastal protection should be encouraged although the practical limitations around their implementation and potential reliability should be appreciated.

5.6.5.3 Design considerations

The key design parameters to be considered when designing these kinds of nature-based solutions are listed in Table 5.28.

Table 5.28: Key design considerations – mangroves, seagrass, and reefs

Parameter	Relevance
External information	
Historical habitat extents	Useful to inform suitable locations to situate the schemes.
Wave climate incl. wave heights, directions, and water levels	Influence net and gross sediment transport rates and patterns while also important for understanding likely success rates for the survival of these habitats – prior to establishment these habitats may need additional

Parameter	Relevance
	sheltering or good fortune in avoiding severe storms during their early years.
Sediment characteristics esp. grain size distributions	Important for the potential establishment of mangroves and seagrass vegetation.
General environmental conditions	As these are most successful when acting as fully functional, healthy habitats, wider conditions such as anthropogenic pressures and surrounding ecological habitats should be understood.
Design parameters – Mangroves & seagrass systems	
Habitat width	The potential to dissipate wave energy is dependent on the width of the system. This is often a key constraint to the use of these systems for coastal protection.
Vegetation height and density	The more complex and dense the structure of the mangrove system, the greater hydraulic interactions it can induce and the more impact it will have on retained sediment and producing biomass. The height of the mangrove and seagrass vegetation relative to the water level will also be a key factor driving the degree of attenuation they will be able to achieve.
Vegetation species	Important to consider in order to increase the likelihood of a naturally functioning and self-repairing system.
Design parameters – Coral reefs	
Habitat width and height	This will strongly influence the degree of wave breaking (or attenuation by other means).
Coral species	Important to consider in order to increase the likelihood of a naturally functioning and self-repairing system.

5.6.5.4 Structural failure

'Structural failure' as it pertains to the recreation or regeneration of natural habitats is assumed here to refer to their unsuccessful establishment due to early die-off. The most common reasons for structural failure are shown in Table 5.29.

Table 5.29: Common mechanisms of structural failure – mangroves, seagrass, and reefs

Potential reasons for structural failure	Comments
Inappropriate environmental conditions	This is likely the most common reason for failure and is typically related to the selected scheme location whereby the site conditions may not be conducive to the establishment of that habitat. Relevant factors can include excessive exposure to waves, excessive anthropogenic pressures, and/or inadequate soil/bed conditions.
Seasonal timing	The timing around the 'construction' of these habitats is often important and needs to be carefully considered alongside seasonal environmental variations and plant/animal behaviour. There is an element of risk to such schemes wherein the occurrence of severe (or less severe) storms prior to establishment of the habitat can cause irreparable damage. For instance, seagrass and mangroves will need time to establish their root systems and grow to a resilient size before they are capable of withstanding significant wave loadings and/or scour-inducing pressures.
Inadequate density	While it is often assumed these habitats will establish and expand naturally, it is common for this potential to be overestimated – habitats should normally be recreated/restored to the intended state as far as possible without overly relying on the system's natural growth. For instance, planting of seagrass beds should be sufficiently dense to ensure a mostly continuous bed cover, thereby reducing the potential for scour and uprooting before the vegetation can establish.

5.6.5.5 Functional failure

Functional failure here assumes successful establishment of the mangrove, seagrass, or coral system but lower-than-anticipated levels of wave attenuation and sediment retention. Common reasons why this may occur are outlined in Table 5.30.

Table 5.30: Common reasons for functional failure – mangroves, seagrass, and reefs

Functional failure	Possible driving factor	Comments
General – insufficient wave attenuation and sediment retention	Overly optimistic expectations	Refer to Table 5.31.
Insufficient retention of sediment	Insufficient vegetation or coral density	-
Insufficient wave attenuation	Insufficient vegetation height and density	-
	Insufficient habitat dimensions	Mangrove and seagrass systems require large areas to notably influence wave behaviour. Coral reefs generally have a greater impact in over a limited width but should also be designed in consideration of optimal widths, heights, and complexity of the underwater geometry so as to maximize attenuation via induced turbulence.

5.6.5.6 Wider implications

The decision to use natural habitats such as these for coastal protection should be assessed critically, considering the wider implications, the most common of which are outlined in Table 5.31.

Table 5.31: Typical wider implications – mangroves, seagrass, and reefs

Wider implication	Comments
Access	Mangroves in particular will inhibit access to the shoreline, from both the sea and the land. Any access through the habitat, especially uncontrolled, informal access, will likely lead to damage.
Risks to vessels	Coral reefs can pose a navigational hazard, especially if situated in areas where coral was not previously present and when situated high in the water column.
Risk to wildlife	While the frequenting and colonisation of these habitats is one of the drivers for the selection of such measures, their location may lead to increased interaction between marine wildlife and humans/vessel traffic.

5.6.5.7 Key difficulties

Some key challenges in the design of mangrove, seagrass, and coral reef creation and restoration have already been alluded to. However, these are reiterated in Table 5.32. Insufficient appreciation of such challenges can lead to uncertainties in design and residual risks in the final solution.

Table 5.32: Key design challenges – mangroves, seagrass, and reefs

Design challenge	Comments
Lack of confidence in available design tools and relationships	Reliable prediction of the performance of nature-based solutions is currently poorly understood and is an area of active research. Designs of nature-based solutions should be particularly conservative and would preferably involve an extended trial period prior to which their performance should not be relied upon. Standards of Protection can generally not be assigned – as a result, a common

Design challenge	Comments
	use of such systems for the reduction of maintenance and performance requirements of conventional defences.
Continuity in performance	While seasonal cycles of die-off are less prevalent in The Bahamas than elsewhere in the world, natural habitats can be significantly affected by storm events. Following such an occurrence, vegetation typically requires a period of regrowth to return to its previous condition. However, it is possible that a subsequent storm event arrives prior to self-repair of the habitat. This possibility should be considered in the design. However, the variation in performance by habitat condition will be difficult to predict.
Quantifying benefits	Quantifying the ecological, social, and other indirect benefits in monetary terms is difficult and inherently uncertain. Furthermore, due to the difficulty in assigning a Standard of Protection to these schemes, quantifying the benefits in terms of coastal protection can also be challenging. This makes it difficult to demonstrate the economic viability of the scheme via a conventional cost-benefit assessment. Nevertheless, an increasing number of tools and alternative approaches are available to support the assignment of monetary values to such benefits. An example is the Themes, Outcomes and Measures (TOM) framework to support delivery and quantification of social value. A similar framework for environmental services is the Ecosystem service valuation. In addition to quantifying such benefits as far as possible, such activities should be accompanied by qualitative assessments that also identify and describe those benefits that are unable to be quantified.
Public perception	Society is generally risk adverse and as such any uncertainty in design and performance is poorly tolerated. The presence of a visible defence typically goes further than a perhaps partially submerged offshore reef in terms of improving public perception of safety. While designs should be driven by reliable performance, this may become important from a political perspective and should be considered in public communications and when managing expectations.

5.6.5.8 Opportunities

While the developer will need to demonstrate that negative impacts have been effectively eliminated or controlled, emphasis should also be placed on the exploitation of opportunities. Common opportunities associated with mangrove, seagrass, and coral creation or restoration schemes are outlined in Table 5.33.

Table 5.33: Common opportunities – mangroves, seagrass, and reefs

Opportunity	Comments
Recreational use	– These habitats provide an opportunity for recreation including walking, snorkelling, and recreational fishing. Increased access to/awareness of such sites should be considered so as to enhance this opportunity. However, this should be balanced with the potential impacts on the habitat condition.
Eco-tourism	– Healthy mangroves and coral reefs especially, can also provide opportunities for eco-tourism activities with subsequent economic, social, and well-being benefits.
Education	– Restoration schemes, particularly of mangrove systems, can often include members of the public to assist with replanting activities. This is an opportunity to raise awareness on nature-based solutions and the role of such habitats in coastal protection. The presence of accessible and managed habitats can also be visited by schools and the wider public.

5.6.6 Dunes

5.6.6.1 Overview

Dunes are a common feature of many naturally-functioning beaches that develop on the upper beach due to wind-blown sand. They typically rely on coastal vegetation to capture and retain sediment. Anthropogenic management measures typically consist of the installation of sand fences, planting of vegetation, and earth (sand) works, and toe protection. Creation of less-natural dunes including formal cores are possible but is less common and is therefore not discussed further. The use of dunes for coastal defence is considered nature-based solution. Many of the considerations made in reference to dune systems will also be relevant to beach berms while the discussions around the use of coastal vegetation will also apply more widely.

A useful external reference pertaining to the management of beaches including dune systems is the Beach management manual (CIRIA, 2010).

A useful external reference pertaining to the use and implementation of nature-based solutions is the International Guidelines on Natural and Nature Based Features for Flood Risk Management (U.S. Army Engineer Research and Development Centre, 2021).

5.6.6.2 Function and applicability

Dunes are dynamic systems that respond to variations in environmental conditions via adoption of an energetically efficient profile. This adaptability also applies to sea level rise, making dune systems suitable for long term strategies. However, this natural response can require substantial space both seawards and landwards which is often limited by coastal infrastructure such as hard defences and roads.

Dune can provide protection against flooding firstly by acting as a physical barrier to waves and increased water levels. However, given these assets are comprised of unconsolidated sediment, providing this function during a storm event will lead to erosion of the dune system. However, given a sufficient accumulation of material, the dune should be able to continue to perform its function for the duration of the storm event. Resilience is provided via natural processes whereby sediment lost from the dune system will remain in the system and will usually accumulate in the nearshore. This displaced sediment will normally form a berm which can induce wave breaking and therefore dissipation of wave energy acting on the beach. As such, dunes are often referred to as sediment stockpiles, improving the resilience of beaches.

While providing some benefits during storm events, the role of coastal vegetation is most important for the longer-term capture and retention of wind-blown sediment; this is thanks to the stabilising role of the extensive root systems and ability of the stems and leaves to reduce bed shear stresses.

In addition to providing flood an erosion benefits, dunes provide important ecological habitats and host unique plant species that have adapted specifically for such conditions.

5.6.6.3 Design considerations

Design of dune management systems should take a cross-disciplinary approach including engineering, geomorphology, ecology, and coastal management. Design of dune management systems should consider the complete beach profile. Key design parameters to be considered when designing this kind of nature-based solution are listed in Table 5.28.

Table 5.34: Key design considerations – dunes

Parameter	Relevance
External information	

Parameter	Relevance
Wave climate incl. wave heights, extent of wave runup, and water levels.	Influences the seawards extent of the dune. An understanding of storm events at the site is also important to understand the resilience and level of protection provided by the dune and beach system.
Sediment budgets and transport processes	Important for the understanding of dune responses and growth.
General environmental conditions	As dunes are most successful when acting as fully functional, healthy habitats, wider conditions such as anthropogenic pressures and surrounding ecological habitats should be understood. Refer also to Table 5.38.
Design parameters	
Dune position and toe level	When creating or improving dune systems, consideration should be made as to its placement along the beach profile. An excessively seawards position will result in rapid erosion of the toe.
Dune height and width	Height and width will be directly related as dunes will tend towards the natural angle of repose of the material. Generally, the greater volume of material accumulated, the greater the resilience to flooding and erosion.
Dune core	Design of artificial dunes (if not allowed to develop naturally), requires consideration of the core composition.
Vegetation species and density	Plants should be suitable for establishment in a dune environment and native to the area. Planting density needs careful consideration.
Planting timings and methods	Planting works should be led by a suitably qualified ecologist to ensure maximum survival rates. Vegetation growth and further colonisation of the dune system can be influenced by a large variety of factors and environmental conditions.

