2 Planning and designing rock works

CHAPTER 2 CONTENTS

2 Planning and designing rock works

Chapter 2 provides an overview of the design process and project considerations. General principles for rock works, applicable throughout the manual, are included here.

Key inputs from other chapters

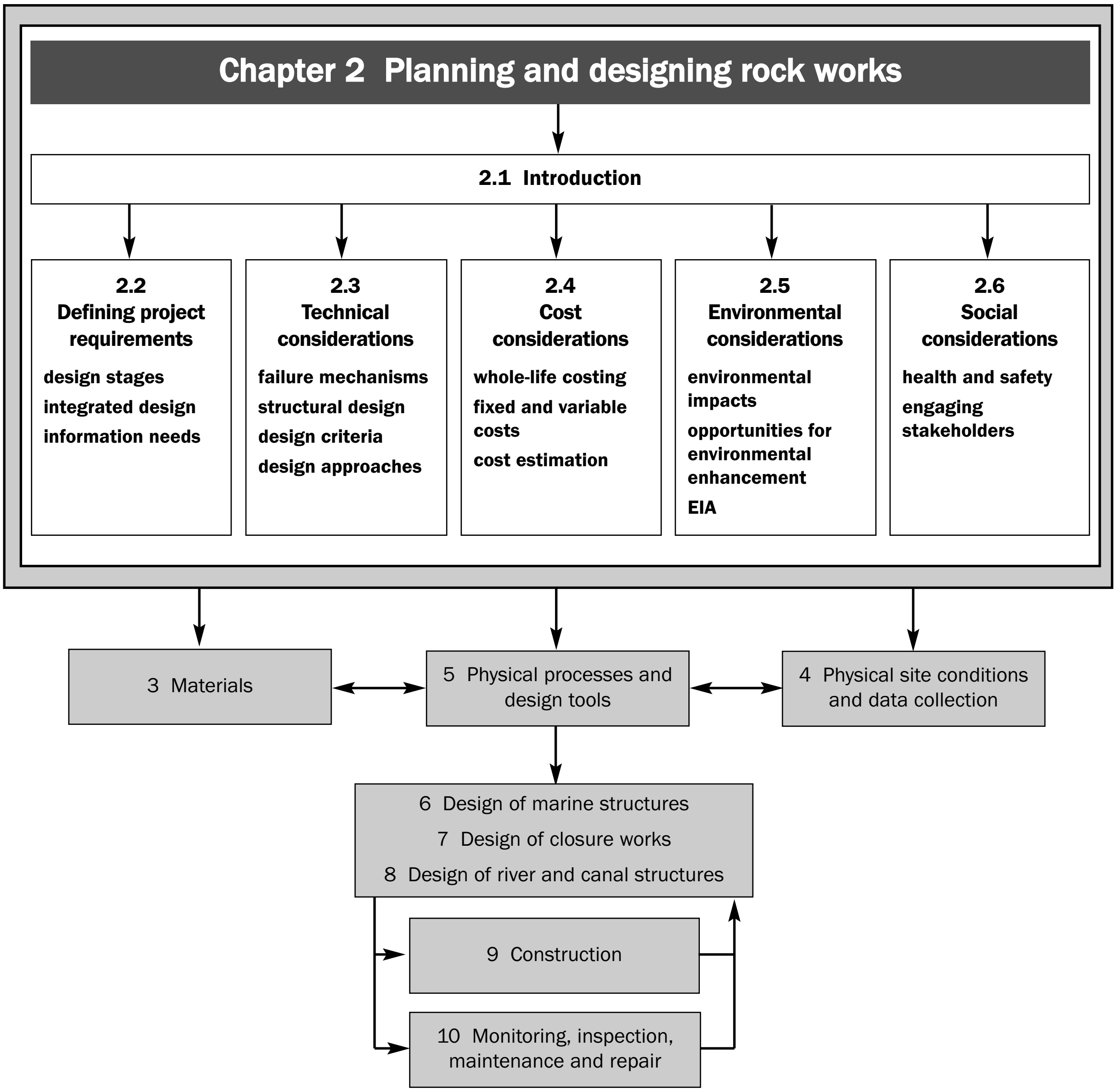
- **starting point** ⇨ for a rock project.

Key outputs to other chapters

- **project requirements** – environment, cost, technical issues and functional requirements ⇨ all chapters.

NOTE: The project process is **iterative**. The reader should **revisit Chapter 2** throughout the project life cycle for a reminder of important issues.

This flow chart shows where to find information in the chapter and how it links to other chapters. Use it in combination with the contents page and the index to navigate the manual.



2.1 INTRODUCTION

All users of the manual are recommended to read this chapter before continuing to subsequent chapters, as it provides an overview of key issues to be considered throughout project development.

Chapter 2 emphasises the need to consider the whole life cycle of works from conception to decommissioning (if appropriate) when planning and designing rock structures. Technical aspects should be integrated together with social, environmental, economic and other factors. The chapter introduces general issues that should be considered for the rock structures discussed in this manual. The information in this chapter is at a high level and cross-refers to other sections of the manual that provide more detailed information.

The chapter aims to raise general questions that the designer should be asking, for example:

- what does the structure need to achieve?
- what does the designer need to know?
- what are the potential problems and/or constraints?
- how should the designer approach the problem and develop solutions?

A *project* generally begins long before the conceptual design of any works is undertaken. The need for particular works is usually established by feasibility studies that should have considered factors such as economic justification and the project's physical, social and environmental impacts. These studies – which may be extensive – are often essential to determine the viability and acceptability of the project. The subsequent input invested in the design of the works can sometimes be small by comparison. Feasibility studies or wider strategic planning prior to a scheme are beyond the scope of this manual.

This chapter, and the rest of the manual, assumes that the need for works that involve the use of quarried rock has already been demonstrated and that alternative options have been shown to be less suitable or less preferred. The guidance may be helpful when reaching that decision during any pre-design/planning assessments. Consequently, references to *the project* throughout the manual apply only to the activities associated with the rock works.

NOTE: The principles described in this chapter apply to the whole planning and design process and indeed to any stage in the asset life cycle. Planning and design are not always restricted to project stages before work starts on new structures. There is increasingly a need to maintain, repair, modify or upgrade existing structures, and these activities also require planning and design. The asset management life cycle is illustrated in Figure 2.1.

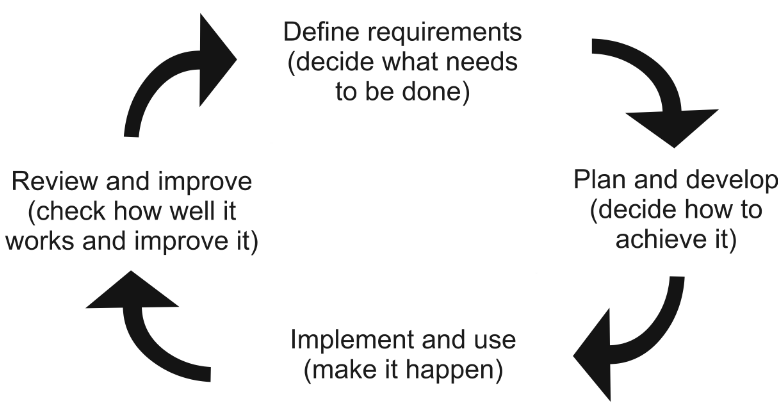


Figure 2.1 *The asset management cycle*

2.2 DEFINING PROJECT REQUIREMENTS

2.2.1 The design process

2.2.1.1 Stages in the life of the works

During the life of any works there are several typical stages where the design of works needs to be considered:

- project definition
- concept design
- preliminary (or outline) design
- detailed design
- construction including working drawings and works preparation
- operation, including monitoring, maintenance, repair and upgrading, if required
- decommissioning, including removal where applicable.

All projects start with a need: something that is desired, required or lacking – the lack of shelter in a harbour, for example. The **project definition** stage defines this need by setting project objectives, typically based on the project promoter's aspirations. These objectives will present requirements (ie what is stipulated) and restrictions (ie what is not wanted or not allowed). Clear objectives will assist in establishing the appropriate engineering solution to meet the identified need. This is the starting point for the designer.

At the **concept design** stage broad solutions are generally developed, such as typical structure types and locations, often to assess the feasibility of the scheme. One of the main activities at this point tends to be the identification of the functions, constraints and information requirements that will enable the design to go forward. Factors for consideration might include permissions needed and the physical conditions data that are required in order that the next stage of scheme development can proceed.

Preliminary design is when many of the investigation and study activities should be carried out, including determination of wave climate or current regime, environmental assessments and economic analysis. At this stage there should be greater focus upon technical feasibility. Designs are likely to be developed to a level where the main structural dimensions such as profiles, elevations and widths are quantified and the principal materials are identified. During preliminary design a number of alternative outline designs may be developed for assessment. The assessment should consider factors such as:

- practicality of the option (including construction)
- achievement of political, social and legislative conditions
- environmental impacts and optimum use of resources
- whole-life costs
- identification of risks (technical, economic and environmental)
- complexity of operation and maintenance.

This should be an interactive process, involving many parties, to gain agreement and select a preferred solution.

Once the various criteria have been satisfied, **detailed design** should involve the development of all structural elements, using further *in situ* investigation and physical and technical data, to produce drawings, specifications and bills of quantities. It may be necessary to work with other parties such as environmental and planning authorities in the design, before approvals to proceed with construction are granted.

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During the **construction** stage further detailed working drawings are prepared and further design modifications may be necessary as a result of on-site difficulties such as unforeseen ground conditions or changes in working approaches. Where this happens, the designer should ensure that the original design concepts are fully understood and the design changes do not compromise any other aspect of structure performance.

In the **operational** stage the continued performance of the structure is ensured by implementing a monitoring and maintenance programme. This may identify the need for repair works. A change in use of a facility may mean that modification or upgrading works are required to ensure that the structure delivers the required performance. These changes need to be made with an understanding of the original structure design and the consequences need to be fully determined.

If a structure has to be **removed**, it is important to understand the original design as well as any subsequent modifications to allow **decommissioning** with minimum health and safety risk, and also to allow the environmental impact(s) of the decommissioning to be understood.

2.2.1.2 Working at different scales

Satisfying needs and wishes, solving problems and developing solutions usually take place at three levels:

- macro-scale: the system (in this case, typically the structure or structures, where a number of structures are required to work together, such as in a groyne system)
- meso-scale: the components of the system (including the components within the structure, such as the armour layer or toe, and the zone of influence such as the ground affected by the structure)
- micro-scale: individual elements (armour stones, concrete blocks, sheet piles, capping beams).

In general, the designer is involved in all three levels.

2.2.1.3 Degrees of specification

The design process exists as a number of design cycles, increasing in level of detail:

1. A first cycle maps out clearly the **objectives** of the project – the need or wish that must be fulfilled – for example, provision of a sheltered harbour or protection of riverbanks against erosion.
2. A second cycle yields quantitative and measurable **functions** or performance requirements, which describe unambiguously what has to be achieved in order to reach a certain goal – eg protection against waves of 3 m height or a water velocity of 4 m/s in a river.
3. A third cycle results in the main form and features or **shape** of the structures – such as a curved, trapezoidal breakwater or groynes or dikes in a river.
4. A fourth cycle results in **specifications**, how the structure shall be built – eg materials, dimensions and tolerances.

2.2.1.4 *Factors to be considered for an integrated design*

All structures are designed to fulfil a specified purpose or purposes – the **functional requirements**, sometimes called **performance requirements**. In addition to these there will be other criteria that the structure will have to meet, which may impose additional design constraints. These can be categorised as:

- technical considerations – physical conditions, engineering, construction, maintenance (Section 2.3)
- economic considerations – capital and maintenance costs, benefits, whole-life costs (Section 2.4)
- environmental considerations – impacts on the natural environment (Section 2.5)
- social considerations – impacts on the human environment comprising the workforce, stakeholders, general public etc (Section 2.6).

These considerations and typical factors under each heading are given in Table 2.1 and are discussed further in the sections of this chapter indicated above. It should be noted that this list is not exhaustive and each project may generate specific issues that need to be considered. Table 2.1 provides cross-references to the sections of this manual where detailed guidance is provided.

All of the factors listed in Table 2.1 may influence the design, although not all of these will be known at the outset of a project. Consequently, the design process is an iterative one.

Table 2.1 *Planning and design considerations*

	Aspect	Considerations	Section
Technical considerations	Functional requirements (performance)	• Achievement of functional requirements (eg limiting overtopping, reducing wave activity in a harbour, preventing riverbank erosion) • Acceptable structural stability and residual risk of failure (factors of safety and choice of design conditions) • Changes in acceptable probability of failure over time • Adaptability (for example, change of use of the structure over time) • In-service health and safety requirements	Section 2.3
Technical considerations	Physical conditions	• Geotechnical ground conditions • Topographic and bathymetric conditions • Hydraulic forces – waves, currents, water levels, flows, ice • Morphological changes • Sediment load and movement • Uncertainties in physical conditions (confidence limits)	Chapter 4
Technical considerations	Technical data	• Material properties (eg armourstone grading), quality, durability and availability • Accuracy of design information, parameters and analytical methods • Structure-specific design methods • Nature of failure (progressive or instantaneous, complete or partial)	Chapter 3 Chapter 5 Chapters 6,7,8
Technical considerations	Construction	• Buildability • Contractor experience and resources • Health and safety issues • Conditions during construction (eg storm or flood frequency and magnitude) • Access of construction plant • Construction materials – properties and quality • Alternative material availability (sources) • Site area for storage of materials and operations	Chapter 9
Technical considerations	Maintenance	• Characteristics of structure response • Frequency and type of intervention • Availability of suitable resources for repair (materials, plant, expertise) • Funding • Accessibility for construction plant	Chapter 10
	Economics	• Derivation of alternatives • Benefit *vs* cost (the balance between full or limited achievement of functional requirements for higher or lower cost) • Acceptable operational risk • Capital cost constraints • Potential maintenance costs	Section 2.4
	Environment	• Accommodating environmental requirements • Preserving resources (water, rock etc) • Potential environmental impacts of construction • Risk of vandalism • Potential environmental benefits of scheme • Morphological and sedimentological impacts • Acceptability of physical appearance	Section 2.5
	Social considerations	• Health and safety • Construction and operation • Stakeholder participation	Section 2.6

The outcome of a successful integrated design should be a structure (eg a revetment, bank protection, closure or breakwater) that delivers the required performance and which is robust, easy to build and maintain, socially and aesthetically acceptable, cost-effective and produces the fewest negative impacts on its environment.

In practice, any project will have to achieve an appropriate balance between all of these requirements. Project economics generally aim to balance the **value** of the project, mainly dictated by functional performance and the impact on the environment, and **cost**, dictated by technical or engineering aspects and by construction. The level of attention paid to these aspects changes over the course of the design. For example, attention to functional performance (and hence value) decreases at later stages, whereas attention to construction (and hence costs) increases.

The planning and design of a structure should take into account all future life stages of the works, including construction, operation and, if appropriate, decommissioning. Changes to conditions or functional requirements within the projected life of the structure should also be considered. Where appropriate, the structure and its planned maintenance should be designed to allow some adaptability to cope with changes in the environment or in functional requirements during the lifetime of the structure. This might include a change of use for the structure, altered wave conditions, rising water levels, variations in scour or sedimentation rates, increased traffic, and changes in the availability of local materials and labour for maintenance etc.

2.2.2 Knowledge required for the design

2.2.2.1 Information needs

Information relating to *understanding the problem* and/or constraints upon the project would usually be provided by the client/operator and planning or regulatory authorities. Information is often very specific to project type and location. When it relates to function and expected use of the structure, information may be broadly defined. The details of performance expectations and constraints might not have been determined at the outset, however, and may need to be defined further by the designer and accepted by the client.

Table 2.1 identified the main design aspects that should be considered. Information will be required on all these aspects to develop an appropriate design, in particular:

- functional requirements
- physical conditions
- technical data (including construction and maintenance requirements)
- economic considerations (including acceptable operational risks)
- environmental conditions and requirements.

Project constraints also dictate aspects of the design. Typical examples might be:

- level of exposure to hydraulic loads at the site that may preclude or dictate the use of certain materials or construction techniques
- ground conditions, such as soft silts that may need to be removed as part of the construction process
- lack of availability of certain materials or plant, which could influence the form and structure of the works
- nature conservation or other environmental interests that may influence the type of construction or maintenance operations possible, or the footprint of the structure itself
- visual intrusiveness, precluding the building of a certain type of structure or restricting it to a certain maximum elevation
- financial balance between the budget available for construction and that for maintenance.

Ultimately it is the designer's responsibility to obtain as much detail as possible on these issues. This information can be used to develop solutions that address the needs, constraints and preferences that exist throughout the life of the project. The available information and knowledge will vary throughout the development of the works and the design should be re-evaluated accordingly as this occurs.

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2.2.2.2 Functional requirements

With any project it is important to have a full understanding of the functions that the structure should fulfil, particular problem(s) that need to be resolved and the requirements for the solution. Performance expectations should be clearly defined at the outset with the client/operator, as problems may arise if each party has different expectations when a design proceeds. Before embarking upon the design, maintenance or rehabilitation of a structure the following questions should be asked:

- what is this structure being designed or maintained to do?
- what are the design performance requirements?

Although these questions seem obvious, they are not always addressed. It is good practice to produce a set of functional requirements for the structure that can be agreed upon and used as design criteria.

As an example, for a port breakwater the following key considerations all have an influence upon the structural design:

- the purpose of the structure
- the use of the facility and the extent of protection required – for example, different levels of protection are advocated for ports, fishing harbours and small boat marinas
- layout of the facility – for example, whether the area directly behind the breakwater is to be used for berthing or storage, or whether access along the breakwater is required
- acceptable downtime – for example, tolerable frequency of exceedance of the above conditions, downtime for operations, offloading of vessels etc
- design life of the facility – not necessarily the same as the return period of the design parameters
- acceptable risks during the structure lifetime, which should influence the choice of design parameters
- level of maintenance and ease of operations or availability of material or plant – inherent damage allowances within designs should be identified and minimised if this is an issue.

2.2.2.3 Physical conditions

Physical conditions are generally the primary determinant in the design and construction of a rock structure. They include hydraulic loading parameters that influence the form of the structure in terms of plan shape, height, profile, width and material composition, and how it is built. Project cost uncertainty can be controlled by increasing understanding of the physical conditions. This may be by investing in data collection on, for example, wave or foundation conditions. The extra effort needed to gather this knowledge is often a small fraction of the cost saving that can be achieved.

Physical site conditions of principal interest include bathymetry, topography and morphology, geotechnical conditions (foundation soil characteristics and pore water pressures), hydraulic conditions (water levels, winds, waves, currents) and other potential loads such as ice or ship collision. Chapter 4 provides details on these information requirements and methods of derivation for environmental loading parameters, for example numerical modelling of waves and water levels. It also discusses how to derive combinations of physical site conditions to be used in design, both for normal service conditions and for extreme conditions. Access to the site for construction and maintenance purposes should also be taken into account.

In terms of whole-life asset management and the possible need to modify the structure in the future, attention should also be paid to monitoring (see Section 10.3). The measurement may be of changes to the structure itself, achievement of performance criteria, and/or impacts upon the surrounding area.

2.2.2.4 Technical considerations

Technical considerations relate to both design and construction. For design, these include selection of an appropriate design approach and tools. It is important to understand how a structure behaves and the function of the various component parts of the structure. These are discussed in Section 2.3, which contains an overview of the technical aspects of design development, primarily focusing on technical principles. More details about the design tools are given in Chapter 5. Design guidance for different structure types is covered in Chapters 6, 7 and 8.

Construction and maintenance considerations usually act as boundary conditions to the solution rather than to the problem and so become part of the iterative design process. Where information is available on the quality of available materials or local constraints on particular working methods, this can be key to defining the solution (see Box 2.1).

Box 2.1 *Key construction considerations for rock solutions*

Essential construction considerations to plan and develop a rock solution include the following:

- **Availability of materials**. In particular, this may influence the choice of armouring (eg armourstone, concrete armour units or other alternatives) and the shape of the structure (such as the adoption of shallower slopes or berm breakwater profile).
- **Local construction resources**. If the quality of construction is questionable, make due allowances in design sizing and tolerances.
- **Best use of materials**. The exact dimensions of a breakwater should ideally be proportioned to optimise the use of the quarry yield, for example gradings designed to use the quarry's whole production. Consider tailoring the design to suit local availability of material.
- **Type of plant**. Consider the maximum reach of plant, particularly in placing large armour units. For example, construction of a breakwater from a barge can take twice as long as construction from the crest, but the latter requires ample working space on the crest.
- **Movement of plant**. For example, consider whether there is sufficient crest width at a construction level above water level to enable plant movement, material supply, crane manoeuvrability, inclusion of passing places as features in final construction.
- **Uncomplicated details**. Strive for simplicity in terms of stone layers etc; keep the number of different construction activities to a minimum.

Construction issues should not compromise or dictate the solution, but they should play a major part in determining the design. Account should be taken of the likely construction method, as invariably the simpler the method, the faster and cheaper the structure can be built, even though it may require more material. This is even more important where the structure forms only one component of a larger development, for example a port breakwater that is required for protection to allow other construction activities to start safely. However, it can be difficult to convince a client or operator that the smallest material volume may not equal the lowest cost. In some circumstances it may be appropriate to design and tender two alternatives, one reflecting lowest volume and the other the simplest construction solution.

Future maintenance requirements form an important element in the planning and design of any rock structure. The designer needs to consider similar issues to those of construction, but should recognise that maintenance matters may be more challenging. For example, access along a structure and the suitability of plant are likely to be of greater significance for maintenance than construction. Activities may be limited by constraints that did not exist during construction, such as the need to avoid disrupting operations or endangering life through a temporary reduction in the standard of protection usually afforded by the structure.

More details on construction, monitoring and maintenance of structures are provided in Chapters 9 and 10.

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2.2.2.5 Economic information

The cost of a project is always a major consideration during design and is affected by many of the factors listed in Table 2.1. Generally only a few of these – usually relating to either material volume or constructability – have a major influence. Other costs may be relatively minor, but should still be considered.

The availability and sources of funds are important. Publicly funded projects may need to satisfy economic criteria, perhaps progressing in stages as criteria are met at each stage.

The client/operator may not at the outset recognise all the economic consequences of performance and level of risk over time (see Section 2.3.3.2). An option may be a structure with a lower initial cost but a higher risk of damage during its operational life. This choice may be acceptable where capital outlay is constrained, but the client should be aware that higher maintenance costs are possible. If so, there should be a degree of certainty that an adequate maintenance budget will be available in the future. Other criteria, such as requirements for public safety or safe working conditions, also need to be established.

Section 2.4 provides detail on the cost considerations of a rock project.

2.2.2.6 Environmental information

The designer, supplier, contractor and operator need to be aware of the environmental implications of using rock in hydraulic engineering. Consideration of environmental issues should normally begin at the definition stage of a project and should continue to be looked at regularly throughout the course of the project. These issues will relate to the works themselves, such as the materials and the methods of construction, and to the impacts of the works. The environment includes the physical surroundings, natural habitats and species, and human/ social activities. The use of resources, pollution of air, water or land, and adverse effects on habitats, flora and fauna by construction-related activities are all examples of environmental impacts. The use of rock may also provide opportunities for environmental enhancement, such as its beneficial use where rock is a by-product of other activities or recycled from previous works, or even the creation of new habitats.

Many environmental considerations are site-specific, relating to local regulations and local features. An environmental assessment might have to be conducted for the project. The assessment procedure is outside the scope of this manual, but it needs to be understood by those involved in the planning and design of a project.

Complying with environmental requirements, which often are driven by legislation or planning policy, can be time-consuming, requiring comprehensive studies and provision of mitigation measures. Planning permissions and licences may have to be obtained from a range of organisations and consultations may be needed. It is important, therefore, that developers, designers and contractors engage with the appropriate authorities as early as possible during the project to ensure the process runs smoothly.

Environmental requirements vary significantly between countries and types of works, so they cannot all be discussed within this manual. However, throughout much of the world some form of environmental impact assessment (EIA) is normally a prerequisite to a scheme being accepted. Section 2.5 presents the general principles of EIAs and discusses specific issues for rock structures.

Methods of construction and working practices may be dictated by environmental and social impacts, greatly affecting the cost of a structure. For example, the stockpiling of rock may be restricted, the ability to transport material by road may be prohibited or it may be critical to prevent losses of fines into the air or water during placement of quarried rock.

Environmental considerations also include the sustainability of material selection, which requires:

- efficient use of materials
- waste minimisation
- recycling of waste.

These factors may be critical to the design, either through using the full quarry production to minimise waste and by-products, using recycled materials, or ensuring the materials can be recovered and reused in the future. Social aspects, such as health and safety of construction workers and stakeholder consultation, are also relevant. A brief discussion on these issues is given in Section 2.6.

Environmental and social aspects should be considered for the whole life cycle of a structure – including operation, maintenance and decommissioning – not just its design.

Sections 2.5 and 2.6 provide more detail on environmental and social considerations.

2.3 TECHNICAL CONSIDERATIONS

The section will help the user to understand how rock structures perform as well as how to design and build them effectively. The information presented here is generic to any type of rock structure. The reader should refer to Chapters 6, 7 and 8 for details of the different structure types and discussion on their design. Supporting those chapters, the tools that are used to develop designs are presented in detail in Chapter 5.

2.3.1 Rock systems and responses

This section describes the general principles of rock systems and their responses.

A rock system is schematised with its hydraulic and structural responses in Figure 2.2. Design methods based on these responses are presented in Chapter 5.

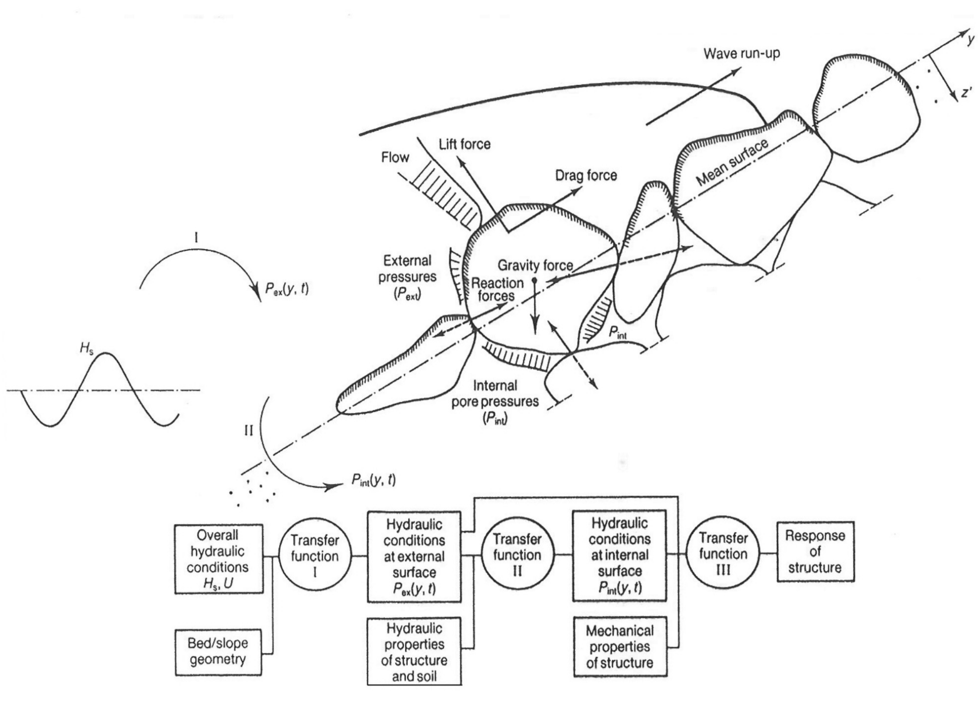

Figure 2.2 *A rock system and its responses to hydraulic loading (waves)*

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A range of scenarios should be considered in the design of hydraulic structures, including those related to normal functioning of the structure in service and also to ultimate or accidental situations. Some degradation or even failure of the structure or elements of the structure may occur as a result of the loadings generated in these situations.