5.6.6.4 Structural failure

Scenarios of 'structural' failure in the context of dune systems can refer to:

- Breaching[21] during storm events
- Overwashing[22]
- Longer-term erosion of the dune including blowouts[23]

Common reasons for structural failure are shown in Table 5.35.

Table 5.35: Common mechanisms of structural failure – dunes

Potential reasons for structural failure	Comments
Dune weakening caused by trampling and human pressures	This is a common reason for damage or loss of vegetative cover. Damage due to localised scour from to foot traffic also has significant potential to propagate beyond the area of the dune directly impacted. For this reason, formalised access routes across dunes is especially important.
Spatial constraints	A lack of space to the rear of the dune system can prevent landwards migration that can be necessary for storm response and, in the longer term, adaptation to sea level rise. Where over washed sediment impacts coastal developments to the rear of the dune, it is often removed from the system via road clearance activities and similar. This reduces the amount of sediment in the budget.
Insufficient sediment budgets	Insufficient dune volumes imply a lack of sediment within the system to allow for temporary erosion of dune systems. Dune systems should perform throughout the duration of the design event. Refer to Table 5.36 for further discussion on reliability.

[21] Breaching: Failure of a shore-parallel defence or landmass during a storm event resulting in water flow through the feature.

[22] Overwashing: While overtopping refers to the flow (or spray) of water over a defence, overwashing refers to same phenomenon when also including the transport of beach material.

[23] Blowout: Localised depressions in dune systems normally arising from a lack of vegetation cover.

5.6.6.5 Functional failure

Functional failure here assumes successful establishment of the dune system but lower-than-anticipated levels of flood protection and sediment retention. It also includes a progressive reduction in performance due to gradual vegetation loss and sediment loss. Key reasons why this may occur are outlined in.

Table 5.36: Common reasons for functional failure – dunes

Functional failure	Possible driving factor	Comments
General – underperformance	Insufficient understanding of storm response and sediment processes.	This is difficult to predict and a key design challenge, as discussed in Table 5.38.
Progressive reduction in performance reliability	Gradual vegetation and sediment loss leading to lower crest heights and dune widths. Sediment loss can be due to insufficient vegetation cover, lack of available sediment in the system, or continued pressures such as trampling.	Dunes should be regularly monitored and maintained.

5.6.6.6 Wider implications

The decision to use natural habitats such as these for coastal protection should be assessed critically, considering the wider implications, the most common of which are outlined in Table 5.37.

Table 5.37: Typical wider implications – dunes

Wider implication	Comments
Access	Dunes will inhibit access to the shoreline. Any access through the habitat, especially uncontrolled, informal access, will likely lead to damage. This may be prevented by using boardwalks elevated from the level of the dunes
Unintended deposition of sediment	If not contained, wind-blown sediment can be transported landwards and impact existing infrastructure such as roads. Theis will usually correspond to this material being lost from the system. In the other direction, improperly managed dunes, especially when the works included import of additional material, can undergo significant erosion with the sediment deposited offshore potentially in navigation channels or smothering sensitive habitats.
Introduction of non-native material	If created or restored using a foreign sediment supply, this material may not exactly match the local sediment characteristics. Furthermore, if ‘harder’ measures are required, for instance using shingle to form a protective berm or boulders to provide toe protection, this too can lead to introduction of foreign material to a frontage.

5.6.6.7 Key difficulties

As the use of dunes for coastal protection is considered a nature-based solution, many of the challenges and limitations associated with their design and implementation will be comparable to those of mangroves, seagrass, reefs, and beach recharge discussed in Sections 5.6.5.3 and 5.6.5.7. Key challenges are outlined in Table 5.38: Key design challenges – dunes. Insufficient appreciation of such challenges can lead to uncertainties in design and residual risks in the final solution.

Table 5.38: Key design challenges – dunes

Design challenge	Comments
Challenging prediction of storm response and subsequent beach and dune recovery, and	Prediction of sediment movements, both long term and during/following storm events is difficult and will normally require numerical modelling. Even with modelling, the reliability of the outputs will be limited by the inherent uncertainty of the field. As a consequence of this uncertainty (in addition to considerations of

Design challenge	Comments
quantification of the impact of vegetation in dune recover.	continuous performance as below), it is often difficult to associate a Standard of Protection to dune systems.
Continuity in performance	Dune systems can be significantly damaged by storm events. Following such an occurrence, the system typically requires a period of recovery (in terms of both levels and vegetative cover) to return to its previous condition. However, it is possible that a subsequent storm event arrives prior to self-repair of the habitat. This possibility should be considered in the design and may require human intervention to accelerate repair. However, the variation in performance by condition will be difficult to predict.
Quantifying benefits	As Table 5.32. Quantifying the ecological, social, and other indirect benefits in monetary terms is difficult and inherently uncertain. Furthermore, due to the difficulty in assigning a Standard of Protection to these schemes, quantifying the benefits in terms of coastal protection can also be challenging. This makes it difficult to demonstrate the economic viability of the scheme via a conventional cost-benefit assessment. Nevertheless, an increasing number of tools and alternative approaches are available to support the assignment of monetary values to such benefits. An example is the Themes, Outcomes and Measures (TOM) framework to support delivery and quantification of social value. A similar framework for environmental services is the Ecosystem service valuation. In addition to quantifying such benefits as far as possible, such activities should be accompanied by qualitative assessments that also identify and describe those benefits that are unable to be quantified.
Public perception	Society is generally risk adverse and as such any uncertainty in design and performance is poorly tolerated. The presence of a visible, hard defence typically goes further than 'softer' solutions in terms of improving public perception of safety. While designs should be driven by reliable performance, this may become important from a social, political, and wellbeing perspectives and should be considered in public communications and when managing expectations.

5.6.6.8 Opportunities

While the developer will need to demonstrate that negative impacts have been effectively eliminated or controlled, emphasis should also be placed on the exploitation of opportunities. Common opportunities associated with creation, repair, or maintenance of dune systems are outlined in Table 5.39: Common opportunities – dunes .

Table 5.39: Common opportunities – dunes

Opportunity	Comments
Recreational use	– While generally not suitable for direct use (due to trampling impacts), dunes contribute to the resilience of beach area providing significant recreational opportunities. Boardwalks providing access in/over the dunes provide an environment conducive to wellbeing and facilitate activities such as walking, exercising, and bird watching. These benefits should be enhanced by increasing accessibility including in terms of physical structures, safety, and parking/transport links.
Eco-tourism	– Dunes provide opportunities for eco-tourism activities with subsequent economic, social, and well-being benefits. However, human pressures should be actively managed to ensure the continued health of the habitats.
Education	– Restoration schemes can often include members of the public to assist with replanting activities. This is an opportunity to raise awareness on nature-based solutions and the role of such systems in coastal protection. The presence of accessible and managed habitats can also be visited by schools and the wider public.

5.7 Maritime structures

5.7.1 Jetties and wharfs

5.7.1.1 Overview

Jetties and wharfs are discussed alongside each other given they will share many similarities in terms of construction, materials, siting, and mostly function given both are normally intended to accommodate vessels. Descriptions of these structures are provided below.

Jetties: Shore-normal, typically suspended structures, with the purpose of providing access offshore. Normally intended to provide offshore berthing facilities. When providing a recreational function, these are commonly termed *piers*. When interrupting, or having the potential to interrupt, alongshore sediment transport shore-normal structures considerations pertaining to groynes will become relevant.

Wharfs: Shore-parallel structures intended to accommodate vessels. Wharfs will normally also need to function as retaining walls. However, for considerations associated with this function, refer to Section 5.6.3 on seawalls/bulkheads and revetments.

5.7.1.2 Function and applicability

Vessels require adequate under keel clearances for safe berthing. Ensuring sufficient water depths is commonly accomplished via either dredging or siting the berth in deeper water. Dredging is accompanied by additional works (both capital and maintenance), impacts, and disruption and is therefore normally avoided if possible. Where the nearshore is relatively deep, wharves may be built along the shore or slightly offshore via a reclamation activity (For guidance on reclamation refer to Section 5.8.2). Jetties are used where the berth needs to be placed further offshore and when reclamation is unnecessary or unfeasible.

Jetties and wharfs will require topside furniture to facilitate berthing and mooring activities including bollards (also cleats and quick release hooks) to tie up vessels and fenders (such as cell-fenders, pneumatic fenders, timber boards, and tyres) to absorb berthing energies and protect ship hulls. Dedicated design will be required to understand the equipment and arrangement requirements; however, the current guidance will focus on design of the structures themselves. Other typical facilities that may be provided include lifesaving equipment, access systems, navigation hazard lights, cranes and marine loading arms, and services such as power and water connections.

5.7.1.3 Design considerations

Key design parameters to be considered when designing jetties and wharfs are listed in Table 5.40. Best practice for design of maritime facilities is reported in Technical Reports published and regularly updated by PIANC (Permanent International Association of Navigation Congresses), specifically those produced under the MarCom Working Groups.

Table 5.40: Key design considerations – jetties and wharfs

Parameter	Relevance
External information	
Environmental conditions, primarily waves, wind, currents, and water levels.	Important to understand wave loadings on the structures as well as other hydraulic interactions such as tidal lag (or the equivalent but driven by surge) and reflections with potential wider implications. Also, relevant to berthing, mooring, and vessel operations and will therefore influence design as well as structure location, and orientation.

Parameter	Relevance
Ground conditions and bed levels	Important for the understanding of vessel grounding risks and geotechnical stability of the structure.
Berthing and mooring loads	Berthing loads are transferred to the structure through the fenders while mooring loads are transferred to the structure at the mooring points. Both need to be considered in the design of the structure, fender, and mooring systems; restrictions on operations such as reduced approach velocities may need to be applied to avoid inefficient design.
Design parameters	
Location and orientation	Such to minimise dredging requirements and downtime and in the context of the wider site.
Structure length and arrangement of mooring points.	The berth length will normally be driven by operations and vessel lengths. However, mooring points beyond the length of the vessel will be required which may be achieved via detached mooring structures known as mooring dolphins.
Deck levels	Important to understand against vessel heights, flood levels, and overtopping.
Health and Safety	Given the function of the structures to facilitate operations over water and from height, H&S considerations should be front of mind in the design process. Following elimination and mitigation of H&S risk through design and operational systems, last-resort measures need to be included. Examples of such measures include regularly placed emergency access ladders, edge protection, navigation lights especially for jetties, and systems to separate people from significant hazards such as high-tension mooring lines.

5.7.1.4 Structural failure

Common mechanisms of structural failure for jetties and wharfs are shown in Table 5.41.