Failure occurs when the response exceeds a value of performance that relates to the structure's functional requirements. Failure is a response that corresponds to a defined loading (the failure loading) for a given design scenario. In general, failure mechanisms are named after their consequent displacements or movements. Failure is thus characterised by a relatively large increase in response that is generated by a minor increase in loading. An overview of the principal failure mechanisms for rock structures and corresponding loadings is given in Figure 2.3.

Each of the failure modes shown in Figure 2.3 should be considered in the design of rock structures, although the degree to which these are relevant will vary for different structures, locations and design scenarios. Some failure modes can be allowed to occur repeatedly up to a certain limit during normal service life, for example overtopping up to an acceptable threshold or displacement of stones on a dynamically stable slope. Other failure modes, such as ship collision or ice loading in normally mild regions, are rarer events that may be considered as ultimate design scenarios. For some failure modes not even a single occurrence can be accepted, such as liquefaction of the subsoil under a breakwater.

In general, very limited damage to the structure is accepted for normal service design scenarios, as the structure is expected to fulfil its functional requirements. For rarer types of event, such as ultimate or accidental situations, some level of damage of the structure or some under-performance may be accepted, as it is usually not cost-effective to design for no damage under extreme conditions. The designer should identify a range of normal service and ultimate design scenarios and evaluate the potential degradation or failure that each one may induce, so they can be compared with defined acceptable levels of performance, ie limited degradation or some degradation. The client may need to confirm selected acceptable levels of performance. Further discussion on acceptable risk levels and selection of design conditions is given in Section 2.3.3. The use of the above approach is fully developed for geotechnical verification of the structure in Section 5.4.

It should be noted that often these failure modes are interrelated: for example, settlement of the structure may lead to increased overtopping, which may cause instability of the inner (rear-side) slope of the structure. Table 2.2 presents a summary of the key failure mechanisms and their characteristic parameters and notes some of the interactions between failure modes, with cross-reference to Figure 2.3. Further discussion on failure mechanisms is given below.

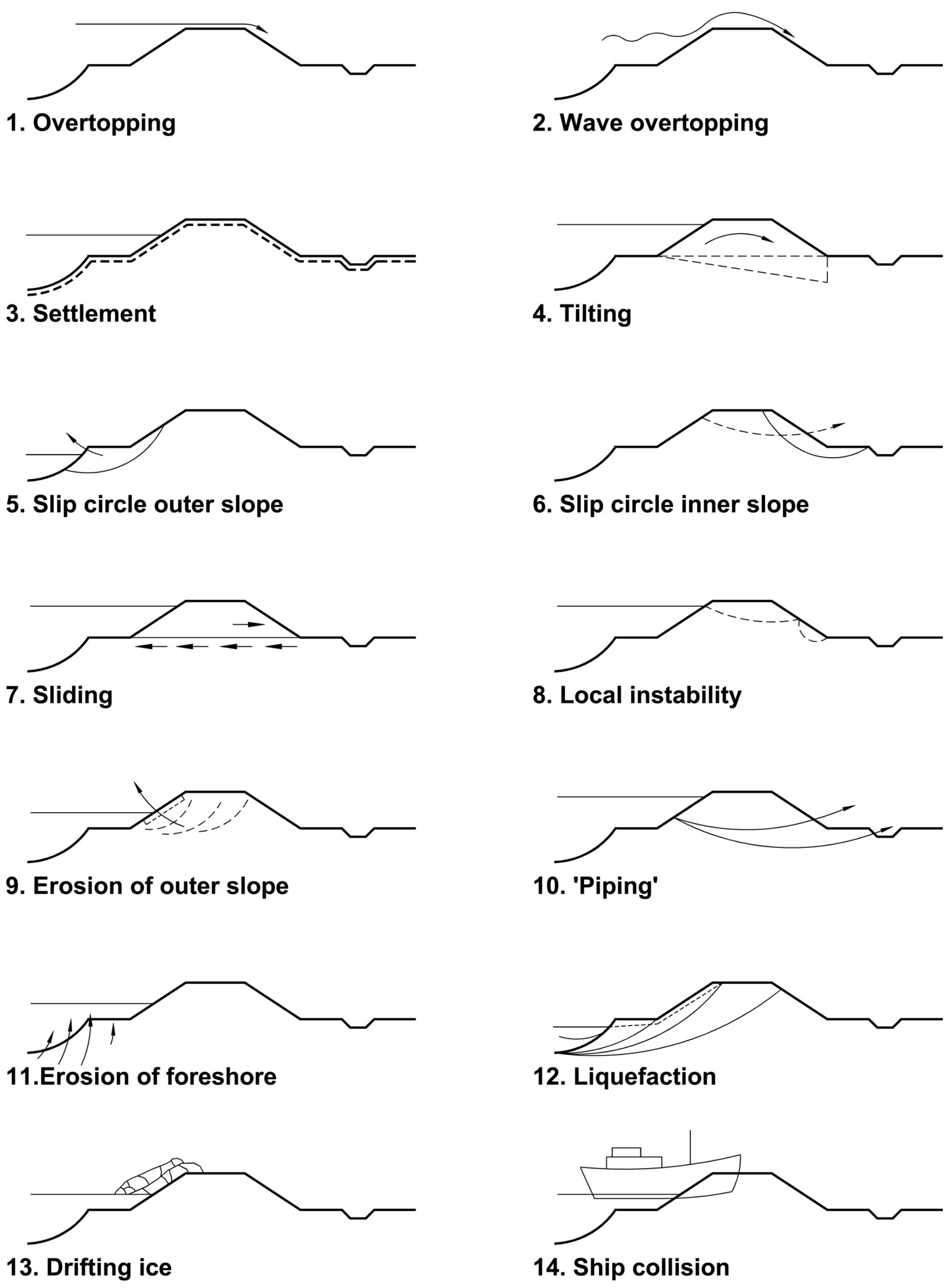

Figure 2.3 *Typical failure modes of rock structures*

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Table 2.2 *Main failure mechanisms and characteristic parameters*

Mechanism	Principal loading parameters	System characteristics	Response characteristics	Ref in Fig 2.3
Overtopping	*Waves* – height, period *Water levels*	Crest level; slope angle roughness and energy dissipation characteristics of outer face and crest	Damage to crest and rear-side slope; undesired water discharge to the rear side	1, 2
Settlement, tilting	*Weight* – specific density of materials; saturation degree; pore water pressure; time	Soil compressibility; soil permeability; layer thicknesses	Crest lowering; horizontal deformations; increased overtopping; increased loading in structure (eg caisson)	3, 4
Slope instability	*Water levels* – differential water levels *Waves* – weight of construction materials; pore pressures; slope angle	Internal friction angle of material	Rotational failure of slope	5, 6
Sliding of structure	*Weight of structure or elements* – weight of construction materials; pore water pressures (influenced by wave height and period); slope angle	Friction angle (between layers); cohesion and permeability of soil, core and cover layer(s)	Sliding of (a significant part of) the structure; collapse (may also take place at the base of a caisson)	7
Movement of rock cover	*Waves* – height, period, angle of incidence *Currents* – turbulence, velocities *Ice* – layer thickness and drift intensity	Stone size and density; permeability of the cover layer	Rocking; sliding; lifting; rolling; loss of armour units leading to erosion of front face and local instability (may induce stone breakage)	8, 9
Migration of sub-layers	*Water level changes* – waves, ship-induced water movements, other dropping water levels; hydraulic gradients; internal flow velocities	Layer permeabilities and thicknesses; grain sizes	Internal material transport rate; local instability or deformation	8, 9
Piping	*Hydraulic gradients* – internal channel flow velocities	Flow path length; hydraulic resistance; grain size	Internal material transport rate	10
Erosion of foreshore	*Waves* – height, period *Currents* – velocities, turbulence	Sediment grain size; structure slope; permeability of structure	Scour of sea bed in front of structure	11
Liquefaction	*Waves* – height and period *Earthquakes* – acceleration, frequency; number of loading cycles; pore water pressures; (relative) shear stress amplitude	Permeability; compaction; thickness of layers; friction angles	Serious deformation of structure; collapse	12

Overtopping

Combinations of waves and water levels or extreme water levels alone can lead to water overtopping the crest of a structure. Small volumes of overtopping water may be acceptable, but larger volumes may damage the structure crest and rear-side face or cause flooding of the hinterland, which may be classed as a failure of the structure in terms of its service requirements. The amount of acceptable overtopping will depend on the robustness of the crest of the structure and its ability to withstand high-velocity flows over the crest.

Settlement

The weight of a structure causes an extra load on the subsoil. As a result it may be compacted or squeezed, either instantaneously or, for low-permeability compressible layers, over time. A further consequence may be the collapse of underground cavities. In addition, the structure itself may become more densely packed during construction or in the first stages of its operation; this can equate to 5–10 per cent of the height for a rubble mound structure.

The above processes cause the crest level to settle, reducing the structure's effectiveness in limiting overtopping during high water levels and/or wave attack. Differential settlements produce uneven surfaces, which can make some stones more susceptible to being displaced. Differential settlements can also lead to undermining of support for crest structures. However, for submerged structures, settlement can improve armour layer stability as the structure moves farther from the zone of highest hydraulic loads.

Slope instability

Low or loss of internal friction within a rock structure can generate slip failures. Where the structure slope angle is close to the angle of repose, small changes in loading may also induce slope instability. Erosion of the foreshore may lead to slope instability if scour damages or undermines the toe of the slope.

Instability can also be caused by wave action or rapid changes in water level, for example when tide levels fall and the internal water level in the structure lowers more slowly, as the structure is subjected to additional forces. Overtopping may contribute to slope instability on the inner (rear-side) face of the structure because of the additional hydraulic loading on the crest.

Sliding of (parts of) structure

The stability of a rock slope is determined by slope angle, specific weight, pore pressures caused by water level differences and wave motion, internal friction and interlocking. Also of importance are horizontal accelerations, which may arise during earthquakes or wave shock loading, for example. Sliding is also more likely along interfaces between different materials, for example armour and underlayer, because the local friction here is reduced, or indeed where other materials are incorporated, such as geotextiles or membranes.

The subsoil plays a part in supporting the structure and can lead to excess pore pressures in the structure and in the foundation. Liquefaction in any fine layers beneath rock structures may be important for toe stability and slope support. Excess pore water pressures also have to be considered when the stability of the slope is calculated, for example where the water level drops more rapidly than the groundwater, which is common in tidal conditions.

Crest structures – usually concrete walls – may move, typically by sliding, under wave loading, so adequate friction between the structure and the underlying rock is critical for stability.

Movement of rock cover

Waves and currents determine the lift and drag forces acting on the stones in the cover layer. The inertial forces are also determined by the stone characteristics. The stone weight and forces due to friction and interlocking are stabilising factors.

The dynamic loss of balance of all these forces may cause stone movements. Displacements are generally associated with the outer (seaward or riverside) face of structures but may also occur on the rear-side face of breakwater roundheads, the lee side of groynes and the landward side of structures as a result of excessive overtopping. These responses may be allowed for in the design, but care is needed to avoid responses large enough to initiate other degradation or failure modes such as damage to the filter layer.

Over time the materials in the structure may become susceptible to deterioration. This can take the form of degradation of the rock, including rounding of stones and reduced interlock. Breakage may occur, as wave action redistributes stones over time. This may loosen the cover layer or reduce the unit weight of the armourstone, making it more prone to failure.

In some circumstances, especially where wider gradings of smaller stone are used such as rip-rap, longshore transport of the cover stones may take place if the angle of the structure is acutely orientated to the direction of wave attack.

Migration of sub-layers

An internal flow may be established because of a difference in water level or local excess pore water pressures. When a certain critical hydraulic gradient and the corresponding flow velocities occur, the finer grains are transported out from the inner layers through the coarser material of the upper layers. Often these finer grains pass easily through the cover layer, resulting in a loss of material from the sub-layers (filter, underlayer) and/or from the core, which may ultimately lead to local settlements.

Piping

Piping refers to the formation of stable open channels in a granular skeleton created by migration of particles out of the system. These short *pipes* may connect up and thus allow progressive internal erosion, eventually causing the structure to collapse. This phenomenon is more likely to occur at structural interfaces, such as boundaries between permeable and less permeable materials, or where loosely packed and densely packed granular materials adjoin one another.

Erosion of foreshore

Waves and currents may generate sediment mobility. Interactions with the structure (wave reflection, wave draw-down, generation of turbulence) may result in scour of bed or beach materials directly in front of the toe of the structure, with the potential to cause undermining.

Liquefaction

Cyclic loadings can generate excess pore pressures when the deformations resulting from the loading cause compaction at the same time that the drainage capacity for dissipation of the resulting increases in pore pressure is low. Liquefaction refers to a situation in fine granular materials where excess pore pressures are generated to such a degree that intergranular contact is lost. The whole medium loses its shear strength and behaves like a thick fluid. Under these circumstances any shear loading may cause sliding or stability failure.

2.3.2 Structural design

2.3.2.1 Structural components

This section provides an overview of how a structure is designed and built to accommodate and counter the failure modes discussed in Section 2.3.1.

A structure comprises various components, each having a specific function critical to the structure's overall performance and adequacy. The most critical elements for rock structures are generally stability of the cover layer, a secure foundation to minimise settlement, toe protection to prevent undermining, and a suitable crest for protection. The components of any rock structure and their relative importance differ according to the structure type. These are described in more detail in Chapters 6, 7 and 8, which cover marine works, closure works and river and canal structures, respectively. For all structures, the main requirement is to understand each component's functions and its importance to the overall design. It should be noted that not all structures require all of the components in order to function properly.

The functions of component parts fall into two categories:

- functions related to the primary function of the structure
- functions related to maintaining the structural integrity of the structure.

These functions are best appreciated by an example. Figure 2.4 illustrates the key component parts of a breakwater, which are also listed in Table 2.3 along with the primary functions they perform. It can be seen that the core of a breakwater fulfils a primary function by preventing or significantly attenuating wave transmission, but it also provides support to the armour layer and overall geotechnical stability.

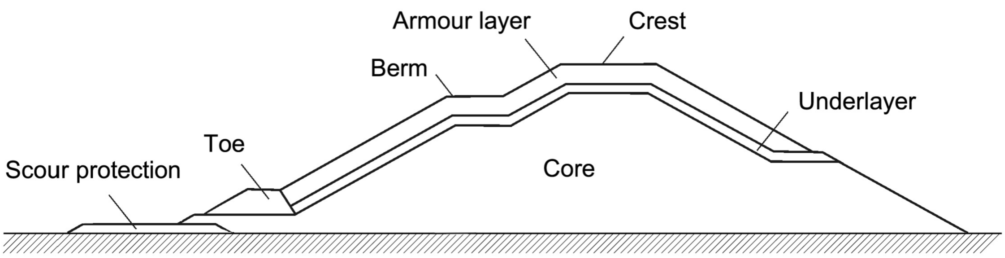

Figure 2.4 *Component parts of a typical rock structure*

Table 2.3 *Functions of typical component parts of a rock structure*

Component	Function
Scour protection	• Prevents erosion and undermining of the toe
Core	• Attenuates wave transmission • Supports armour layer and underlayers • Provides geotechnical stability
Berm	• Attenuates wave action, run-up and overtopping • Provides additional geotechnical stability
Toe	• Provides stable footing to armour layer
Underlayer	• Acts as a filter • Protects subsoil/core from erosion • Provides in-plane drainage • Regulating or levelling layer that provides appropriate surface for armour layer placement • Separates armour from smaller sized materials and reduces hydraulic gradient into subsoil/core
Armour layer	• Prevents erosion of underlayer and core by wave action • Dissipates wave energy
Crest	• Attenuates wave overtopping • Allows access for maintenance
Crown wall *(not shown in Figure 2.4)*	• Attenuates wave overtopping • Allows access for maintenance • Provides support for facilities such as cabling and pipework
Roundhead *(not shown in Figure 2.4)*	• Terminates the structure in a stable manner • Diffracts waves

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2.3.2.2 *Structure loading*

When designing a structure it is important to understand which loading cases (intensity and duration) apply to each element of the structure. For example, the design of toe or scour protection of a structure should take into account a range of water levels, in combination with waves if appropriate, to establish the critical conditions for stability. By contrast, in the design of a structure crest for satisfactory overtopping performance, the highest water levels are generally the most important. A typical example of loads and the zones of the structure where they apply is presented in Figure 2.5, illustrating a coastal structure in a tidal region. The four loading zones are defined as follows:

- Zone I – permanently submerged zone below mean low water (MLW)
- Zone II – zone between mean low water (MLW) and mean high water (MHW) with continuous low-intensity wave action
- Zone III – the zone between MHW and the design (extreme) water level, which can be heavily attacked by waves; the frequency of wave attack decreases moving further up the slope
- Zone IV – the zone above design level, which will experience wave run-up and overtopping.

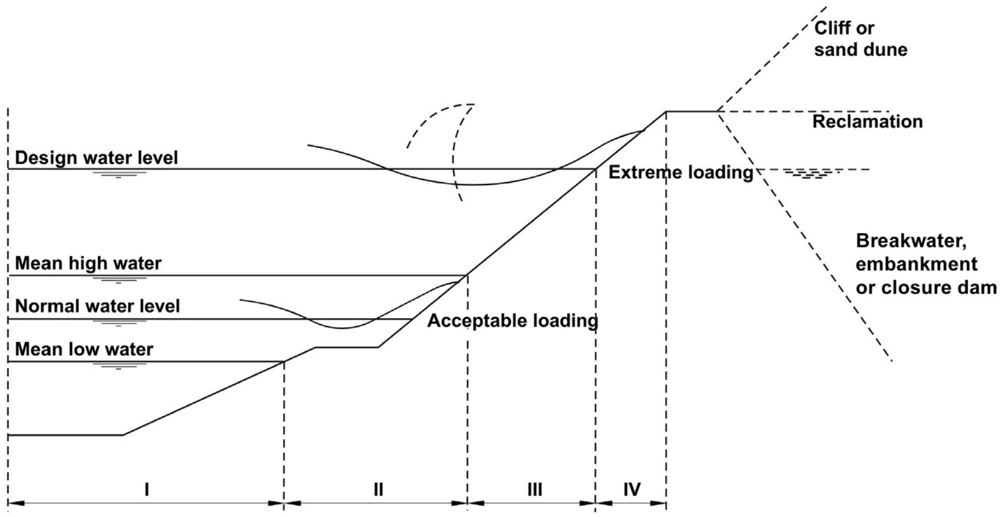

Figure 2.5 *Exposure zones for a structure exposed to waves*

Similar zones may be identified for river structures, depending on the range of expected water levels under normal and extreme conditions. These zones will be categorised in terms of flow conditions, although, where appropriate, consideration may also have to be given to ship-induced waves under various navigable conditions.

Considering a structure in terms of loading zones should ensure that it is designed against the relevant failure modes for each zone. The appropriateness of the design for each zone should also be checked, including the identification of appropriate materials, the construction and maintenance methods to be employed, the potential environmental consequences of the construction and the cost implications.

More details on hydraulic loading conditions can be found in Chapter 4.

2.3.2.3 *Analysis*

As a minimum, the design of a rock structure typically needs to include analysis and design of the following:

- armour layer (seaward/riverward face, crest, rear-side face protection)
- toe (anti-scour protection)
- underlayers and filters
- core and foundation (drainage/settlement).

The design should consider the overall plan geometry, main cross-sections, arrangements at the limits and transitions in the structure and avoidance of outflanking.

Section 3.1.2 discusses material functions and properties that are important for design, relating to the different structure components. More detail on the requirements for design of each component for specific structure types is included in Chapters 6, 7 and 8. Chapter 5 provides information on the design tools for the structural design relating to each of the above components. Typical structural analyses for different structure types are listed in Box 2.2, although it should be noted that this list is not exhaustive and other site-specific analyses may also be required.

Box 2.2 *Typical analyses required for rock structures*

Typical analysis for a structure in the **marine environment**, exposed to waves, currents and tidal water levels, should include the following:

- run-up, and overtopping of waves to define structure profile and elevation
- armour stability, to establish required material sizes and placement method for slope, toe and crest
- filter criteria calculations to design underlayers etc
- wave reflections and currents to help determine scour potential (and, occasionally, the effect on navigation or reflection performance)
- wave transmission to confirm crest elevation
- scour potential for toe design
- geotechnical stability related to pore pressures including settlement, piping etc
- slope stability and foundation stability
- flooding and rear slope integrity where breaches occur
- ship-wash, propeller cavitation and squat (where in close proximity to vessels, eg in a port or harbour).

Typical analysis for a structure in a **fluvial environment**, exposed to waves, currents and water levels, should include the following:

- range of water levels to define structure profile and elevation
- armour stability, to establish required material sizes and placement method for slope, toe and, if required, crest protection
- filter criteria calculations to design underlayers etc
- scour potential for toe design
- pore pressures for geotechnical stability, allowance for settlement
- local and global slope stability
- impact of waves if relevant (eg wind-generated waves in a flood storage reservoir, or boat wash on navigable rivers).

2.3.3 Design

2.3.3.1 *The design process*

After selecting one or more solutions that meets the functional requirements of the project (see Section 2.2.2.2), the next stage is design and detailing. Figure 1.1 (Chapter 1) summarises the project and design process and includes cross-references to relevant chapters of this manual. The design stage consists of a series of calculations, and possibly model tests, to check and adjust as necessary all details of the structure and its construction. This is often an iterative process that starts with the development and assessment of various preliminary design options, from which a preferred one is selected. This preferred option will be developed at the detailed design stage, but further alternatives may be identified as part of the process of balancing the greatest functional efficiency with the least total cost. At this stage, the alternatives are usually minor variations on the basic design option.

Early in the design process, alternative solutions should be considered. Simple methods can be used to develop these preliminary designs, but a more thorough approach is required for the detailed design stage. The hydraulic and geotechnical tools used to check and adjust the hydraulic and structural performance in the detailed design should be a combination of established theoretical and empirical approaches, along with numerical and/or physical modelling where appropriate, notably for complex or very large projects. These approaches are presented in detail within Chapters 4 and 5.

NOTE: Empirical methods do not always cover the range of situations that may be encountered – the range of applicability for any empirical method used should always be checked. Physical modelling can be useful as a way to gain more accurate measurements of stability or performance for a particular design. Such modelling may also be useful to optimise designs and can produce cost savings.

The objective of the calculations and model tests is to ensure that the final structural design meets the functional requirements, given the physical site conditions and other boundary conditions. All available information on boundary conditions should be included, particularly details of physical site conditions. Depending on the schedule, results from surveys commissioned earlier in the design process may only become available during the detailed design stage. Where possible, the preferred construction techniques for the project should also be considered, preferably in consultation with potential contractors.

2.3.3.2 *Technical design criteria*

As stated in Section 2.2.2.2, it is good practice to produce a set of functional requirements for the structure that can be agreed upon and used as design criteria. Acceptable damage levels should be properly defined before the design process proceeds. The criteria should relate to the design methods being used. For example, maximum permissible overtopping discharges should relate to a particular frequency of event occurrence and must be clearly stated.

The balance of economics and operational safety relating to performance and level of risk over time should also be calculated. It should be expressed in terms of risk of non-performance or exceedance of specified conditions. This is illustrated by Table 2.4, which presents the risk of event occurrence during the lifetime of a structure. For example, a structure built to last for 30 years (ie it has a 30-year design life) has a 45 per cent chance of being exposed to a 1 in 50-year wave condition, and a 14 per cent chance of being exposed to a 1 in 200-year wave condition. Designing to resist damage for the latter condition might be more expensive, but it will mean there is a much lower likelihood that the structure will have to be repaired during its operational lifetime.

Table 2.4 *Percentage chance of a particular return period event occurring during the design life of a structure*

Design life (years)	Event probability (per cent) for various return periods (years)								
	5	10	20	30	50	100	200	500	1000
1	20	10	5	3	2	1	< 1	< 1	< 1
2	36	19	10	7	4	2	1	< 1	< 1
3	49	27	14	10	6	3	1	< 1	< 1
5	67	41	23	16	10	5	2	1	< 1
7	79	52	30	21	13	7	3	1	1
10	89	65	40	29	18	10	5	2	1
15	96	79	54	40	26	14	7	3	1
20	99	88	64	49	33	18	10	4	2
30	> 99	96	78	64	45	26	14	6	3
50	> 99	99	92	82	64	39	22	9	4
75	> 99	> 99	98	92	78	53	31	14	7
100	> 99	> 99	99	97	87	63	39	18	10
150	> 99	> 99	> 99	99	95	78	53	26	14
200	> 99	> 99	> 99	> 99	98	87	63	33	18
300	> 99	> 99	> 99	> 99	> 99	95	78	45	26
500	> 99	> 99	> 99	> 99	> 99	99	87	63	39
1000	> 99	> 99	> 99	> 99	> 99	> 99	99	86	63

Designers should identify and calculate responses for a range of events, including conditions above and below the nominal design level, and not just for a single *design event*. This provides the necessary inputs into sensitivity analysis and/or risk analysis and into whole-life costing. For consistency in evaluation it is suggested that, as a starting point, responses are calculated for the events of the return periods given in Table 2.5.

Table 2.5 *Key events for use in project appraisal and performance evaluation*

Subject of evaluation	Event frequency and return period (years)				
	Frequent	Probable	Occasional	Remote	Improbable
Permanent structure design (lifetime 30–100 years)	0.1	1	10	100	1000
	In addition, if the structure is designed to be optimal, or if its performance is to be changed significantly, at other annual frequencies of event occurrence, information should be given and evaluation prepared for those events as well				
Design for temporary state during construction (duration: a few months or years)	0.01	0.1	1	10	100

2.3.3.3 Design approaches

A technically sound design is essential to ensure the level of stability and protection of any particular area of the structure is delivered as intended. The primary risks are either under-design, leading to potential failure, or over-design, producing a *safe* but possibly more expensive and inefficient structure than necessary. The likelihood of either of these situations arising depends to some extent upon the design approach used.

Three generic approaches to design are:

- **deterministic** – single characteristic values are used for all variables and input values, giving a single value as the output, therefore not acknowledging uncertainty in the result
- **deterministic with sensitivity analysis** – the above method is repeated with a range of input values to assess the sensitivity of the results
- **probabilistic** – input values are described by probability distributions, giving a result as a probability distribution.

Traditionally design practice has been deterministic, usually with sensitivity analysis to give confidence in the selected design. In the past there has been little comprehensive application of probabilistic approaches. This is a consequence of three factors.

1. Existing data on progressive failure mechanisms has been sparse because of the past lack of problems.
2. Structural response models (eg design equations) are largely deterministic, because they have been developed from failure criteria.
3. There is a mistrust of results and a desire on the part of those involved to ensure that any design is robust, providing a comfort factor.

While the first two points can limit the application of particular analytical methods, the last arises from not knowing enough about the actual risks inherent within a design.