Table 5.41: Common mechanisms of structural failure – jetties and wharfs

Mechanism of structural failure	Comments
Various geotechnical failures	When retaining earth or fill, the geotechnical considerations described in Table 5.18 in relation to seawalls will apply.
Corrosion of piles and structural elements	Design will require consideration of thickness loss over the full lifetime of the structure. Refer to Section 5.5.3 for further considerations on corrosion and protective measures.
Corrosion of reinforcement	To be avoided via mass concrete designs, sufficient cover, appropriate concrete gradings and additives, and others.
Loss of fill material	Relevant to wharfs, loss may occur following formation of voids, for instance through complete section loss of sheet pile, cracking of concrete, or loss of sealant at joints and interfaces.
Vessel impacts	The risk of vessel impacts will always exist but should be managed in the design and management of operations. Designs should be resilient such that damage is limited locally.
Scour	Scour can be due to propeller, wave, and current action which can be exacerbated locally where they interact with the structure. The need for scour protection such as mats and rock armour should be assessed.

5.7.1.5 Functional failure

Common reasons that may describe why a jetty or wharf does not function as intended are outlined in Table 5.42. In the case of jetties and wharfs, function refers to the accommodation of vessels and the associated loading/unloading operations.

Table 5.42: Common reasons for functional failure – jetties and wharfs

Functional failure	Possible driving factor	Comments
Hull damage	Inadequate fender systems	Berthing loads are transmitted to the structures through the fenders. However, these also include reactive forces to the vessel hulls which should be assessed against hull strengths.
	Non-compliance with, or lack of, operational restrictions	Restrictions may include limits on vessel sizes, approach angels, berthing velocities, and environmental conditions.
Detachment of vessels from moorings	Inadequate mooring systems	
	Non-compliance with, or lack of, operational restrictions	Restrictions may include limits on vessel sizes, lengths, and environmental conditions. It is common that, prior to inclement weather, vessels anchor offshore as opposed to remaining at berth.
Excessive downtime due to ship movements at berth	Inadequate understanding of environmental conditions against operational limits.	This will be driven by exposure of the site, which is best managed via proper siting and orientation of the structures.

5.7.1.6 Wider implications

The decision to use groynes to increase beach widths should be assessed critically, considering its wider implications, the most common of which are outlined in Table 5.43.

Table 5.43: Typical wider implications – jetties and groynes

Wider implication	Comments
Reflections	Hard structures tend to reflect wave energies with potential impacts of sediment navigation, vessel operations, and sediment transport.
Obstacle to vessel movements	Jetties, given their shore-normal and often-lengthy footprint, can impede vessel movements and act as a navigational hazard.
Access to the sea	The allocation to a length of shoreline as a wharf for use by vessels implies that this area will not be suitable, or even accessible to the public.
Characteristics of the frontage	The construction of wharfs may represent a change of use of the frontage with implications on the wider character of the area. Similarly, the construction of a jetty will have a significant visual impact.

5.7.1.7 Key difficulties

Some key challenges in the design of jetties and wharfs are outlined in Table 5.44. Insufficient appreciation of such challenges can lead to uncertainties in design and residual risks in the final solution.

Table 5.44: Key design challenges – jetties and wharfs

Design challenge	Comments
Corrosion	Loss of thickness over the lifetime of the structure should be accounted for in the design. However, it can be difficult to accurately predict corrosion rates and the risk of either over- or under- design is significant. Assumed rates should vary by height in the tidal range and be appropriate for the local climate. A key risk is the occurrence of Microbial Induced Corrosion (MIC) also known as Accelerated Low Water Corrosion (ALWC) as discussed in Section 5.5.3. Greater confidence in actual corrosion rates and early identification of AWLC/MIC can be achieved via a regular and proactive monitoring scheme which should include steel thickness measurements (normal practice is via non-intrusive techniques), both above and below water. Protective measures include painting and cathodic protection. The former is straightforward for new-builds but reapplications are normally difficult. The latter

Design challenge	Comments
	can be effective and efficient below mean water though benefits to the high-attack splash zone is limited. Additional maintenance and servicing will also be required.
Access	While structures can be designed for low maintenance, some degree of maintenance and inspection will always be required. However, access constraints will be common including lack of immediate visibility to below water portions of the structure and the potential need to temporarily pause operations. Whether a structure will be publicly accessible or not should be understood as this may influence the design for safe use (i.e. trained vs. untrained users). Public access may also introduce risks associated with further activities such as fishing.
Change of requirements	Changes to functional, and therefore also structural requirements during the lifetime of jetties and wharfs are probable due to developments in the shipping industry both in terms of technologies and practices (most likely the continues trend for larger vessels). Adaptability to, or design for, future conditions may be considered at initial design. However, this will be based on rough predictions of assumed trends.

5.7.1.8 Opportunities

While the developer will need to demonstrate that negative impacts have been effectively eliminated or controlled, emphasis should also be placed on the exploitation of opportunities. Common opportunities associated with the development of jetties and wharfs are outlined in Table 5.45.

Table 5.45: Common opportunities – jetties and wharfs

Opportunity	Comments
Multi-functional use and convertibility	Structures can generally be designed suitable for accommodation of multiple categories of vessels, thereby diversifying the functions of the facility. Furthermore, modification from commercial to recreational use will be relatively straightforward; for instance, jetties, can be transformed into recreational piers providing a public amenity while wharfs may be transformed into waterside developments.

5.7.2 Dredged channels and basins

5.7.2.1 Overview

Dredging, i.e., below-water excavation and removal of material, is often required where vessel access is needed in areas of insufficient water depth. Minimum water depths, and therefore dredging requirements, will vary by the vessel types for which the facility is designed. Dredged channels (generally *approach channels* whether dredged or not) will often be required and are essentially narrow passages for vessels to enter and exit the harbour/port/marina. Channels may often be restricted to one-way systems for larger vessels. Dredged basins are wider areas intended to provide space for vessel manoeuvres. The term dredged pocket is also commonly used to refer to smaller dredged areas directly in front of a berth.

Useful external guidances on the design of dredging works may be found in:

- BS 6349-5:2016 Maritime works Part 5: Code of practice for dredging and land reclamation (BSI, 2016)
- Report N°121, Harbour Approach Channels Design Guidelines, (PIANC, 2014)
- Report N°104, EnviCom WG104 Dredged Material as a Resource – Options and constraints (PIANC, 2009)
- Report N°108, EnviCom WG108 Dredging in Ports and coral reefs, (PIANC, 2010)

5.7.2.2 Function and applicability

Siting of berths and other developments requiring access by vessels normally places high priority on the avoidance or minimisation of dredging requirements due to the potential environmental impacts and cost implications, among other factors. Following capital works, maintenance dredging will normally also be required as a result of siltation/sedimentation due to normal sediment movements. This can be a significant ongoing cost that should be considered in whole life cost estimates.

Dredging will normally be technically feasible in most instances. However, the onerousness of the works will be dependent on ground conditions with excavation of bedrock requiring significantly more effort than that of sand or other mobile sediment.

5.7.2.3 Design considerations

Key design parameters to be considered when designing dredged channels and basins are listed in Table 5.46.

Table 5.46: Key design considerations – dredged channels and basins

Parameter	Relevance
External information	
Ground conditions	Understanding required to select appropriate equipment. Existing bed levels required to understand material quantities.
Environmental and metocean conditions.	Understanding required to assess environmental impacts and also potential operational constraints during dredging operations. This may include sensitive habitats, existing navigation channels, and buried services.
Design parameters	
Dredged depth	Typically defined on the basis of the design vessel's characteristics and environmental conditions, in addition to various tolerances. In some cases the required depth cannot be achieved necessitating restrictions on operations (such as restrictions on vessel loads or tidal access).
Channel and basin geometry	Channel slopes and widths influence vessel manoeuvrability, ability for vessels to safely pass one another, and general grounding risk. Geometry should be a key design consideration, designed in line with the appropriate standards and guidance, and supported by navigation studies as appropriate.

5.7.2.4 Structural failure

Structural failure of dredged assets may be understood as the failure of the asset to retain its designed geometry for a tolerable period of time.

Common mechanisms of *structural* failure for dredged channels and basin are shown in Table 5.47.

Table 5.47: Common mechanisms of structural failure – dredged channels and basins

Mechanism of structural failure	Comments
Excessive siltation	The greater the change from existing conditions, the more rapid siltation can generally be expected. Siltation may not be uniform across the dredged area but is often concentrated in local areas.

Mechanism of structural failure	Comments
	Normally exacerbated by inappropriate siting. Where significant siltation is anticipated, control structures may be appropriate. A common scenario is the use of groynes (sometimes referred to as jetties in this context) extending seawards to flank channel inlets. The geometry of offshore breakwaters may also be modified to influence sediment transport.
Slope collapse (slumping etc.)	Normally attributed to excessively steep channel slopes, collapse of such slopes can lead to areas of local grounding risks due to the displaced material.

5.7.2.5 Functional failure

Common reasons that may describe why a dredged channel or basin does not function as intended are outlined in Table 5.48.

Table 5.48: Common reasons for functional failure – dredged channels and basins

Functional failure	Possible driving factor	Comments
Inadequate space for safe manoeuvres	Inadequate understanding of environmental conditions and their impact on vessel manoeuvrability.	This is a common consideration when facilities are modified to accommodate larger or less agile vessel. Use of dredged channels and basins by vessels / in situations non-compliant with the design conditions should only be undertaken following a dedicated study to assess suitability and identify any remedial actions, such as the use of tug assistance, which may be required.
	Non-compliance with design operational constraints.	
Inadequate under keel clearance	Non-compliance with design operational constraints.	As above but in relation to water depths and bed levels.
	Occurrence of debris	Particularly following incidents such as lost cargo or the occurrence of severe storms, large debris should be removed from all navigation channels following their identification via a bathymetric survey.
	Insufficient maintenance dredging	-
	Inadequate navigation aids (e.g., channel lighting and buoy markers)	Especially in low light and rough conditions, navigating within poorly marked channels can be difficult with risks of vessels running aground. Markers should comply with local requirements and conventions.

5.7.2.6 Wider implications

The decision to carry out dredging works should be assessed critically, considering its wider implications, the most common of which are outlined in Table 5.49.

Table 5.49: Typical wider implications – dredged channels and basins

Wider implication	Comments
Environmental impacts	Environmental impacts are to be considered prior to and throughout the duration of the design process for all coastal infrastructure. However, these are generally particularly relevant for dredging works given their often-large scale and potential for direct and indirect habitat loss, mobilisation of contaminants, and impacts on water quality.

Wider implication	Comments
Risk to vessels	Dredging works will normally correspond to an introduction of larger and potentially less-manoeuvrable vessels to an area shared by smaller recreational craft. This will lead to an increase in the risk of collisions. Also, there will be increased risks to the larger vessels themselves of grounding and damaging the asset
Impacts on sediment transport and hydrodynamic processes	Capital dredging works can reduce wave attenuation, introduce refractive patterns, and increase current speeds, potentially leading to increased wave energies and changes to sediment transport.

5.7.2.7 Key difficulties

Key challenges in the design of dredged channels and basins are outlined in Table 5.50. Insufficient appreciation of such challenges can lead to uncertainties in design and residual risks in the final solution.

Table 5.50: Key design challenges – dredged channels and basins

Design challenge	Comments
Prediction of sedimentation rates	Particularly when unsupported by dedicated numerical sediment modelling, which is normally onerous, predicting sedimentation of dredge areas is difficult. Estimated maintenance requirements should be conservative while actual maintenance should be informed by regular bathymetric surveys.
Uncertainties	Uncertainties may be related to a number of parameters as described in Section 3, like seabed conditions, elements affecting above water clearance. Uncertainties are also linked to data and operational models used to simulate vessels' behaviours, which in turn are also dependent on human behaviour. Measures should be implemented to reduce these uncertainties at design stage, such as detailed surveys and more sophisticated design tools like, for instance, real time ship simulation.

5.7.2.8 Opportunities

While the developer will need to demonstrate that negative impacts have been effectively eliminated or controlled, emphasis should also be placed on the exploitation of opportunities. Opportunities associated with dredged channels and basins are primarily associated with the beneficial use of sediment, common examples of which are outlined in Table 5.51.

Table 5.51: Common opportunities – dredged channels and basins

Opportunity	Comments
Intertidal habitat creation or maintenance by maintaining or replenishing sediment budgets	– Appropriate use of dredged material will strongly depend on the characteristics of the sediment and the intended use. While some grading may be possible, this can be an onerous activity. – Non- beneficial use is typically disposal on land or offshore.
Beach renourishment	
Reclamation	
Construction aggregate, typically for core material	

5.7.3 Marinas

5.7.3.1 Overview

The term marina refers to the wider development that consists of wharves, jetties and pontoons providing berthing facilities and/or act as retaining structures, dredged areas, as well as supporting services. Guidance on wharf and jetty structures is provided in Section 5.7.1 while consideration of dredging works is captured in Section 5.7.2. Supporting services are not discussed in depth in this guidance.

Useful external references, among others, on the design, construction, and operation of marinas include:

- Guidelines for design of marinas, AS 3962 (The Australian Standard, 2020)
- Guidelines for Marina Berthing Facilities, 2005, published by the state of California.
- RecCom WG 149 Guidelines for Marina Design part 1 (RecCom, 2016)

Marina may take on a number of forms, including:

- Recessed or semi-recessed basins comprising no, or few channels connected directly into the adjacent harbour or ocean.
- Essentially land-locked canal systems where a single entrance splits into a sometime-extensive system normally to maximise the number of sub-lots with private berths.

Marinas of the former kind are typically smaller developments and will normally rely on artificial defences such as breakwaters for shelter from wave energies.

5.7.3.2 Function and applicability

Typical characteristics distinguishing marina from other coastal developments with similar functions such as commercial ports, which are also designed to accommodate vessels, include:

- Recreational use: this also implies a many users may be less experienced and potentially less physically-able as compared with commercial port personnel and pilots who are normally trained professionals.
- Inland development: this implies a typical need for significant dredging or excavation works.
- Numerous berths/docks; marinas are normally intended to provide a high number of berths in a relatively small area.
- Design for range of vessels that are generally smaller than commercial tankers, barges, etc.

Marinas are typically only connected to the sea via the relatively narrow entrance/exit channels. This provides good sheltering from wave action but at the expense of normally significant dredging works. To reduce these works, marinas are often proposed at low-lying areas which frequently correspond to existing mangrove systems – valuable and sensitive habitats that may be incompatible with the intensity of marina activities.

5.7.3.3 Design considerations

Key design parameters to be considered when designing marinas are listed in Table 5.52.

Table 5.52: Key design considerations – marinas

Parameter	Relevance
External information	
Wave climate including wave heights, directions, and water levels	Mostly important for the vessel approach, as described in Section 5.7.2.7, but also for the location and orientation of the marina opening which should be such that vessels are not broadside to the waves (i.e. parallel with wave crests). This information is also relevant to the prediction of sedimentation and internal currents and flushing times. Wave reflections within the marina itself should also be considered. Energy-absorbing features such as internal beaches may be required.
Surge	Depending on the configuration of the marina, there is potential for exacerbated surge. This is generally driven by the ease in which flows can enter the marina system vs subsequent restrictions.
Sediment transport patterns	To understand the potential of siltation and maintenance dredging requirements.
Ground conditions	To understand dredging requirements and foundations for wharves and jetties etc.

Parameter	Relevance
Design parameters	
Channel widths	Critical for safe navigability of the marina. Widths should consider the various vessels frequenting the development including their sizes and manoeuvrability as well as any required clearance from submerged hazards such as supporting structures. Vessel wake from passing vessels should be considered.
Dredged depths	To reduce dredging requirements, berths accommodating larger vessels are normally situated close to the marina entrance while vessels with lesser draughts would be accommodated in the more distant marina extents. For further dredging considerations refer to Section 5.7.2.3.
Berth/dock types	Refer to Section 5.7.1. Multiple design options are available including closed berths, open berths, and floating docks.
Flushing times and overall circulation	Such to avoid stagnant water and enable the dispersion of contaminants.
Operational constraints	Constraints on operations will usually be required such as limitations on: ● Vessels speeds – to manage vessel wake, bed scour, and collision risk ● Informal fuelling activities – to reduce contamination risks ● Use of non-biodegradable cleaning products ● Fish cleaning – especially in cases where flushing times are of concern or when undesirable in light of the intended marina use.
Access	Access to the site from both land and sea should be considered at the development siting phase. Access to and from the vessels themselves need to be carefully considered, particularly as users normally include inexperienced persons potentially of limited mobility. Safe access is commonly provided via gangways and ladders that should also account for variability in water levels and vessel deck heights.
Health and Safety	As per Table 5.40. In addition to managing H&S aspects through intentional design and operational restrictions, safety measures such as emergency access ladders, navigational aids, and lifesaving equipment should be in place and regularly inspected.
Mooring systems	As per Table 5.40
Supporting services	Significant supporting infrastructure and services will be required to facilitate the wider marina activities. These will not be explored in depth but should normally include: ● Refuelling stations – careful management of contamination risk will be required ● Shore-based power and water, Shore-based power (as opposed to that produced by the vessel itself) is significantly more sustainable and less impactful and should be encouraged where practicable. ● Security measures and marina controllers ● Firefighting, to be situated near refuelling points in particular ● Waste management systems ● Boat ramps and slipways Marinas should consider accommodation for alternatively fuelled vessels, or as a minimum consider the adaptability of the marina for such provisions in the future.

5.7.3.4 Structural failure

Structural failure in relation to marinas will be those associated with failure of the individual assets and as such are discussed in Section 5.7.1.4 and Section 5.7.2.4.

5.7.3.5 Functional failure

In addition to the common functional failures of wharves and jetties and dredged channels as described in Sections 5.7.1.5 and 5.7.2.5, common reasons that may describe why a marina may not function as intended are outlined in Table 5.53.

Table 5.53: Common reasons for functional failure – marinas

Functional failure	Possible driving factor	Comments
Stagnant and contaminated water	Insufficient flushing	Ensuring adequate flushing is a key design challenge, as discussed in Table 5.55. Adequate flushing is required to ensure acceptable water quality.
Vessel collisions	Inadequate internal configuration.	The internal configuration of berths and channels need to be carefully considered taking into account key hazards such as larger or less manoeuvrable vessels, potentially blind corners and bottlenecks (which should normally be designed out), and residual submerged hazards which should be clearly marked.
Energetic wave conditions	Internal wave reflections	This can apply to both incoming ocean waves and vessel wake and can manifest in locally energetic areas of the marine, inhibiting navigation.

5.7.3.6 Wider implications

Marinas are typically high-impact developments with implications to and beyond the site itself. The most common of implications are outlined in Table 5.54.

Table 5.54: Typical wider implications – marinas

Wider implication	Comments
Environmental impacts	Environmental impacts are to be considered prior to and throughout the duration of the design process for all coastal infrastructure. However, these are generally particularly relevant for marina developments given their often-large scale and potential for direct and indirect habitat loss. Marina operations will also inevitably lead to an increased concentration of boat traffic at and around the site with associated increases in pressures due to sound and vibrations in particular.
Sediment transport	Marinas will normally require a dredged channel, considerations of which are discussed in Section 5.7.2.3. The dredged marina entrance, along with control structures (essentially groyne structures) commonly constructed alongside, can interrupt alongshore sediment transport processes, potentially starving the downdrift side of sediment resulting in erosive pressures. This may be managed by sediment recycling scheme although this can represent a significant maintenance operation.

5.7.3.7 Key difficulties

Key challenges in the design of marinas are outlined in Table 5.55. Insufficient appreciation of such challenges can lead to uncertainties in design and residual risks in the final solution.

Table 5.55: Key design challenges – marinas

Design challenge	Comments
Navigability	Maximising number of berths while maintaining safe navigability.
Flushing	Predicting and ensuring adequate water circulation, particularly for extensive channel systems with a single entrance and with the limited Bahamian tidal range.
Sedimentation	Normally at approach channels – refer to Section 5.7.2

5.7.3.8 Opportunities

While the developer will need to demonstrate that negative impacts have been effectively eliminated or controlled, emphasis should also be placed on the exploitation of opportunities. Common opportunities associated with the development of marina are outlined in Table 5.56.

Table 5.56: Common opportunities – marinas

Opportunity	Comments
Multi-functional use	In addition to accommodating vessels, marinas may be suitable to host other activities with associated social benefits. This may include integration of publicly accessible waterfront areas and hosting of regattas or similar events. Accommodate recreational vessels Safe haven harbour – careful legal implications
Safe haven harbour	While this term has a formal definition and is dependent on a harbour demonstrating achievement of certain performance criteria, the concept of a safe haven harbour can be relevant to marinas. Where capable of providing confident protection to vessels during storm events, marinas may be used to temporarily host vessels during storm events.
Integration with natural habitats	While commonly completely lined with hard structures or exposed rock, marinas may also integrate coastal vegetation to provide aesthetic and ecological benefits. However, the intensity of disturbances due to marina activity means that coexistence with a naturally functioning ecosystem is very unlikely. As such, the potential for greenwashing[24] should be understood.

5.8 Miscellaneous structures

5.8.1 Intakes and outfalls

5.8.1.1 Overview

Intakes and outfalls represent connections between the sea and onshore facilities. This guidance will focus on the coastal and marine elements of these systems only.

Intakes are structures that extract seawater typically for industrial purposes. However, they may also be located in lakes or other freshwater sources, installed on vessels/barges/offshore platforms, and used for other purposes. Common use cases include:

- Intakes for firefighting systems
- Cooling water for industrial processes
- Desalination for production of freshwater
- Aquaculture

Considerations around intakes may also be relevant to dredging works that make use of slurries. However, the focus of this Section will be on permanent structures.