There may also be an assumption in design approaches that the structure remains safely intact, providing the same level of protection until the end of its theoretical design life. In most cases this is not realistic: as structures age, the likelihood of failure usually increases. Furthermore, the uncertainties in the performance of an ageing, deteriorating structure are inevitably higher than for a new structure. A risk-based design approach allows for the changing probability of failure, which accounts for uncertainty instead of assuming that data values and prediction/design methods are known precisely. This approach can be constrained by points 1 and 2 made above, but does not necessarily require complex analysis. It can simply involve a rational assessment of potential failures employing engineering judgement. The alternative approach, which goes some way to addressing all three points, is to assess the sensitivity of failure to variation in different parameters and incorporate this into the design development. A useful tool for undertaking this type of assessment is the fragility curve approach to describing structure performance – see Box 2.3.

The design assessment should identify a range of scenarios for evaluation, taking into account loading conditions, potential for degradation, and relevant failure modes and mechanisms. In designing flood defence structures, for example, this is likely to include at least a breaching mode, and overtopping or overflow without breaching. It can prove useful to develop possible failure mechanisms in the form of *fault trees* or *event chains*. Where more than one mechanism may lead to failure, these should be analysed separately to establish their relative likelihood and importance. If necessary, they should be combined to determine the overall probability of failure; the *strength* of the structure is equal to the weakest failure mechanism.

Particular attention should be paid to unusual structures and features for which typical failure mechanisms may not be applicable. The question to ask is "what mechanism or sequence of events could result in degradation or failure?".

Further details on probabilistic design methods can be found in Vrijling (2001), Schiereck (2001), Mockett and Simm (2002), Oumeraci *et al* (2001), Van Gelder (2000). Also see the website of the Joint Committee on Structural Safety, <www.jcss.ethz.ch/>.

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Box 2.3 *Fragility curves*

Calculations of structural response for loading events of the return periods in Table 2.5 allow derivation of the probability of failure for that event. Failure can be described as the situation where the reliability, Z, becomes negative, when the relevant design equations or model is expressed in the general form:

$$Z \text{ (reliability)} = R \text{ (strength)} - S \text{ (loading)} \tag{2.1}$$

where R represents the characteristic *strength* of the structure and S represents the characteristic magnitude of the loading.

Monte Carlo simulation based on the reliability function given in Equation 2.1 can be used to derive the probability of failure. The values for probability of failure (or probability that Z is negative) can be expressed in the form of a fragility curve. A fragility curve (see example in Figure 2.6) expresses the probability of a failure response, Di, with respect to failure mode, i, $P(Di|x)$, conditional upon the given loading condition, x.

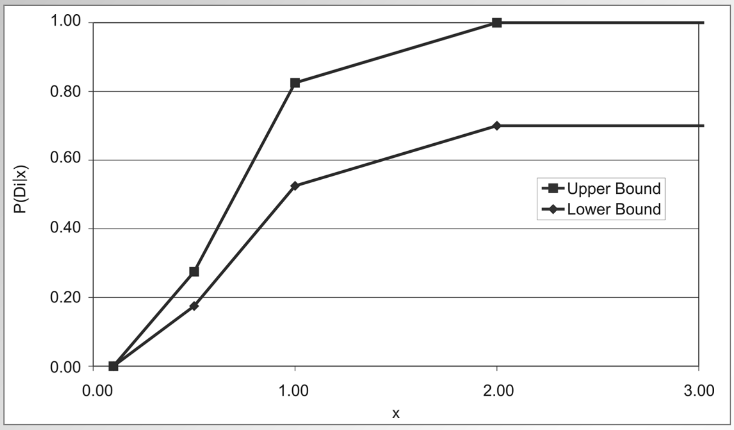

Figure 2.6 *Example fragility curve*

To identify which responses should be calculated, reference should be made to the design objectives and the models described in Chapter 5. Typically it will be necessary to calculate the probability of a relevant hydraulic response (eg maximum desirable overtopping rate) and a relevant structural response. The hydraulic response may need to be calculated taking account of the probability of a particular structural response occurring (eg crest lowering.) The fragility curve can be converted into a performance curve in which the horizontal axis is the probability of the loading event and the vertical axis represents the probability of a failure response, $P(Di|x)$ (see Figure 2.7). The area under this curve is the annual probability of failure, a very useful number, which can be incorporated directly into whole-life cost analysis.

Further discussion on the use of fragility curves is given in Dawson and Hall (2001) and Buijs *et al* (2005).

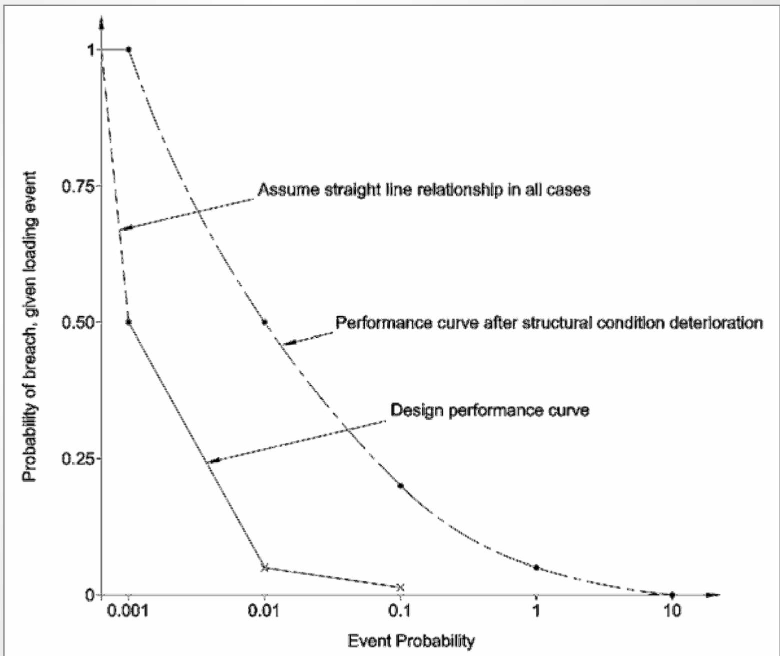

Figure 2.7 *Example performance curve for a rock structure*

2.4 COST CONSIDERATIONS

It is essential to have a good understanding of the project costs throughout the life cycle. There are various methods and requirements for determining costs, many being specific to particular countries or the structure's function.

2.4.1 Whole-life costing

As for all projects, a fundamental principle in the design of rock structures in hydraulic engineering is minimisation of total cost over the life cycle within the limits of the functional requirements and boundary conditions, including its construction and its eventual removal or replacement. It includes the costs of maintaining and operating the structure. It may also include the potential reuse of the materials in the future.

Whole-life costing can be used to support the decision-making process for investment. For example, it can be used to identify whether a higher initial capital cost for a structure is justified instead of a lower initial cost with higher maintenance costs during the operational phase of the project. In this approach, costs are often expressed in terms of their *present value* (*present value* is the capitalised value of a stream of future costs, damages and benefits) using an economic technique called discounting, see Equation 2.2:

$$\text{Present value or capitalised costs} = \sum_{t=1}^{N}\left(\frac{C_t}{(1+r)^t}\right) \tag{2.2}$$

where:

N	=	design life (years)
t	=	time (years)
C_t	=	cost expenditure in year t (€) or (£)
r	=	market interest minus inflation rate (–).

This permits the calculation of a total whole-life cost based on the capital and discounted mean annual maintenance (monitoring, appraisal, repair) costs, together with the discounted costs of any major repair, rehabilitation or removal works expected during the lifetime of the structure.

The economic optimum may be a reduced capital cost requiring more frequent maintenance expenditure. However, high-maintenance solutions may be unrealistic for practical or environmental reasons and will need to be considered together with the economic case. Obtaining funding for maintenance may also be difficult. Owners or public authorities may make a policy choice to fund projects with high initial investments, to ensure better safety and less maintenance over the structure's lifetime. There can be a high degree of uncertainty in the calculation of repair costs because of the high number of variables involved. This uncertainty may also influence the final decision. For commercial developments, cash flow can be important. In some cases a rapidly built structure with low capital cost but high maintenance costs may be attractive because it generates an earlier revenue stream, which can then fund future maintenance.

In addition to the above costs, allowance might need to be made for the interest charges involved in financing a project. The relative balance of the cost components is not only project- and site-specific but is also affected by the economic conditions in the countries in which (or from which) engineering, material production, construction, maintenance and financing resources originate.

For further discussion on whole-life costing, see Mockett and Simm (2002) and PIANC (1998).

2.4.2 Cost elements

2.4.2.1 *Cost categories*

The costs involved in a rock structure generally fall into the following categories:

- sourcing of materials
- construction
- maintenance and repair
- removal.

These categories are discussed in more detail in Sections 2.4.4–2.4.7 below. In addition there are costs of investigations and studies leading to detailed design and preparation of contract documents. These costs usually constitute no more than 5–10 per cent of the overall project costs. Additional investment at the earlier planning and design stages is often relatively inexpensive and can reduce uncertainty and bring about significant savings for the project as a whole. For example, the cost of detailed numerical wave modelling studies or physical model tests are often equivalent to only 2–3 m of constructed breakwater. This illustrates the advantage of undertaking appropriate levels of initial study to fine-tune the design. Similar arguments may be applied to other aspects of the design process.

2.4.2.2 *Fixed and variable costs*

The costs of a project may be split into fixed and variable costs. Variable costs relate to the time expended or to the quantity of material handled. Examples of all of these are presented in Box 2.4, while further details are presented with reference to construction in Section 2.4.5.

Box 2.4 *Examples of fixed and variable costs related to rock construction*

Fixed costs

- Opening/closing of dedicated quarry (if necessary or beneficial)
- Mobilisation/demobilisation of floating or land-based plant
- Establishment/removal of accesses
- Trials and testing to identify general material properties and site characteristics.

Variable (time-related) charges

- Maintenance of quarrying activities
- Maintenance of floating/land-based plant
- Standing time for plant (eg when weather or hydraulic conditions prevent work progressing)
- Maintenance of accesses
- Designer's quarry inspections
- Supervision and administration
- Maintenance of survey and monitoring equipment (eg wave buoys).

Variable (quantity-related) charges

- Site investigations including geotechnics, wave measurement etc
- Excavation (and re-excavation)
- Excavation ancillaries (eg trimming of slopes)
- Filling (eg placing armourstone in bulk or individually)
- Filling ancillaries (eg trimming slopes, placing geotextiles)
- Testing (to confirm continuing acceptability of materials).

Generally, cost assessment should concentrate on the following:

- items that give the largest contribution to the total cost
- elements that are subject to significant uncertainties or have a major impact on the project.

For example, time-related charges may be important when there is risk that the programme will not be met. The economic consequences of higher or lower production rates may have to be considered where planning and cash flow consequences for the owner are critical. In this situation, a reduced construction time at the expense of higher production costs may prove most economical to the owner.

2.4.3 Cost estimation

In the design process, cost optimisation takes place at different levels and different phases of the design (see Table 2.6).

The project definition and conceptual design phases lead to alternative solutions that should be cost-analysed. Since this will generate choices, one of which is likely to form the basis for the final design of the project, every effort should be made to make the solution as realistic as possible.

Because of the inherent inaccuracies in the initial estimates, it is often advisable to bring forward more than one solution, eliminating options as the estimating process is refined. Design and construction (production, transport, phasing) costs are estimated with greater accuracy than maintenance and repair costs because the latter involve greater uncertainties (see Section 2.4.1). In assessing the options, the minimum cost for each should be considered, plus the potential risks attributable to errors in the estimates at this stage together with the reliability of the various estimates. At this stage it is often advisable to err on the side of a slightly higher capital cost and lower maintenance cost.

In the early stages of the process, estimates based on historic rates are adequate for arriving at an approximation of the cost. A rudimentary approach is to take the major quantities, cost them and add an allowance to cover the cost of the remaining minor items. The problems with this technique are that the rates may be broad-brush, or site-specific and difficult to update (even the update information is likely to be historic). Better accuracy can be obtained by using analytical estimating techniques once the major features of the design(s) are known.

An analytical estimate can be considered as a mathematical model of the project that gives cost as the final output. It involves looking at each operation required to execute the works, deciding what resources in terms of labour, plant and materials are needed to do it in what time, then applying up-to-date cost rates and summing the costs for all operations. There are computer programs available to help with this. This technique will also generate a realistic construction programme. It will be necessary to add allowances for mobilisation, demobilisation and any essential temporary works, operating costs, profit margin and risk or contingency.

During the tender phase, the various contractors will carry out the same estimating process, taking into account their unique experience and optimising the use of any specialist equipment they may own or be able to source and adding allowances for supervision, overheads, profit margin and risk to arrive at their final submission. Various procurement approaches may be adopted, such as a priced bill of quantities or a target cost based on an activity schedule. Incentives on early completion and cost may also be agreed between client and contractor. This process will also differ where a dedicated quarry is used and the design is supply-based – see Section 3.9.5.

Table 2.6 gives more detail on costs at each of the phases described above. It provides an indication of the typical accuracy that might be expected at each stage, although this can vary dramatically depending upon uncertainties associated with structure type, location and available information.