Outfalls are structures that facilitate the discharge of wastewater (refer to Section 3.11.2.2 for considerations on water quality) into the sea. Similarly, to intakes, these may also be located in freshwater sources and have a variety of use cases such as discharge of:

- Sewerage
- Flood waters
- Industrial effluent
- Brine (water with high salt concentrations)
- Cooling waters (hot/warm water)

Useful external guidance for the design of intakes and outfalls include:

[24] Greenwashing: Where the advertising and public communications imply a greater environmental benefit than that actually achieved for reputational gain.

- Marine outfall construction: Background techniques and case studies (ASCE, 2009).

5.8.1.2 Function and applicability

While discharge/intake waters are conveyed through pipes (of varying materials, typically forms of PVC), they will normally also require protective housing. Such structures generally need to protect the conveyance pipes from sources of impacts and loadings such as activities on the foreshore, vessel collisions, erosion and scour, and wave action.

The functioning of outfalls will normally be driven by dispersion of the discharge to adequately mitigate environmental impacts. The functioning of intakes will often be driven by the avoidance of siltation and the water characteristics required for the intended purpose (e.g., limiting intake of suspended particles).

While intakes will typically require pumping systems, outfalls commonly function under gravity.

5.8.1.3 Design considerations

Key design parameters to be considered when designing intakes and outfalls are listed in Table 5.57.

Table 5.57: Key design considerations – intakes and outfalls

Parameter	Relevance
External information	
Metocean conditions incl.: – Currents – Wave climate incl. wave heights & directions – Water levels incl. tide and surge	– Dispersion of discharged water and impact on water quality. – Influence on sediment transport. – Wave loadings. – Potential for scour, siltation, and sediment transport. – Tidal locking.
Sediment characteristics	Potential for scour, siltation, and impacts on sediment transport.
General environmental conditions and habitat extents	Identification of sensitive human and ecological receptors, risks such as anchoring areas, etc.
Water depths and bathymetry	Dispersion of discharge, risk to and from vessels, wave loadings, siting, etc.
Ground conditions	Risk of scour, siltation, and general design and construction.
Design parameters	
Design flows	Dimensioning of pipes. Design against scour (exacerbated by high flows) and siltation (exacerbated by low flows).
Hydraulic head levels (hereafter referred to as *head levels*)	To design against tidal locking. Especially important for gravity systems.
Structure length	Typically, a balance between reaching generally more desirable deeper water with the costs of works and scale of impacts (e.g., protrusion into navigation channels).
Invert levels and additional screens etc.	Influence on head differences, risk of siltation, and scour due to discharges, risk of vessel collision.
Bed stability	Where the outfall is placed on the bed it is necessary to ensure that it is stable under design wave and current conditions. High loads can be generated in the surf zone. Gravity structures, weights on the pipes, are often used but it may be necessary to anchor into the bed.

Parameter	Relevance
	Buried pipelines across the surf zone are an alternative if construction is practicable. Micro tunnelling to form the outfall is a viable option if there are suitable ground conditions.

5.8.1.4 Structural failure

Common mechanisms of structural failure for intakes and outfalls are shown in Table 5.58.

Table 5.58: Common mechanisms of structural failure – intakes and outfalls

Mechanism of structural failure	Comments
Multiple failure mechanisms	Due to wave loadings. This will often be most relevant in the nearshore where waves can break directly onto the housing structure.
	Due to vessel or anchor impacts. Particularly susceptible to poor siting.
Geotechnical failure	Due to scour. Wider sediment movements should be investigated to ensure stability of the complete length of the asset. Local impacts, especially at locations of strong currents (including those due to the discharge itself) or breaking waves should be considered.
	Due to differential beach heights should the structure also impact alongshore sediment transport, acting as a groyne.

5.8.1.5 Functional failure

Common reasons that may describe why an intake or outfall does not function as intended are outlined in Table 5.59.

Table 5.59: Common reasons for functional failure – intakes and outfalls

Functional failure	Possible driving factor	Comments
Intakes and outfalls		
– Siltation	Inadequate consideration of sediment movements.	Siltation should be explicitly designed against. Invert levels and pipe diameters should be assessed against variable bed levels and the potential accumulation of mobile sediment. While discharge flows will be beneficial in preventing siltation, this would normally need to comprise high flows at a regular frequency. For instance, such benefits would be limited for a storm water outfall only operating during low frequency extreme events. The need for mitigation measures such as sediment screens should be considered.
Upstream intrusion of seawater	Lack of flap valve and insufficient understanding of extreme water levels.	The installation of flap valves (to be designed in consideration of water levels and head levels) will normally be required. Flap valves will require regular monitoring and maintenance.
Outfalls		
Poor water quality includes excessive: – Temperature – Salinity	Inadequate dispersion potentially due to: – Overprediction of currents.	The mitigation of environmental impacts should be the driving consideration when designing these structures. The performance of these systems should be

Functional failure	Possible driving factor	Comments
– Concentration of contaminants	– Insufficient water depth at outlet. Actual quality of discharge water worse than that assumed in the design due to: – Inadequate treatment prior to discharge. – Change of source.	comprehensively and reliably demonstrated. Such a failure should therefore not realise.
Tidal locking	Inadequate consideration of variable water levels and head levels.	This will be particularly relevant for storm water outfalls as the peak drainage requirements are likely to also correspond with surge.
Intakes		
Poor quality of intake water	Inadequate or lacking sediment screens or inadequate understanding of water characteristics at the location of the intake. Likely exacerbated by intakes positioned in shallow water, placed too near the seabed, or placed in areas with significant mobile sediment or organic matter.	The extracted water needs to be suitable for the intended use. For some purposes, there will be significant flexibility here (e.g., firefighting). For others, restrictions may be placed on suspended sediment or organic matter content.

5.8.1.6 Wider implications

The decision to develop intakes and outfalls should be assessed critically, considering their wider implications, the most common of which are outlined in Table 5.60.

Table 5.60: Typical wider implications – intakes and outfalls

Wider implication	Comments
Environmental impacts	As previously discussed, Impacts are varied and can include: – Change in temperature (increase or decrease) – Change in salinity (increase or decrease) – Introduction of contaminants – Introduction of nutrients – Typical consequences may include: – Contaminated swimming waters – Algal blooms – ‘Dead zones’ – Bleached corals – Contaminated sediment with potential introduction into the food chain
Sediment transport	Structures on the beach and in the nearshore can impact alongshore sediment transport. In the event protruding structures are proposed in this area, they should be assessed as a groyne as per Section 5.6.1.

5.8.1.7 Key difficulties

Key challenges in the design of intakes and outfalls are outlined in Table 5.61. Insufficient appreciation of such challenges can lead to uncertainties in design and residual risks in the final solution.

Table 5.61: Key design challenges – intakes and outfalls

Design challenge	Comments
Prediction of dispersion	Hydrodynamics are typically complex, requiring assessment by experienced engineers/scientists often requiring numerical modelling activities.
Site constraints	Site conditions may often place constraints on structure length, depth, etc. that may be in conflict with the ideal design. However, minimum standards in terms of performance reliability and environmental impacts should be maintained.

5.8.1.8 Opportunities

While the developer will need to demonstrate that negative impacts have been effectively eliminated or controlled, emphasis should also be placed on the exploitation of opportunities. Common opportunities associated with intakes and outfalls are outlined in Table 5.62.

Table 5.62: Common opportunities – intakes and outfalls

Opportunity	Comments
Incorporation into other structures	– Outfalls may be incorporated into other structures such as groynes or piers to provide a multi-functional asset.
Intertidal habitat	– While any structures proposed in the coastal environments should be seen as impactful, the ecological impact may be mitigated through eco-enhancements such as texturing surfaces and providing artificial habitats for marine life (e.g., artificial rock pools).

5.8.2 Reclamation

5.8.2.1 Overview

Reclamation refers to the creation of new, dry, land area which may take the form of a new artificial island or an advancement of the shoreline. Reclamation is distinct from recharge, which is the creation or expansion of beaches. For guidance on recharge and recycling, refer to Section 5.6.4.

Useful external guidance on the design of reclaimed land may be found in BS 6349-5:2016.

5.8.2.2 Function and applicability

The decision to reclaim land is often driven by the need for additional space for development, often as a result of population growth and/or economic growth. However, reclamation is often driven by the availability of excess material commonly sourced from large dredging operations, especially as the use of contaminated sediment will normally be suitable. The reclamation process typically comprises:

1. Construction of a retaining structure. This may be a combi-wall, sheet pile, caissons, possibly rock armour, or others.
2. Deposition of fill material. This will often be a slurry with associated drainage requirements.
3. Consolidation of the fill material.
4. Surface finishing works such as paving.

Reclamation is commonly used to expand port areas but is generally widely applicable. However, the area of potential reclamation will be directly related to the quantity of sediment available and water depths.

5.8.2.3 Design considerations

Key design parameters to be considered when designing reclamation works are outlined in Table 5.63. Considerations relating to any dredging works are discussed in Section 5.7.2.3.

Table 5.63: Key design considerations – reclamation

Parameter	Relevance
External information	
Sediment properties	Influences suitability for use and design requirements including drainage and settlement rates as well as final ground bearing capacities. The in-situ characteristics of the fill material at the borrow site will also inform selection of the most suitable equipment and means of transport from the borrow site, and reclamation method.
Topography and bathymetry	Existing above and below water bed levels will dictate the volumes of material needed and inform selection of the most suitable location.
Contamination	While the use of contaminated sediment may be appropriate, in conformity with local regulations, additional controls will be required at both the dredging (discussed in Sections 3.11 and 4.4) and deposition phases. Controls include restrictions on discharged waters from any dewatering processes; proper disposal of waste material; additional controls on runoff; and limitations on suitable retention structures which should normally be impermeable in such instances.
Environmental conditions, primarily waves and water levels.	Understanding required for design of retention structures and also design levels, in particular for the management of flood risk.
Borrow area	The local conditions of the borrow site like depth, exposure, distance from the reclamation site, need to be factored in to identify the most cost-effective solution.
Design parameters	
Fill properties	Properties like bearing capacity, density, stiffness, permeability will influence the quality of the reclamation, i.e., its stability.
Design levels	Relevant to flood risk. To consider anticipated settlement.
Drainage	During construction and over the lifetime of the development. During construction, material is often deposited as a slurry; the excess water will therefore need to be drained. Drainage is often accomplished via vertical wick drains, drainage routes through the retention structures, unenclosed sections in partially constructed retention structures, or a combination.
Settlement	During construction and over the lifetime of the development. Sediment will settle, the rate and extent of which will strongly depend on sediment characteristics and drainage. A vertical surcharge (i.e., placement of material to levels greater than final design elevations) will normally be required to allow for settlement and/or to increase vertical loads to accelerate consolidation. Alternative methods are also available to increase settlement rates, such as vibro-compaction. A combination of methods will normally be most appropriate. Settlement criteria should be set to establish tolerable settlement limits over a defined period of time. Monitoring will therefore be required.
Runoff	Uncontrolled runoff should normally be avoided to reduce impacts relating to increased turbidity and potential contamination. While impacts are best managed at the source, silt screens may be required until paving and formal drainage can be installed.

5.8.2.4 Failure

Failure for reclamation works will normally relate to either failures in the retention structures or unanticipated ground performance. For consideration relating to the former, refer to Section 5.6.3.4. For common failure mechanisms relating to the latter, refer to Table 5.64.

Table 5.64: Common mechanisms of failure – reclamation

Mechanism of failure	Comments
Low settlement rates	A period between deposition of material and commencement of works on the surface will normally be required to allow the ground to settle and consolidate. The rate of consolidation will normally be driven by sediment properties and drainage, the two of which are interlinked. Drainage and settlement will be more difficult the finer the sediment. Even with active drainage systems, settlement rates may be excessive and potentially limit the suitability of the material for

Mechanism of failure	Comments
	reclamation. Alternatively, the use of the land may need to be limited to activities insensitive to longer term settlement.
Excess scour	Excess scour at the toe of the structures may expose the foundations and lead to failure mechanisms involving both the containment structure and the reclamation surface area. The failure mechanism involves extraction of sediment from the reclamation through the toe or foundation, with consequent tilting of the retaining structure, or sliding of the armour in the case of a rubble mound structure. The reclamation surface may also be affected and collapse locally, as a consequence of voids forming underneath. A useful external reference is the Toe structures management manual (Environment Agency, 2012).

5.8.2.5 Wider implications

Common implications of reclamation developments are outlined in Table 5.65.

Table 5.65: Typical wider implications – reclamation

Wider implication	Comments
Implications relating to dredging activities	Refer to Table 5.49.
Implications on coastal processes due to changes in the shoreline position.	Reclamations protruding from the shoreline have the potential to impact alongshore sediment transport processes. Refer to Table 5.5: groynes.
Implications relating to the creation of hard structures on the coast.	Refer to Table 5.20 and Table 5.43.
Characteristics of the frontage	Reclamation can represent a significant variation from historical conditions with subsequent implications on the character of a frontage.

5.8.2.6 Key difficulties

Key challenges in the design of reclamation activities are outlined in Table 5.66. Insufficient appreciation of such challenges can lead to uncertainties in design and residual risks in the final solution.

Table 5.66: Key design challenges – reclamation

Design challenge	Comments
Prediction of settlement	Predicting settlement rates of material can be complex and is of significant importance for the performance of the ground.
Mitigation of environmental impacts	Reclamation represents a permanent modification of the natural shoreline and has the potential for a wide range of environmental impacts all of which need to identified, understood, and mitigated.

5.8.2.7 Opportunities

While the developer will need to demonstrate that negative impacts have been effectively eliminated or controlled, emphasis should also be placed on the exploitation of opportunities. Common opportunities associated with the decision to carry out reclamation schemes are outlined in Table 5.67.

Table 5.67: Common opportunities – beach recharge and recycling

Opportunity	Comments
Flexible use	– Reclamation is essentially creation of new land area. The best use of this new area should be properly assessed.
Beneficial use of dredged sediment	– Reclamation is one of many possible beneficial uses of dredged sediment, as already discussed.

5.8.3 Access

5.8.3.1 Overview

Access to the beach and coastal areas is commonly inhibited by a variety of alongshore features including natural habitats such as dunes and vegetation, coastal defence structures, and generally soft and uneven surfaces. Formal access are structures or measures connecting the hinterland to the foreshore or sea that have undergone intentional design to provide safe and useable access from the hinterland suitable for its intended users. Common access structures include steps, ramps (including those for pedestrians, vehicles, plant, and boat trailers), and boardwalks. Where access is required through a flood defence moveable or removeable barriers such as stop logs or flood gates may be required. Common users for which access structures should be designed include:

- The general public including those of limited mobility. Access facilities to connect users of significantly reduced mobility – such as those in wheelchairs – to the sea itself are feasible. However, associated risks will require significant attention and as such, these kinds of facilities are not discussed further in this guidance. However, a useful external guidance to support the delivery of an inclusive environment is the Planning and access for disabled people: a good practice guide (DCLG, 2003).
- Maintenance workers and their equipment.
- Contractors and associated plant carrying out maintenance and repairs to beaches and coastal infrastructure.
- Boaters including fishermen and jet ski operators launching their vessels.
- Emergency services.

5.8.3.2 Function and applicability

Formal access points increase the connectivity of the foreshore to the hinterland, increase accessibility especially for those of limited mobility, improve safety, and provide necessary services such as access for plant and facilities for launching of vessels.

Access points are commonly designed to:

- Overcome level differences, whether across a coastal defence, dune system, or a steep slope.
- Improve safety by providing access, and also egress, for instance via an even surface of the appropriate grading and supporting elements such as handrails.
- Prevent damage to natural habitats or susceptible assets, such as the provision of boardwalks over dunes and coastal vegetation to avoid trampling pressures.
- Reduce beach use pressures by increasing the number and distribution of access opportunities.

Access points are generally always applicable. However, they can be seen as invitations to the foreshore; therefore, their placement should be well considered and lead to a safe environment. Any residual risks and restrictions on use should be clearly communicated.

5.8.3.3 Design considerations

The key design parameters to be considered when designing access structures are listed in Table 5.68.

Table 5.68: Key design considerations – access structures

Parameter	Relevance
External information	
Variations in beach levels	Access points should normally be designed to the lowest credible beach level to avoid large stepped access during periods of low beach levels.
Tide levels	Influences placement of the structure. Boat ramps should extend down to low water while most other access types will preferably remain above the tidal range.
Wave heights	While access structure will normally be designed in sheltered locations, if significant wave action is anticipated the structure should account for this loading. Understanding of anticipated wave conditions will also be relevant when locating the structure.
Degree of wetting	Regularly wetted surfaces are susceptible to marine growth which significantly increases the risk of slips and falls. Management of this risk is best accomplished via careful placement of the asset and regular maintenance.
Design parameters	
Level of toe and end of access	As above for variations in beach levels, but also considering the need to design against scour.
Slope	General pedestrian ramps and those intended for light vehicles should normally not exceed 1:8. Fully accessible ramps for users of limited mobility and for plant should not exceed 1:20. Slope will have a significant impact on material and spatial requirements.
Bearing capacities	To be suitable for the intended use. Loading restrictions should be clearly communicated.
Materials	The choice of material will have a significant impact on maintenance requirements. Timber is often more sustainable and aesthetic but is susceptible to rotting and marine boring. Concrete is generally low maintenance but usually has significant embodied carbon, can be less suited to raised platforms, and may have a greater visual impact. Steel is normally an appropriate material for handrails but should be of marine grade.
Maintenance requirements	Removeable or moveable barriers such as stop logs and flood gates normally require a high degree of maintenance. The party responsible for the management and maintenance of these assets should be identified.

5.8.3.4 Structural failure

Access points are often integrated into the design of coastal defence structures. Therefore, many of the failure mechanisms discussed in Section 5.6 will also apply here. Nevertheless, the most common mechanisms of structural failure for access structures are shown in Table 5.69.

Table 5.69: Common mechanisms of structural failure – access structures

Mechanism of structural failure	Comments
Concrete damage	Abrasion of the concrete can lead to loss of integrity and reduction in protection to any reinforcement. Sea water is aggressive to concrete; an inappropriate concrete mix will lose strength and integrity For reinforced concrete, the steel will eventually corrode, spalling the concrete and the section will lose strength, eventually collapsing.
Rotting	Timber in the marine environment is susceptible to rotting and action from marine life. Timber should be marine grade.
Scour	The impermeable nature of the most materials can increase the risk of scour of beach material, undermining and collapse.
Various failure mechanisms due to excessive loading	Structures should communicate the maximum permissible load, for instance to prevent use of pedestrian ramps by heavy plant.
Multiple failure mechanisms	Due to wave loadings.

5.8.3.5 Functional failure

Common reasons that may describe why an access structure does not function as intended are outlined in Table 5.70.

Table 5.70: Common reasons for functional failure – access structures

Functional failure	Possible driving factor	Comments
Lowered beach levels	Insufficient understanding of variations in beach levels	To prevent H&S risk associated with beach levels falling below the access structure (i.e., below the final step or ramp end), structures should be designed to the lowest credible beach level to provide continuous safe access.
Unsafe egress	Obstructions to, or lack of visibility of egress routes.	Emergency egress from the coastal area should be considered in the design. Unsafe practices should be avoided such as: 1. Irregular step geometry and alignment 2. Areas of entrapment 3. Intrusions to egress routes
Marine growth	Insufficient understanding of anticipated maintenance requirements or placement such that the structure is regularly inundated.	Where the structure must be placed in the tidal zone or with the extent of typical wave run-up, marine growth will almost certainly become established. This is a common challenge and is discussed further in Table 5.72.
Low use	Insufficient understanding of the level of beach use.	While the provision of formal access is to be encouraged, high-use areas should be prioritised for efficient use of resources.
Lack of space for safe manoeuvres	Most relevant for vehicular and boat ramps (i.e., slipways), this is normally due to insufficient space on or at the top of the ramp.	While this can be difficult due to site constraints, ramps should be carefully located such that they are separated from busy roads and such that vehicles, especially those towing trailers, can safely manoeuvre. Areas to store boats and trailers off the ramp should also be provided nearby to avoid parking of vehicles on the ramp itself.
Locked or open flood gates / stop logs	Lack of management and maintenance of the flood gates and stop logs	Removeable or moveable barriers such as stop logs and flood gates normally require a high degree of maintenance. A lack of management and maintenance can lead to gates corroded shut, objects obstructing opening/closing, or gates remaining locked. Consequences can be prevention of access, unrestricted access when not desired, or a localised point of failure in the defence from the perspective of flood protection if left open. Implications around management and maintenance requirements should be understood early on and agreed during design and the responsible party identified.

5.8.3.6 Wider implications

The provision of access points should undergo a dedicated design process to ensure that design requirements and wider implications are adequately considered. Common wider implications are outlined in Table 5.71.

Table 5.71: Typical wider implications – access structures

Wider implication	Comments
Safety and liabilities	Access points may be seen as invitations to the foreshore. Therefore, the foreshore should be safely for use in typical conditions. Significant risks or restrictions on use should be adequately communicated.
	Formal access points that are inadequately maintained may increase the risk of slips, trips, and falls with associated liability concerns.

Wider implication	Comments
Characteristics of the frontage	The introduction of hard structures on a frontage may impact its character. Furthermore, the provision of formal access may lead to an increased use of that area; this can be negatively perceived by existing users and increase pressures on previously un- or little-disturbed habitats.

5.8.3.7 Key difficulties

Some key challenges in the design of access structure have already been mentioned. Nevertheless, these are outlined in Table 5.72. Insufficient appreciation of such challenges can lead to uncertainties in design and residual risks in the final solution.