Table 2.6 *Cost estimation associated with different stages in a project*

Stage	Key word in cost determination	Typical basis for cost determination	Notes/example
		Design stage	
Project definition	Rough estimate	Historical data and reference projects including whole-life maintenance (Accuracy: ±40%)	1 breakwater × price of similar breakwater + inspection and maintenance record
Conceptual design	Estimate	Standard rates or approximate unit rates + whole-life costs (Accuracy: ±20–40%)	800 m of rock structure × rate per linear m of similar size rock structure plus maintenance costs
Preliminary design	Approximate calculation	Typical unit rates and approximate quantities of each material + administration (contractor's and designer's) and whole-life costs (Accuracy: ±10–20%)	80 000 m^3 of armourstone × typical price per m^3 of armourstone for similar projects in the region plus maintenance costs
Detailed design, including bills and specifications	Engineer's estimate	Unit rates and quantities + additions as above (Accuracy: ±5–10%)	80 000 m^3 of armourstone × price per m^3 of armourstone, ancillaries, enabling works, constraints and whole-life costs
		Market stage	
Tendering	Target budget	As above less whole-life costs	Inclusive of project management, insurances, taxes etc
Project acquisition	Tenderer's calculation	Analytical estimate based on the total resources required to construct the project	Company's data
Submission of tender	Tenderer's bid	As above + profit and risk	Contractor's experience of similar projects and conditions
Award of contract	Contract value	Agreed price	Target budget versus price
		Construction stage	
Preparation of works	Project budget	Last modifications, including contractor's suggestions	Changed opinions, cost variations
Execution	Project cost	Planning and production control	Project management
Execution	Contract price	Monitoring	Resident engineer
		Maintenance stage	
Routine inspections	Planned monitoring	As identified in arriving at whole-life costs	Annual inspections for damage, wear and degradation
Routine maintenance	Planned maintenance or modifications	As identified in whole-life costs modified by actual requirements	May feed back to modify monitoring programme and future maintenance costs
Critical inspections	Required after any major event that may have caused damage	Critical repairs – these should have been anticipated in the whole-life costs modified by a relevant formula based on probability and time	Serious departure from original scenarios may call for modifications to control future maintenance costs
Unplanned modifications	Unexpected change of use or physical conditions	This is likely to require a full-scale re-evaluation, starting from the design stage; a key factor will be how much of the existing facilities can be incorporated in the new design	Loss of fish stocks may lead to a fishing port being adapted as a marina; an offshore oil strike may lead to modification to allow support vessel facilities; collapse of undersea mined-out coal seams; changing bathymetry or sea levels may alter the wave climate

2.4.4 Armourstone sourcing, production and transport

A significant part of the cost of a rock project is the expense of sourcing, producing and transporting the armourstone and core material.

Sourcing and production

One of the first considerations for a project should be whether armourstone of sufficient size, quantity, quality and durability is available. There are constraints upon the maximum size of armourstone that can be produced from any particular quarry. Where a local quarry is to be used, the design will need to reflect the size, quality and quantity of armourstone available, where this is practical (known as "supply-based design"). Local quarries are often preferred, as it may be impractical to obtain larger stones or material of superior quality from another source because of transport, cost and environmental factors. For example, several berm breakwaters in Iceland were designed and constructed making maximum use of the quarry yield obtained from areas adjacent to the site. Selection of a local rock source may require the use of lower-quality (less durable) rock (see Section 3.6). The design and maintenance planning for the structure should take this into account (see Section 10.2) and this aspect should be evaluated in terms of the whole-life costs of the project (see Section 2.4.1). Section 3.1 provides further details on the selection of appropriate materials.

Transportation

Transportation to the site – for example by water or by land – can dictate the source of rock. Factors influencing the choice include the preferred method of construction, accessibility, environmental constraints and costs, recognising that the costs are directly influenced by each of these factors. Market forces may also be involved, for example the regional availability of appropriate barges to service all ongoing projects.

2.4.5 Construction

The largest item within the whole-life cost of a project is usually the construction. This will break down into three types of cost, which will vary in importance with the nature of the project, the type of contract and the equipment used. The latter is particularly important when there is a significant element of the works needing floating plant as much of the available plant is unique and there are likely to be issues of availability and precise suitability to the task. Costs can be divided into three categories.

1 **Fixed costs.** These include mobilisation, demobilisation and remobilisation of offices and plant; establishment and removal of the site compound and any temporary works or accesses; insurances, trials, opening and closing dedicated quarries or casting yards, manufacture of moulds; temporary fencing or barriers to separate the public from the works or for health and safety reasons; personal protection for operatives, public viewing areas and information boards, road and footpath closures/diversions; liaison with fishing authorities, moorings, anchorages and temporary jetties etc; and final site clearance. Most contractors will include allowances for risks they are required to assume under the contract in this category (weather downtime, subsidence etc), together with any inflation allowances.

2 **Time-related costs.** Included in this category are site supervision, plant (particularly equipment that is not fully employed but is needed full time on site, such as re-excavation machines, cranes) and office hire; control of public at work/public interfaces, update of information boards and maintenance of any of the items listed above.

3 **Remeasureable costs.** These are costs directly related to the quantity of work done, such as the quantities of materials incorporated (with allowances for conversion and waste) and the actual labour and plant required to manufacture, handle, prepare for and place them.

Some items may not always fall in the same category, such as divers (who may be employed on a minimum charge per shift), drilling and blasting operations, quality control operations, mould filling and re-preparation, part-load costs, tidal and phased working. The method of costing these items will depend on the sensitivity of the unit cost rates to changes in quantity.

To optimise the costs of the works, the designer and/or employer need to address a number of issues. These can be resolved into a series of questions that should be answered clearly before the design and tender documents are finalised. The following list includes many of the questions associated with a major coastal project, including the placing of armourstone or concrete armour units.

- Can the contractor get the plant and materials to site efficiently? If not, how can this be achieved?
- Does the contractor have adequate space for offices, storage and a safe area in the event of bad weather affecting the works? If not, where and how can these facilities be provided?
- Is a production facility (casting yard, quarry etc) needed? If so, where can it be sited?
- Does the programme allow sufficient lead-time to set up the facility, manufacture moulds, open the quarry, build up or cure initial stocks, and begin production at a slow rate as the site team moves up its learning curve?
- Are working hours or phasing required, for example tidal working? If so, can the contractor complete the works in the allotted time? What are the implications for costs, especially if expensive equipment, such as floating plant, cannot work efficiently?
- Can local materials be used? This concerns quality, durability, size and delivery rate.
- Is there an advantage in ensuring that the full range of quarry products is used? This is usually an issue for dedicated quarries (or quarry faces) or for local quarries that do not usually produce the grades required and need to maintain their core business.
- What is the maximum load to be placed and at what reach? Can the reach requirement be reduced by modifying the design?
- Is geotextile to be placed under water? If so, what ballasting methods are acceptable?
- Are the contract tolerances and profiles consistent with what can be achieved under the placing conditions?
- Does the design dictate that floating plant will be needed? Can the design be modified to allow use of much cheaper land-based plant?
- Are adequate labour skills available locally? If not, is accommodation for travelling labour available? Could redesign allow better use of local skills?
- Is the design over-complicated? Can it be simplified to use fewer armourstone gradings or types and hence allow the more efficient working of a reduced amount of equipment?
- Is there a key plant item needed to do the work? Can the design be modified to increase its productivity?

Following this checklist should provide best value for money given the prevailing conditions and constraints at any one site. The reader should refer to Chapter 9 for a detailed discussion on the construction issues that should be considered during the development of the design.

Typical cost breakdowns for different rock structures are given in Box 2.5.

Box 2.5 *Examples of relative costs for rock structures*

The case studies given here illustrate how costs can vary, depending on whether the armourstone is supply- or demand-based, and on the method of transport. They are indicative only and site-specific factors will affect costs for any particular project.

Case study 1: Modifying production from an existing aggregate quarry, delivery by road (courtesy Jones Bros)

For this project a protective rock bund was constructed to contain dredged fill material as part of a port expansion, using 120 000 t of core material and 30 000 t of 1–3 t armourstone. The contractor took over operation of four faces in two aggregate producing quarries and accessed the construction site from land. Surplus production from the quarry was stockpiled and used in surfacing fill areas after the fill was placed. Relative percentages of the cost for the core and armourstone production and supply are given in Figure 2.8.

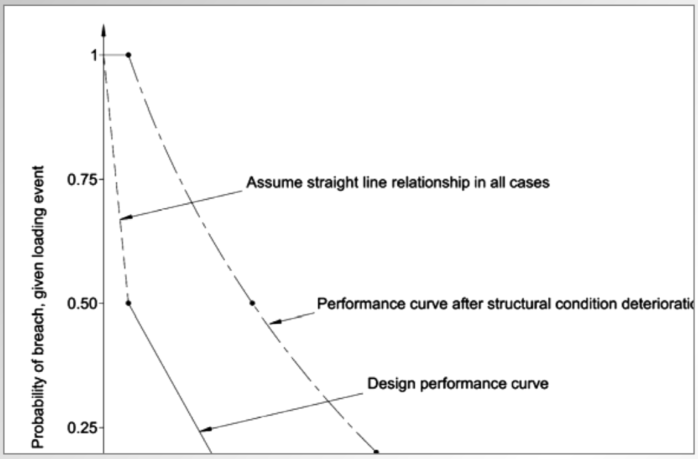

Figure 2.8 *Breakdown of costs – Case Study 1*

Case study 2: Modification of design to use existing quarry production, delivery by sea (courtesy Foster Yeoman and RJ McLeod)

This project consisted of a harbour development on the west coast of the UK. Quarried rock quantities were: 700 000 m^3 of fill/core material, of which 550 000 m^3 was imported and 150 000 m^3 was obtained by reusing material on site, 29 500 m^3 of primary armourstone and 14 250 m^3 of armourstone for the underlayer. Armourstone was sourced from an existing quarry located about 50 km from the project site. The contractor produced an alternative, more economical design that made use of available gradings. Armourstone was delivered to site in approximately 40 000 t cargoes on a specialised self discharging vessel. A percentage breakdown of the key cost items for the imported armourstone is given in Figure 2.9. This includes tax that had to be paid on the newly produced aggregate.

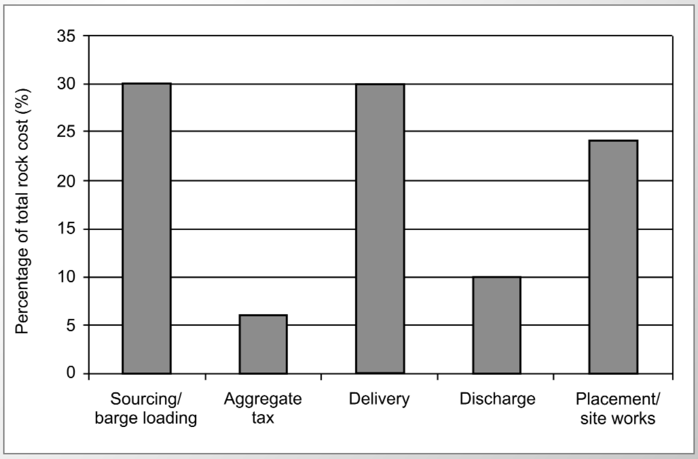

Figure 2.9 *Breakdown of costs – Case Study 2*

2.4.6 Maintenance and repair

There are ongoing costs associated with a structure, including the following:

- monitoring and inspection of the structure and surrounding environment (eg beach levels)
- evaluation of condition and performance
- repair
- rehabilitation or replacement.

The level of activity, and thus cost, of any of the above tasks depends on aspects such as frequency and severity of storm events and accidental damage. It is also influenced by decisions on design life, design damage levels and monitoring frequency that were made at the time of planning and design of the works (see Section 2.3.3.2). Cost items whose probability of occurrence in a particular year can be estimated (eg from fragility curves – see Box 2.3), can be included as a multiple of the cost item and its probability of occurrence. For example, an item costing €10 000 with an equal probability of occurrence of 10 per cent in any one year in a 10-year period (eg between years 10 and 20) could be included in each of these years as 0.1 × €10 000 = €1000.

For rehabilitation or replacement of a structure, the factors described for construction in Section 2.4.5 apply, for example the cost of sourcing and delivering materials, plant and accessibility.

Chapter 10 discusses monitoring, maintenance and repair strategies and methods in detail.

2.4.7 Removal

Under some circumstances a structure may be expected to be decommissioned in the future and require removal. The costs of this may include:

- equipment
- removal of materials from site
- dumping or reuse
- dealing with polluted materials.

In such situations, these costs should be recognised at the design stage and are likely to influence the choice of design.

2.5 ENVIRONMENTAL CONSIDERATIONS

Rock works have the potential to cause serious impacts on the environment and there are different pressures at each stage of the project. This section outlines the environmental issues that arise when planning, designing or constructing rock structures. Environmental issues are of consequence not only in the construction area but also at the sites where materials are quarried and stored and along transport routes. They apply, too, where modification of the physical conditions could induce damage to habitats or cause changes in activities.

There is a considerable amount of literature and legislation attached to environmental assessment of projects. This section focuses on specific environmental considerations for the use of rock in hydraulic engineering and identifies the type of information that can be used in environmental assessment of rock structures. An overview of the Environmental Impact Assessment (EIA) process is provided in Section 2.5.4. In addition, Section 3.13.4 deals with the environmental risk analysis of alternative and secondary materials.

2.5.1 Sustainable use of rock as a construction material

Alternative materials should be evaluated on their environmental performance rather than simply because a particular material is preferred. The Brundtland Report (WCED, 1987) encourages increased use of materials from alternative sources to meet quarried rock needs for construction. These include secondary materials, industrial by-products and wastes. This principle of sustainability in the construction industry requires:

- efficient use of materials
- minimisation of the production of waste
- recycling of wastes.

Sustainable rock works should aim to reduce energy and rock resource consumption, transport and waste production. For each project option, whether using rock or alternative materials, the source, transport, placing, use and dismantling should be studied over the whole life cycle – from "cradle to grave". Criteria such as energy, waste, raw materials and human perception may be assessed to rank the preferred options. A tool for scoring the whole-life environmental impact of project options is given by Masters (2001) in a guidance document on sustainable use of new and recycled materials in coastal and river engineering. Calculations are based on the quantities of each type of material, the distances required to transport them to the construction site and the anticipated service life. These parameters are then related to the anticipated environmental impacts, such as greenhouse gas emissions, associated with the production and transport of each material.

Alternative materials to quarried rock and associated issues are specifically addressed in Section 3.13. Reviews of alternative materials are given in Brampton *et al* (2004) and Masters (2001).

2.5.2 Assessing environmental impacts through the project cycle

Many environmental matters need to be addressed when planning, designing, constructing and operating rock structures. Many of these are common to any project constructed in a marine or fluvial environment, and include effects on the physical environment (geomorphology, landscape) and those on physical processes (waves, currents). Often these impacts are actually the primary function of the works! Projects can affect ecology, social function, recreation, amenity, human senses, air and water quality etc. These factors all require consideration as part of any project, but are not considered in further detail here.

The remainder of Section 2.5.2 relates only to aspects specific to rock structures for those conducting such assessments. The discussion looks at the following environmental issues:

- physical features
- ecological and biological features
- air, water and soil quality
- heritage and landscape
- social and socio-economic features
- natural and industrial risks.

Typical considerations under each of these headings are given in Table 2.7. This list includes many factors that are relevant to a range of projects, not only those involving quarried rock. This list is not exhaustive and different projects may encounter other site-specific issues. Later sections discuss environmental aspects for rock works at each project stage. Many of the points listed in Table 2.7 require data that may also be necessary for design, so it is advantageous to address environmental issues as early as possible in the design process. This will allow data collection programmes to be designed to provide data to meet the needs of the design studies and the environmental studies, as well as any data required for construction planning.

Further general discussion on environmental assessment can be found in a range of literature, eg Morris (1995), Simm *et al* (1996), Budd *et al* (2003), VNF (1998), Michel (1998, 2001), SETRA (1996), CETMEF (1978).

Table 2.7 *Key environmental considerations for rock structures*

Physical aspects	● Climate change: sea level rise, changes in physical processes, eg sediment transport ● Weather and ice conditions ● Changes to waves, tides, currents, flows due to project using rock structure ● Physical data for design, construction and monitoring (bathymetry, waves, flows, water levels) ● Potential for changes in design conditions during project life ● Interruption of drainage from land ● Potential geomorphological changes to existing physical systems: coastal estuaries, shorelines, saltmarshes, dune systems, river bathymetry and morphology ● Coastal squeeze ● Stabilisation of active sediment feeds, reducing sediment supply, affecting coastal evolution ● Scour, outflanking and need for future extension of defences ● Loss of designated geological landforms or rock exposures beneath structure footprint
Ecological and biological aspects	● Direct impact on or reduction of protected habitats (mudflats, saltmarsh, dunes, river banks) and species because of structure footprint ● Indirect loss of habitats or landforms – transfer of erosion to another location, scour, beach lowering ● Stabilisation of naturally dynamic habitats or landforms in lee of structure ● Risk of disturbance to feeding and roosting birds etc during construction ● Change in habitat due to rock structures ● Impact of construction or maintenance access on habitats ● Destruction of potential habitat on rock structures during decommissioning
Air, water and soil quality	● Emissions from rock transport, construction and maintenance ● Accidental releases of pollutants during rock transport, construction and maintenance ● Potential exposure of existing contamination ● Change in water and air quality due to suspension of fine particles during construction ● Leaching from construction materials
Human sensory, heritage and landscape aspects	● Visual intrusion, eg colour, shape of armourstone and type of placement ● Noise and vibrations caused by armourstone production, transport and placing ● Odour attributable to collection of debris or organic matter ● Impact on amenity beaches from stone fragments following construction ● Modification of landscape ● Effect on views from local housing ● Covering over archaeological features ● Other issues: light, historical, cultural aspects, palaeontology
Social and socio-economic aspects	● Changes in local employment during construction and operation ● Immigration into small community during construction ● Effects on local commerce ● Effects on recreation, eg loss of amenity beach due to structure footprint, loss of safe areas for children's play ● Effect on pedestrian and vehicle access to beach, shoreline or river, including disabled access ● Effects on fishing ● Effect on flood risk of adjacent properties ● Vulnerability to vandalism ● Public health and safety risks ● Safety of rock structures ● Effects on navigation ● Sustainability of development
Natural and industrial risks	● Health and safety of construction workers ● Safety of rock structures ● Presence of cables or pipelines ● Need for consents where works are in hazardous industrial sites

2.5.2.1 Project concept and design stage

There are many opportunities for reducing environmental impacts during scheme concept and design stages. These include material selection and specification and integrating environmental considerations into the comparison of project options.

Rock structures are generally considered to be less reflective to waves than vertical structures. This may be of significance where foreshore or riverbed scouring is a concern. Where a physical habitat adjacent to the structure is protected by legislation (eg in Europe by the Habitats Directive) adverse impacts on this physical habitat must be avoided.

Transport of materials can be the most significant environmental issue. A suggested hierarchy of material sourcing options for consideration during design is given below (see Masters, 2001).

1 Suitable materials available on site from a previous project or structure.

2 Locally sourced reclaimed or recycled materials appropriate to fulfil the needs identified in the functional analysis.

3 Reclaimed or recycled materials from further afield that can be delivered by sea or rail or locally sourced primary materials.

4 Reclaimed or recycled materials transported from further afield by road or primary materials transported from further afield predominantly by sea or rail.

5 Primary materials transported from further afield by road.

Avoiding over-specification of materials in the design process can help reduce waste and encourage recycling of materials. Some organisations have already implemented site waste management plans that analyse the waste likely to be produced on site and minimise what is sent to landfill. Where possible, environmental factors should be included in benefit-cost analysis. This might be by using contingent valuation, which involves asking people in a survey how much they would be willing to pay for specific environmental services or, alternatively, the amount of compensation they would be willing to accept to give up specific environmental services.

The public perception of the advantages or disadvantages of a project needs to be addressed. Public consultation exercises will be of greatest value when there is an intention to allow those views to influence the design of the project. There may be statutory requirements for public notification and consultation. Early consultation and communication with site users and associations (recreational, fisheries and environmental bodies) is advised to improve public perception of the scheme both when planning to use quarried rock and perhaps especially when alternative materials are proposed.

The issues listed in Table 2.7 should be reviewed to assess which should be considered at this stage. In particular, key issues to be considered during design are:

- localised changes to waves, tides and currents and consequent patterns of scour and deposition
- provision of alternative habitats on soft shorelines, estuaries or rivers
- identification of potential mitigation measures with environmental monitoring
- landscape issues, especially with regard to colour and shape of armourstone and type of placement
- coverage of archaeological features
- safety of the rock structure.

2.5.2.2 *Project approvals stage*

As described in Section 2.5.4.2, the Environmental Statement (ES) will form a principal part of the planning (or other) application. The Environmental Impact Assessment (EIA) tackles issues such as impacts on protected habitats and reduction of the marine habitats area. The EIA forms an integral part of the public consultation process.

2.5.2.3 *Project construction stage*

When considering the use of quarried rock, the following environmental matters need to be taken into account at the construction stage:

- sourcing armourstone
- transportation of armourstone
- placing armourstone.

Sourcing armourstone

Armourstone in hydraulic engineering is usually a primary aggregate and is a non-renewable resource. In some cases, however, armourstone is a secondary aggregate obtained as a by-product from quarrying other material, eg dimension stone, road or concrete aggregate, so it is used as waste from other operations.

Armourstone is generally quarried using drilling and blasting or diamond cutting. Rock material suitable for particular uses is selected and processed by various sorting methods (detailed in Section 3.9.7) and by rock cutting. Potential environmental impacts of quarrying and associated rock processing operations, include:

- noise and vibration from blasting, crushing and sorting
- habitat disturbance and removal
- disturbance and removal of topsoil
- particulate emissions to air and water
- interruption of surface water and groundwater flows
- traffic disruption to local communities
- carbon dioxide emissions from fossil fuel burning
- energy consumption during screening, sorting, crushing, drilling and transportation
- production of solid waste
- visual impacts.

The use of quarried rock should be compared with alternative materials commonly used in hydraulic engineering structures, for example timber and concrete. Timber for use in the marine environment generally has to be tropical hardwood because of its durability and resistance to marine borers. This is theoretically a renewable resource, but, despite considerable efforts (eg by the Forestry Stewardship Council in the UK and other certification organisations), doubts remain over the sustainability of harvesting practices for preferred timber such as greenheart. Timber can be recycled from coastal structures but has a limited life, after which it has to be replaced. Concrete is a manufactured material but requires raw materials such as aggregates and cement; many of the same arguments apply as for sourcing rock.

A full appraisal of the relative environmental impacts of rock and other construction materials requires a life cycle analysis. This looks not only at the sustainability of raw materials but also at the environmental impacts associated with material sourcing or production, transportation, use and eventual disposal, including the relative energy consumption to source or produce different materials. A wide range of concepts and analytical tools have been developed to assist in this process (eg Howard *et al*, 1999). The outcome of such an appraisal will inevitably depend on the weighting assigned to each factor through multi-criteria analysis. However, in view of its durability and flexibility for reuse, it is at least arguable that rock, particularly if obtained as a quarry by-product, is often more environmentally acceptable and sustainable than timber, and no more environmentally damaging than sourcing materials for concrete.

Transportation of armourstone

For many projects, in particular maritime structures, rock is delivered directly to site by barge from its source. This avoids an impact on the road network, which may be counted as an advantage of quarried rock over other bulk materials that are usually delivered by lorry. Barge transport also uses significantly less energy and produces lower carbon dioxide emissions than road transport. However, it should be noted that double handling usually takes place. Short distance road transport may first be required to reach barge loading facilities; cargoes from large barges often have to be offloaded into smaller barges that can reach the shore. (Accidental release must be avoided when discharging the armourstone from one barge into the other.)

Barge transport has implications for other marine uses and users such as recreation, shipping and especially fishermen. Fixed fishing gear such as nets and pots are vulnerable to damage from barges that need to approach close inshore to discharge their loads. This is usually addressed by agreeing a single point of delivery on each frontage, with an associated barge route, notified and, where possible, agreed with fishermen in advance. Standard marine safety rules should cater for possible conflicts with other vessels, though recreational activities may have to be restricted while quarried rock deliveries are in progress. Local requirements may make it necessary to give advance notice to mariners of works that are to take place.

Water-borne transportation of construction materials may be possible in navigable rivers and canals, but for many rivers and streams the only practicable means of transportation will be by road. Appropriate methods of transport and routes of access should be chosen, taking due account of environmental sensitivities.

Rail transport has a high capacity and a limited impact on the environment, allowing transport of large quantities of armourstone. Depending on the vicinity of the rock source and the construction site to the rail network, there may be a need for additional handling and also road transport in some cases.

Armourstone deliveries may have implications for nearby residents, particularly if they have to be made at night as a result of 24-hour or tidal working. Unloading usually requires the use of heavy plant, which inevitably generates noise. Reversing alarms on plant are typically found to be the most disturbing noise source owing to their pitch, tone and volume. Unless a method can be found to enable these to be safely turned off, night-time disturbance is likely to occur while working close to residential areas. Approaches to mitigation can include:

- confining deliveries that are closest to residences to daylight hours, with deliveries to other parts of the scheme at night
- erecting temporary noise barriers between residences and the working area
- on frontages where tourism is important, scheduling armourstone deliveries outside the peak months.

An alternative in coastal locations is for stone to be tipped from a specially designed ship directly on to the beach, which not only avoids the use of excavators, dump trucks and shovels for unloading but also reduces both energy consumption and noise generation.

Placing armourstone

Environmental impacts of armourstone placement include:

- noise nuisance
- effects on the physical environment (eg beach or river bed), habitat and sediment disturbance as a result of excavation (though this is generally less than for concrete structures, as armourstone does not require such substantial foundations)
- visual impact and habitat disturbance from stone stockpiles
- energy consumption by vehicles
- disturbance of local fauna such as birds, limiting the area for feeding and roosting.

Environmental benefits of using rock include relatively low wastage and reduced risk of air and water pollution, compared with construction using ready-mixed or locally batched concrete. Surplus armourstone can be added to the structure or stockpiled to provide a resource for future maintenance operations.

The construction work itself may provide much-needed employment or it may interfere with the livelihood of existing residents. Other social impacts may result from the influx of an outside workforce during construction of a major project in a sparsely populated area.

Once in place, rock structures are unlikely to cause any particular noise problems and have a low vulnerability to vandalism. Measures to mitigate environmental issues on site may be found in *Environmental good practice – working on site* (Coventry *et al*, 1998) and in the *Coastal and marine environmental site guide* (Budd *et al*, 2003).

2.5.2.4 Project operational stage

Rock structures can provide habitats and new ecological niches for organisms such as crustaceans, molluscs, fish, algae and birds. Since rock is usually foreign to the location at which it is used, such habitats may be considered alien, particularly within soft coast environments. For this reason, biodiversity gain may not be accepted as contributing to nature conservation objectives. The impact on fisheries resources may, however, be beneficial. Monitoring on the north-east Norfolk coast in the UK, for example, has shown that the construction of a series of large offshore breakwaters is associated with a large increase in shrimp populations. On the other hand, the breakwaters have limited the access of trawlers to the inshore zone where shrimps are concentrated.

Rock structures generally require maintenance, as they are located in a dynamic hydraulic environment. Stones can be displaced, abraded or fractured. Heavy plant may be needed to undertake such maintenance, though associated environmental impacts are generally small.

Unless buried beneath natural material or under water, rock structures can have significant effects on the landscape and visual amenity. This is often raised as a concern when such structures are proposed. Nonetheless, it can be argued that timber structures such as groynes have a similar impact, but through long periods of use they have become accepted as part of many beach scenes. Over time, rock structures may become similarly accepted.

Effects on recreational amenity are another area of concern. Rock structures may trap weed and litter, which can be unattractive and cause an odour problem as it decays. This is less likely to be a problem where voids are largely filled (with beach sand, for example) or in high-energy locations where voids are regularly scoured and kept clear by wave or current action. It may be more troublesome in areas already prone to accumulation of vegetation or litter, in which case a commitment may have to be made by the owner or operating authority to clean the rock structures periodically.

Rock structures do present potential safety hazards to the public, because of the risk of people slipping or falling. Pedestrian access along rock structures can be difficult to provide. In certain cases it may be necessary to maintain public access along a particular stretch of shoreline or riverbank. However, while members of the public would see access along a breakwater as advantageous, it may be cheaper and safer to prevent it. Concerns have also been expressed that people could become trapped in voids between armour stones and drown. These risks are generally addressed through signs warning the public not to climb on the structures. Localised packing of stones to provide ramps and footways to selected areas can also mitigate this. The safety risks of rock structures are potentially no greater than those associated with other types of coastal structures such as concrete walls; both types present a risk of injury from falling.