Table 5.72: Key design challenges – access structures

Design challenge	Comments
Understanding lowest credible beach levels	In the absence of suitable historic data, lowest credible beach levels can be difficult to ascertain. Structures may be extended to bedrock or very consolidated layers; however, this will often represent inefficient design. Alternatively, it may be appropriate to make use of best engineering judgment supported by local knowledge (preferably supported by photos) of typical beach behaviour.
Marine growth	Marine growth is almost certain to occur on any structures in the tidal zone or within normal extents of wave runup. Maintaining a structure consistently free of marine growth requires significant cleaning effort, normally requiring frequent jet washing. A more efficient approach may be to lessen cleaning requirement during periods of reduced beach use. Reducing the risk of slips and falls may be accomplished by increasing the texture of the surface to improve grip. However, this can often lead to even greater marine growth as the texture encourages colonisation of the surface. Integration of steps within a ramp can help such that users do not have to stand on a slope. Horizontal rails across the ramp may be beneficial but are susceptible to damage. Wherever appropriate, handrails should be installed.
Effectively restricting use of the access structures to the intended conditions	Even where constraints are placed on the use of access structures, such limitations on their use will not necessarily be followed. While the communication of risk may help limit liabilities, safety concerns remain relevant. In addition, damage due to loading beyond design conditions can result in further costs on asset owners. This risk may be reduced by physically restricting access to the structure through measures such as bollards, leaving space only for typical vehicles of acceptable categories (such as restricting ramp openings to allow golf carts, but not larger vehicles). With that said, access for emergency vehicles should be considered.
Providing access while retaining defence height	Access through or over structures can lead to long ramps, demountable defences such as flood gates, and generally additional design and material requirements.

5.8.3.8 Opportunities

While the developer will need to demonstrate that negative impacts have been effectively eliminated or controlled, emphasis should also be placed on the exploitation of opportunities. Common opportunities associated with the creation of access structures are outlined in Table 5.73.

Table 5.73: Common opportunities – access structures

Opportunity	Comments
Integration with coastal defences	There is an opportunity to integrate access structures with coastal defences, for instance via design of a stepped revetment intended for access as well as coastal protection. This has the potential for financial savings as well as addressing a common issue of hard defences – that of disconnecting the sea from the land.
Manage human pressures	Formal access points can encourage use of that portion of the frontage. Therefore, intentional placement of access points can better distribute use of a

Opportunity	Comments
	frontage and spread pressures on residents, habitats, and services over a wider area.
Protect and connect people with natural habitats	The absence of formal access over dunes typically results in significant damage due to loss of vegetative cover and local scour due to trampling pressures. The installation of boardwalks over such systems is feasible and can provide an opportunity to protect these habitats and inform beach goers on their value.

5.8.4 Infrastructure within the coastal zone

5.8.4.1 Overview

This section pertains to general infrastructure whose function is not inherent to the coastal environment such as promenades, buried water mains, lighting, and ancillary items such as handrails. The objective of this section is to highlight additional considerations that will be required due to the placement of such infrastructure in the coastal zone.

A useful external reference providing guidance on both technical and commercial matters is the Manual of Contract Documents for Highway Works (MCHW) (Highways England, 2016).

5.8.4.2 Function and applicability

Examples of infrastructure to which the current section will be relevant include:

- Paved promenades, commonly constructed to the immediate rear of seawalls and revetments
- Access roads
- Buried services such as power, water, and internet lines
- Above-surface electrical services such as power connections and lamp poles
- Handrails

Key factors that will need to be considered when placing assets such as these in the coastal environment will include saltwater inundation, additional loading due to overtopping, and increased exposure to salt/chlorides. Generally, the infrastructure being considered will be integrated in larger coastal structures. However, they will normally have lower design lives; therefore, designs should make allowances for maintenance and eventual replacement.

5.8.4.3 Design considerations

Key design parameters to be considered when designing infrastructure in the coastal zone are listed in Table 5.74.

Table 5.74: Key design considerations – infrastructure in the coastal zone

Parameter	Relevance
External information	
Environmental conditions, particularly wave heights and water levels	To understand anticipated overtopping rates and volumes, in addition to water levels and their predicted frequencies of occurrence.
Design parameters	
Foundations and underlayers	Particularly for pavings and bedding for buried services; to be resilient to inundation. This will typically involve measures to minimise the potential of losing material mobilised by draining waters. This is commonly achieved via avoiding material with a high percentage of fines, provision of formal drainage routes, and the use of geotextiles. Design loads should consider potentially less frequent but greater loads such as that due to plant required for maintenance.

Parameter	Relevance
Contact of electrical connections with flood waters	Separation typically achieved by installation above anticipated inundation levels and by proper sealing measures.
Materials	This is a key consideration to ensure durable and resilient coastal infrastructure and is described in Section 5.5.1.

5.8.4.4 Structural failure

Common mechanisms of structural failure for infrastructure due to inadequate design for the coastal environmental are shown in Table 5.75.

Table 5.75: Common mechanisms of structural failure – infrastructure in the coastal zone

Mechanism of structural failure	Comments
Settlement and subsequent differential movements	Inadequate foundation and bed material, improper use of geotextile, and a lack of adequate formal drainage can lead to loss of material, especially fine components.
Corrosion of metal components including fixings	Potentially due to use of non-marine grade metal, insufficient concrete cover, and bimetallic corrosion (whereby contact between incompatible metals accelerates corrosion).
General degradation of materials including sealants and plastic components	Use of materials inappropriate for the marine environment that can accelerate degradation due to significant exposure to salt and chlorides, UV radiation, wave energy, cyclic wetting and drying, and abrasion, among others. Refer to Section 5.5.1 for guidance on the selection of appropriate materials.
Dislodgment during storm events	Handrails and lamp poles for instance, should consider loading due to overtopping which can be significant, especially when placed on the crest of defence structures. If fixings are improperly designed, these can become loose. Loose objects can then pose risk to people and structures.

5.8.4.5 Functional failure

Common reasons that may describe why infrastructure may not function as intended due to its placement in the coastal environment are outlined in Table 5.76.

Table 5.76: Common reasons for functional failure – infrastructure in the coastal zone

Functional failure	Possible driving factor	Comments
Siltation and tidal locking of drainage systems	Inadequate consideration of mobile sediment	Drainage outlets can easily become blocked by mobile beach material; this risk can be mitigated by extending outlets into deeper water, regular flushing (typically challenging for systems designed to low frequency events), regular maintenance, and careful placement of the outlets especially in relation to beach/bed and inlet levels. Drainage systems can also experience tidal locking, also applicable during surge events, whereby the increased water level at the outlet impacts head differences and therefore the ability of the system to function with potential for the system to back up. Backing up can normally be prevented by the installation of flap valves. Refer to Section 5.8.1.3 on outfalls for further considerations.
Non-functional electrical systems or leaking taps and similar	Degradation of seals	Sealants made of rubber and plastic-type materials are particularly susceptible to exposure to UV radiation and salt. The need for such materials should be designed out. Where this is not feasible, regular replacement and maintenance requirements should be understood and communicated.

5.8.4.6 Wider implications

The decision to install infrastructure in the coastal zone should be assessed critically, considering the wider implications, the most common of which are outlined in Table 5.77.

Table 5.77: Typical wider implications – infrastructure in the coastal zone

Wider implication	Comments
Maintenance requirements	Maintenance requirements of infrastructure can sometimes be significant, normally relatively more so than the larger structures. Developers should be account for these costs and ensure proactive maintenance schemes are in place. The lack of maintenance can lead to disruptions in services as well as Health and Safety risks due to degrading assets.
Scour and algal growth	Surface water flows, for instance resulting from the creation of an impermeable promenade or the installation of drains to the upper beach, can lead to localised scour resulting in undermining of hard assets and also contamination of the beach and nearshore. Taps providing washing facilities situated adjacent to access points, or drains embedded in seawalls can encourage marine growth which can be unsightly and also present a slip hazard. Drainage routes should be considered and controlled.
Ecological impacts of lighting	Lighting has the potential to disturb nocturnal animal behaviour. This will not usually be a significant issue at developed sites but could be a driving factor at sensitive sites such as turtle nesting areas.

5.8.4.7 Key difficulties

Key challenges in the design of infrastructure in the coastal zone are outlined in Table 5.78.

Table 5.78: Key design challenges – infrastructure in the coastal zone

Design challenge	Comments
Constraints due to non-bespoke components	Infrastructure such as handrails and electrical housing is not typically of bespoke design for the project. Therefore, contractors are normally limited to available models with predetermined specifications. Sourcing of items suitably specified for the marine environment can also be costly and subject to issues of availability.
Definition of design conditions	Especially when infrastructure is established as a separate endeavour from any fronting coastal defences, it can be difficult to understand the design conditions particularly as minor works of this nature may not warrant a comprehensive study. For instance, installation of additional lighting along a frontage would not normally be undertaken alongside assessments of overtopping rates or extreme water levels; however, such parameters should be considered for a reliable design. Generally, information developed during design of the adjacent defences can be used; however, in the absence of such information, it will normally be appropriate to make reasonable assumptions based on typical conditions anticipated at that site.

5.8.4.8 Opportunities

Common opportunities associated with the installation of infrastructure in the coastal zone are outlined in Table 5.79.

Table 5.79: Common opportunities – infrastructure in the coastal zone

Opportunity	Comments
Manage human pressures	Similar to the opportunity described in Table 5.73. Intentional placement and arrangement of infrastructure can influence the intensity and way in which a portion of a frontage is used. For instance, provision of supporting services can facilitate the formalisation of vendor activities.

6 Construction

6.1 General

The design process should be developed in consideration of its implications on the construction phase including but not limited to buildability, safety, as well as impacts and disruptions on people, the environment, and operations. This way of thinking, particularly in relation to Health and Safety (H&S) risks, is known as Safety in Design and is discussed in Section 5.3.

Notwithstanding the need to consider construction in design, best practice is that it is not the designer's responsibility to determine how the design is implemented as that is within the expertise of the competent contractor. However, controls should be imposed, typically via technical specifications and other construction documents such that the intended design and reliability is achieved, and risks mitigated. Key consideration should be given to conveying any design assumptions and specific construction sequencing if required by the designs.

To bridge the gap between designer and builder, adoption of an Early Contractor Involvement (ECI) approach as discussed in Section 5.2 recommended.

The underlying principles of best practice at the construction phase, in addition to most considerations around their application, will be common to both works in terrestrial and coastal environments. Therefore, the purpose of this section is not to comprehensively capture best practice but rather to highlight aspects unique, or of particular importance, to works in the coastal environment. These include:

1. The specialist nature of the works.
2. The challenging working environment, and associated H&S risks.
3. The environmental sensitivity of most sites.

Notwithstanding this emphasis, key considerations around best practice in construction are also reiterated.

6.2 Quality and workmanship

6.2.1 Quality

In the first instance, quality is controlled by appointment of designers and contractors experienced and competent for the intended works which, in the case of coastal infrastructure are normally specialised in nature. This approach represents international best practice. An example of effective implementation and control of good practice is the UK's 'CDM' regulations as described in Section 5.3.

Quality controls should also be captured within technical specifications, including:

- Definition of tolerances that explicitly control any deviation from the intended design. A degree of tolerance will be necessary for constructability.
- Requirements for material certifications and samples to demonstrate compliance with the specifications for materials.
- Requirements for trial panels or similar to demonstrate compliance with the intended design.
- Provision for regular audits by the developer or their representative (typically the supervising engineer).