Other potential environmental impacts associated with the operational stage of rock structures include:

- direct loss or coverage of coastal habitats under the structure footprint
- visual intrusion and impact on the landscape (eg sea view from houses)
- effects on recreation (including change in access to shoreline and loss of safe or shallow areas for children's play)
- safety of rock structures
- need for ecological monitoring.

2.5.2.5 *Project decommissioning stage*

Environmental matters to be considered at the decommissioning stage of rock structures are mostly the same as for the other stages in the structure's lifetime. An often-quoted advantage is that rock structures are relatively straightforward to dismantle and constituent rock can be reused or recycled into other projects. Even if rock has been severely abraded and degraded in the marine environment, it can still be recycled into primary aggregate.

Environmental aspects that should be considered at the decommissioning stage include:

- destruction of potential habitats on rock structures
- re-activation of a former sediment feed and re-creation of natural coastal habitat and transition
- accidental release during demolition, or unintended failure to remove the entire rock structure
- modification of the landscape once again
- presence of services within the structures.

2.5.3 Opportunities for environmental enhancement

Rock structures can offer opportunities for environmental enhancement, for example by providing habitats for marine and river life. Some guidance is given by Jensen *et al* (1998), who discuss habitat creation, present suggestions to encourage colonisation of aquatic life that is naturally attracted to hard surfaces, and identify the types of species that may be attracted.

Structure design should aim to reproduce rock environments such as foreshores and river beds as found in nature. Typical features should be a range of stone and crevice sizes, irregular outlines and surface orientations to provide a variety of micro-habitats for small mobile and immobile species as well as larger species. For structures in the littoral zone, features of a rocky shore may be reproduced by providing hollows and crevices to form rock pools, projections to create overhangs and placing stones in isolation from the main works to create scour pools. As with all design aspects, costs and practicality will need to be considered.

The colonisation and distribution of plants is subject to their ability to survive at various levels of dryness (normally linked to height above low water) or light penetration when under water. For marine structures, elements at or below low water level may be colonised by kelp, which, like most seaweeds, attracts a wide range of animal communities for shelter or feeding. At mid-beach levels, seaweeds like bladder wrack may colonise.

Fish and crustaceans can use the crevices between stones and concrete blocks to hide from predators, lay eggs, or feed on organisms growing on the structure. If the structure is submerged, shelters for edible crab (crevices on the outside of the structure) and lobsters (galleries within the structure), and shelter for fish species such as wrasse, lumpsuckers and conger eels can all be incorporated.

Under normal conditions, surfaces of concrete or quarried rock structures in the marine or fluvial environment are rapidly colonised by naturally occurring micro-organisms that consume many of the dissolved and suspended substances in water. Settlement of larger organisms, such as barnacles and mussels, which can directly filter suspended matter for their food, can also occur. Grazing and browsing organisms living on rock structures devour many of the plants and animals living sedentary lives on the hard surfaces, creating scope for continued colonisation.

When a structure is constructed there is inevitably a loss of habitat and, with it, associated species. Sandy or muddy sea beds and foreshores and river beds and riverbanks contain a multitude of organisms (worms, crabs, molluscs etc) many of which are important to the food chains of commercially fished species and birds (particularly in the intertidal zone).

As a starting point for ecological enhancement, the points in Box 2.6 should be considered when planning rock structures in the hydraulic environment. See also Irving and Northen (1999) for details of ecological survey of rock structures.

Box 2.6 *Considerations for ecological enhancement of rock structures*

The following points should be considered to provide opportunities for environmental enhancement (adapted from Jensen *et al*, 1998):

1. Location. Consider the appearance of rocky habitat and reproduce it where you plan to build the rock structure. For marine structures below the low tide level, opportunities for fishery habitat enhancement increase with water depth.
2. Maximise the diversity of crevices created. The greater the heterogeneity of the habitat the more diverse the final biological community is likely to be.
3. Consider using a mix of materials – does everything have to be made from the same rock type?
4. Be creative. Provide a structure that has rough surfaces rather than one that is smooth, neat and symmetrical.
5. Build in animal-friendly features, intertidal rock pools, isolated boulders for scour pools, projections to create overhangs.
6. Consult local residents and users. Conservation groups or environmental organisations at local and national level, local authority ecologists, academics and fishery organisations are professionals too and will be delighted that nature conservation and/or fishery provision is being considered.
7. Use the fact that you are taking extra care to promote your approach to rock structure construction. A project that blends into the existing landscape will be more popular than one that visually conflicts.
8. Be realistic. No single project will do everything. Take a long-term view and over time the benefits will mount up.
9. To assess these benefits be prepared to monitor. Quantification of benefits may require professional surveys, especially sub-tidally, but descriptive evaluation allows local enthusiasts to become involved. Encourage local schools and colleges and/or conservation groups to adopt the structure as a study site (shore or river ecology is a favourite theme for field trips). You will be able to use their data and images to follow the biological community development over time.

2.5.4 Environmental Impact Assessment process – an overview

2.5.4.1 *EIA legislation*

Projects have to comply with a large number of statutory requirements. For many projects there is a need to prepare an Environmental Impact Assessment (EIA) before the project can proceed. This is a tool for assessing construction and operational impacts. Where European sites of nature conservation importance Special Protection Areas (SPAs) and Special Areas of Conservation (SACs) or Ramsar sites may be affected by construction, there is a need to comply with the requirements of the EU Habitats Directive. Some authorities require projects to seek biodiversity gains, particularly relating to protected habitats and species. In the UK these are covered by Biodiversity Action Plans (BAPs). Increasingly, EIAs are also expected to consider environmental issues associated with material sourcing.

This document does not fully describe the legal requirements for environmental assessment, as these vary internationally and are also subject to changes with time, but some of the main European and international legislation to be complied with is summarised in Table 2.8. Reference is made in this section to this legislation although it is recognised that outside Europe some of the requirements may not apply.

Table 2.8 *Main international and European environmental laws related to Environmental Impact Assessment*

Issue	European community law	International law
Wildlife and nature conservation	• Environmental Impact Assessment Directive 85/337/EEC amended by 97/11/EC • Surface Waters Directive 75/440/EEC • Bathing Waters Directive 76/160/EEC • Dangerous Substances in Water Directive 76/464/EEC • Fisheries Directive 78/659/EEC • Agricultural Sewage Sludge Directive 86/278/EEC • Urban Wastewater Directive 91/271/EEC • Nitrates Directive 91/676/EEC • Environmental Strategy Assessment Directive 2001/42/EEC • Shellfish Directive 79/923/EEC • Birds Directive – 79/409/EEC • Habitats Directive – 92/43/EEC	• Ramsar Convention on wetlands of international importance – 1971 • Convention on protection of world cultural and natural heritage Stockholm declaration – 1972 • World Charter for Nature – 1982 • Bonn Convention on the conservation of migratory species of wild animals – 1979 • Bern Convention on the conservation of European wildlife and habitats – 1982 • Rio Convention on biological diversity declaration – 1992 • Espoo Convention – 1991
Water and marine pollution	• Water Framework Directive – 2000/60/EEC	• Marpol Convention 1973-78 • London Convention – 1972 • Ospar Convention – 1992 • Barcelona Convention – 1976, amended in 1985 • Bremen Declaration – 2003

Note

Table compiled from Fowler *et al* (2001), André (2003), Sunkin *et al* (1998) and Morris and Therivel (1995).

The project promoter may perceive environmental assessment as an additional financial burden. However, the cost of Environmental Impact Assessment, which depends on project size, existing environmental data and sensitivity of the environment, will in most cases be a small proportion of overall project costs.

The environmental assessment procedure has the following advantages for the promoter:

- identifying environmental impacts during the planning and design stage will lead to the most cost-effective inclusion of measures to mitigate adverse impacts
- liaison and consultation, which is normally an integral part of the assessment, will reduce the risk of an unexpected refusal of development consent at a late stage
- probable areas of objection to a project will be identified at an early stage and enable sensitive matters to be addressed and project delays minimised
- the opportunity for public consultation can result in greater acceptance of a project in the affected community
- minimisation of unforeseen adverse environmental impacts that may incur considerable future financial liabilities
- establishing licences or consents that are required can facilitate some aspects of the development.

Failure to conduct appropriate environmental assessment at the correct time can be costly, as the start of the project may be delayed.

2.5.4.2 Environmental Statement

The results of an EIA are normally presented in an Environmental Statement (ES). For mandatory assessments this report will form a principal part of the planning (or other) consent application.

The Environmental Statement contains:

- a full description of the proposed project
- a description of the existing environment in which the project is to be situated and that may be affected by the proposed project
- a brief description of other options considered (including the option of doing nothing) and reasons for their rejection
- a statement of the predicted environmental impacts of the proposed project
- where the predicted impacts are adverse, a description of the measures that will be adopted to mitigate those impacts
- a description of analysis methods used.

2.5.4.3 EIA process

The European EIA Directive sets out the main phases of EIA:

- compilation of information on the likely environmental effects of the project into an Environmental Statement (essentially the four steps referred to below)
- publicising of the ES and the project to which it relates to seek public response on the project and ES
- determination of the acceptability of the project by the relevant authority, referred to as the *competent authority* (normally the local authorities where the project is to be located), taking into account the ES, possible mitigation measures proposed and any feedback or comments received from the consultation.

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There are four main steps for compiling information on the likely environmental effects.

1 **Scoping**, to identify priority issues for detailed assessment.

2 **Baseline survey**, to define the existing environment.

3 Projection of the proposed project on to the existing environment and the **assessment of probable impacts** (beneficial or adverse).

4 Investigation of **measures to mitigate impacts** that are found to be adverse, and the possible incorporation of those measures into the design.

Scoping

Scoping identifies the priority issues to be assessed. The environmental aspects that rock engineering works may affect or may be affected by include those listed in Table 2.7 together with the interactions between them.

Initial consultations should take place with the planning, coast protection, river drainage and navigation authorities and other statutory bodies whose consent will be required to allow the project to proceed. Statutory bodies advise on designations relating to nature conservation (eg wildlife) and other environmental aspects (eg water, air, landscape, geology). It is usually beneficial to consult all organisations whose interests are likely to be directly affected by the proposed works. As a general rule, consultation should be as widespread as practicable.

Baseline studies

Environmental data can be collected by existing literature and *in situ* surveys. The latter can be time- and money-consuming but may be the only way of securing local information. The objectives should be focused on the description of the existing environment with background data in order to assess future modifications due to the proposed engineering project.

Impact identification and prediction

This step identifies the range of potential environmental effects and ascertains the significance of each. It can be complex and time-consuming. Environmental effects can be categorised as follows: beneficial or adverse, direct or indirect, widespread or localised, permanent or temporary, reversible or irreversible, short- or long-term, cumulative or immediate.

Mitigation and enhancement

To obtain consent, it may be necessary to identify mitigation measures that will avoid, reduce or compensate for predicted major negative environmental impacts of shoreline, coastal or estuarine and riverine engineering projects. They may also aim to enhance positive effects. One such measure is to put in place an environmental monitoring programme (see below).

Environmental monitoring

The aims of environmental monitoring are to provide:

- **before construction** of the works: input data for calibration of numerical models and baseline study
- **during and after the construction** of the works: indicators or environmental parameters for quantification of predicted impacts and mitigation, as well as of remedial measures or warning of unexpected impacts.

The site and the probable impacts of the project will dictate the frequency and extent of the monitoring.

2.6 SOCIAL CONSIDERATIONS

Construction works are generally undertaken to benefit society in some way. These social factors need to be considered in planning and design. These include:

- health and safety
- social impacts of construction and operation
- engaging stakeholders.

2.6.1 Health and safety

Working in water is often hazardous because of the nature of the environment. The coastal marine environment can be highly volatile, and at times unpredictable, with sudden, strong changes in winds, waves, currents and water levels. Rivers can be equally challenging, subject to flash floods and strong seasonal flows. The risks to the works, equipment and human life cannot be overstated and must be addressed during planning, design and construction.

The potential risks to safety in this dynamic physical environment include changing ground conditions (on the river or sea bed), access and working space. Planning and design should aim to avoid such hazards. Protecting operatives is a fundamental requirement. The designer should consider how the structure will be built, to ensure that the design allows appropriate safe working practices to be adopted.

Protecting the public and/or future users of the facility is important. Rock structures in areas where the public have access are often hazardous. For example, small children could become trapped within the voids of the cover layer or injured and crushed by the movement of unstable armour stones. Such issues should be addressed at an early stage, perhaps by stipulating that armourstone be correctly shaped (eg sharp and angular, not smooth and rounded) to ensure it interlocks securely.

Signs can be used to inform the public of the safety hazards of structures and raise awareness of their purpose.

It is essential to remove or reduce risks at source early in the project planning stage. Section 9.5.3 discusses these health and safety matters and measures for addressing them. Further details can be found in Simm and Cruickshank (1998).

2.6.2 Construction and operation

Construction works can be disruptive and intrusive for local communities. Constraints and opportunities should be determined through public engagement (see Section 2.6.3) and identified during the planning stage. Where possible, constraints should be overcome at the design phase. Points to address include:

- local employment opportunities
- plant access to the site
- restricted working time
- specified construction methods
- public access over and around the structures
- potential aesthetic or amenity value (eg angling or waterfront access).

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2.6.3 Engaging stakeholders

More acceptable designs can be produced and problems avoided if stakeholders are approached at an early stage. There can be a significant gap between what the designer perceives to be an issue and the stakeholders' views. In many cases, accommodating local needs has little impact upon the cost or constructability of a scheme, but may enhance the quality of service provided by the structure.

Engaging stakeholders early helps to educate those affected by the technical processes – about how and why certain decisions need to be taken, for example. This understanding can result in acceptance of preferred construction methods despite short-term disruptions.

In some parts of the world the use of local materials and labour provides major benefits to the local population in terms of money and employment. Different designs might be expected in these circumstances.

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