The considerations above will generally also apply to most terrestrial constructions. However, they become especially important in coastal designs due to:

- The prevalent use of natural materials which will inevitably include a greater element of variability such as the use of natural rock for revetment armouring.
- The use of specialised construction techniques such as the pouring of concrete underwater, or random placement of breakwater armour units, which is often more difficult to control than regular placement.
- The greater reliance on the expertise and judgment of the contractor to manage uncertainties on site – the most efficient approach when designing coastal infrastructure will often be performative rather than completely prescriptive.

Given the significant need for active controls during the construction phase and reliance on the expertise of the contractor, greater emphasis will often be placed on the role of the supervising engineer for coastal developments as compared with their terrestrial counterparts.

6.2.2 Workmanship

Similar to management of quality, the control of workmanship should be specified by the designer but managed by the contractor. Common controls to be captured in construction documents include:

- Explicit requirement to not damage any existing assets during the works and clarification that any eventual damage be rectified at the cost of the contractor. To support this, photo records of the site and existing assets should be captured prior to commencement and upon completion of the works.
  - In most instances, additional construction footprint is required for elements such as welfare facilities, site compounds, working areas especially for plant, and temporary works. In the event that this additional footprint impacts on existing structures, it should normally be the responsibility of the contractor to reinstate assets to a similar or improved condition.
  - Of particular importance is the maintenance of any flood defences affected by the works and maintaining adequate levels of protection during construction. Temporary provision of flood protection may be required and should be specified when necessary.
- Requirements pertaining to maintenance of a restricted, orderly, safe, and tidy site.
- Any site-specific constraints such as avoidance of undermining existing structures.

The need for, and design of, temporary structures is normally best determined by the contractor. However, these should be constructed following a dedicated design process which are normally led by either a qualified engineer and/or in accordance with the specifications of the manufacturer, as appropriate. Refer to Table 2.1 for Consequence Class for minimum performance criteria for temporary works.

Best practice is to include a period following completion of the works whereby the responsibility for any construction defects remains with the contractor. This is commonly known as a defect period or maintenance period, the length of which will normally depend on the type of works but is typically 6 months. For nature-based solutions the maintenance period for the establishment of the plants should be at least 2 years and in some cases up to 5 years.

6.3 Safety in construction

Safety in design, which is directly linked with safety in construction, is discussed in Section 5.3. The same principles adopted by the designer should also apply to the contractor, specifically the principle to manage hazards via a hierarchical approach starting with elimination as far as reasonably practicable. Works in the coastal environmental bring with it additional hazards and unknowns, reinforcing the need to appoint a suitably qualified and experienced contractor.

Typical hazards or working scenarios unique to or likely to be encountered in the coastal and marine zone include:

- The occurrence of tides with associated risk of entrapment.
- Increased exposure and potential for rapid changes to environmental conditions such as wind and waves.
- Work from a vessel.
- Constrained working areas.
- Use of divers with numerous associated risks including drowning and vessel collisions.
- Use of plant on uncertain ground conditions with associated risk of entrapment, for instance in mud or soft sand.
- Water ingress into excavations, including those that may appear above the tide level but may flood during rising tides.

Safety principles applied to standard construction works will also apply here but should normally be afforded even greater attention. A key system to manage risks, also mentioned in Section 5.3, is the Design Hazard Elimination and Management Record (DHEMR) and its cross-referencing to risks clearly identified on drawings.

A Health and Safety file should be prepared to capture items such as:

- Variations of the construction from the design including as-built drawings
- Maintenance or inspection requirements
- Datasheets for the works such as those managing hazardous substances. Refer to the UK legislation for the control of substances hazardous to health (COSHH), 2002.
- Any residual hazards for maintenance, operation, and demolition should be communicated via the as-built drawings.

This should to be passed on to the developer / asset owner or manager for the management, maintenance and any demolition for the rest of the assets life cycle. Refer to Section 7 for further discussion on the management and demolition of assets.

6.4 Environmental and planning compliance

Environmental considerations should be regarded with the utmost importance for coastal works given the increased sensitivity of the environment as compared to typical terrestrial conditions. The Environmental Impact Assessment process is discussed in Section 4.4, the principles of which should also apply to the construction phase – especially the principle to manage hazards via a hierarchical approach starting with elimination, similar to that for the management of H&S hazards.

Various systems for the protection of the Bahamian environment are already in place and captured in existing legislature including, most notably at the time of publishing, the Environmental Planning and Protection Act, 2019. Key existing controls include established designated areas afforded particular protection and requirements for Environmental Impact Assessments (EIA) and Construction Management Plans (CMP).

The CMP should record all measures to mitigate and control impacts during the construction phase that were unable to be eliminated in the design. Where residual risks, that is the risk after mitigation, are significant, an effective monitoring scheme should be implemented for the entire duration of construction, as appropriate. Monitoring should include establishment of baseline conditions against which construction impacts may be assessed.

The assessment of environmental impacts and controls should be integrated throughout the planning process, from early conceptual designs to construction. Planners should be aware and take advantage of the opportunity to impose controls and influence design to reduce impacts

and enhance positive elements; this is best done as early in the design process as possible. Planners should also seek to understand the complete construction phase, captured in the Construction phase plan which will include sequencing for set-up/mobilisation, import of materials, movements especially for large plant or materials and those requiring traffic controls, construction works including those for temporary structures, and demobilisation.

7 Management, Maintenance, and Demolition

7.1 General

Design should consider the complete lifecycle of the development including construction, the operational life, and demolition. Following construction, the developer should have received a copy of the Health and Safety file (Refer to Section 6.3). This should be retained and updates as necessary throughout the entire lifetime of the asset.

While developments are normally assigned a design life, it is common for structures to remain in place for significant periods even after their originally intended operational life has ended. This is not bad practice and in fact can lead to financial savings and reduced environmental impacts. However, such a practice should be actively managed to ensure the assets remain fit for purpose and do not pose any risk to the public or the environment.

It has been reiterated that design should consider the full lifetime of the development; this should by supported by costing exercises that consider whole life costs including capital works, maintenance and any replacement of components, and demolition. Such an exercise should be carried out from the optioneering stage such that developers and designers can make informed decisions to avoid commitment to an un- or less- sustainable (from financial, economic, and environmental perspectives) design. This process, to be undertaken in greater detail, will also be required to support the final design.

When assessing whole life costs, it is normally appropriate to apply discount rates to future costs to account for the idea that future spends are ‘less expensive’ than those in the present day. While developed in the context of the UK, useful guidance on financial, economic and embodied carbon appraisals may be found in the British HM Treasury’s Green Book.

7.2 Design for maintenance

Coastal infrastructure should be designed to an appropriate level of maintenance which should be explicitly defined and agreed with the developer, stakeholders, and regulators. Funding streams to support both expected and unexpected maintenance activities should be identified prior to construction. The DHEMR should demonstrate how maintenance and operational hazards have been considered and designed out as far as is reasonably practicable. Low cost and low impact solutions will often require reduced capital works but greater maintenance throughout the life of the development; this is a common design approach for coastal infrastructure in particular as design for no-damage is often overly-onerous especially for rock structures or beach recharge schemes.

Nevertheless, as far as practicable, all designs should consider the need for maintenance and design out elements or components that introduce high-cost or difficult maintenance requirements. Examples of low-maintenance design include:

- Careful consideration of foundation and underlayer rock grading such to avoid the need for geotextile.
- Use of mass concrete, as opposed to reinforced concrete, solutions to avoid issues of corrosion and subsequent spalling/cracking/etc. Note that this may increase material requirements but in the long run can sometimes represent the most sustainable option.
- Avoidance of high-maintenance elements such as gabions or many steel solutions.
- Protection of vulnerable elements of a development, such as:

  - the separation of vegetated areas from regular footfall.
  - the protection of elements from loads to which they are not designed such as restriction of pedestrian access ramps from vehicular traffic.
- The use of nature-based solutions, or hybrid solutions, many of which have the potential for self-repair.

For all remaining elements, maintenance should be explicitly designed for. Examples of such considerations include:

- Inclusion of safe access for inspections and maintenance works – for both existing and new assets.
- Consideration of the replaceability or repairability of components with a design life lower than that of the wider development.
- Design of elements such that they are suitable to accommodate maintenance works that may be more onerous than typical operational conditions.

Maintenance requirements should be formally captured by the designer and communicated to the developer via management and maintenance plans and supported by proper record keeping such that any future works may understand as-built conditions and design assumptions. The DHEMR, mentioned in Sections 5.3 and 6.3, should also capture hazards relevant to the operation, maintenance, and demolition of a development.

7.3 Structural performance monitoring and maintenance

Assets should be regularly, methodically, and proactively monitored throughout its lifetime to inform an active maintenance regime. This becomes increasingly important as assets approach their end of life. A monitoring regime will provide the opportunity for early identification of defects that may have an impact on performance and longevity thereby providing an opportunity for early repair.

Regular maintenance is typically the most cost-effective approach, even before considering the benefits relating to risk mitigation and confidence in performance. The cost of repairs typically increases with the severity of the defect; therefore, early repairs can be simple and avoid the need for complex works that may also lead to disruptions and temporary operational closures. Such an approach can also be advantageous from the perspective of cash flow as it will normally be easier to allocate small, regular maintenance budgets than those required for less frequent but significant works.

A useful external reference providing guidance on inspection and condition assessments of flood and erosion coastal infrastructure includes the Condition Assessment Manual and associated appendices issued by the UK Environment Agency (Environment Agency, 2006). Useful references for management of maritime infrastructure include:

- Report N° 103, Life cycle management of port structures – Recommended practice for implementation (PIANC, 2008).
- Report N° 153, Recommendations for the design and assessment of marine oil and petrochemical terminals (PIANC, 2016).

Techniques to capture, record, and manipulate asset information are rapidly changing with some innovative techniques now common practice in some parts of the world (such as the use of drones). Developers should consider the best way to manage their assets effectively and efficiently. Common challenges include:

- The need to effectively capture findings in a consistent manner throughout the lifetime of the assets to facilitate an understanding of asset degradation and to manage the impact of subjectivity in assessments.

- Changes to data collection methods and the ability to take advantage of new technologies.
- Potential changes to best practice especially in terms of digital collection and management.

7.4 Demolition

Demolition works should be undertaken with as much of an understanding of the structures and site conditions as possible. For this reason, proper record for the complete lifetime of a development is important. While residual risks relevant to demolition should be captured in the DHEMR and on drawings, it should be noted that these will have been initially prepared during the design phase. Therefore, the site may have undergone subsequent changes which may introduce new risks; such changes should be properly captured and recorded but Contractors involved in demolition works and the developer should be aware that this is commonly not done. Therefore, depending on the nature of the demolition works, additional surveys may be required, for instance to identify the location of recently installed buried assets. The health and safety files should be the first point of reference when considering the demolition of a structures as this should be kept up t date with and changes to the structure or development site, to inform future works.

Generally, however, requirements for demolition works will not be significantly different from those of construction as described in Section 6. This is true for both partial and complete demolition although considerations often of increased importance include the protection of existing assets, proper capture and disposal of waste, and the reuse of materials.

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