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The Rock Manual

The use of rock in hydraulic engineering (2nd edition)

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The Rock Manual. The use of rock in hydraulic engineering (2nd edition)

CIRIA, CUR, CETMEF

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Ministerial foreword

Our ports, coastal and river defences and inland waterways are vital to the maintenance of trade and economic development. Natural and durable rock is one of the main materials employed in marine and river construction works to prevent scour and erosion, and to limit wave overtopping and flooding. It is estimated that at least 10 million tonnes of armourstone are used each year across Europe, in construction works valued at nearly €1 billion. Yet many engineers still employ traditional techniques in the use of rock and fail to gain the benefits of industry experience and new research. They also need guidance to ensure that the projects they conceive are environmentally friendly and sustainable.

Our national governments realised there was a need to sponsor the production of a single reference source on good practice in the use of rock in hydraulic engineering, drawing on the expertise of the limited number of real experts across Europe. The project to produce this manual is therefore, very appropriately, the fruits of collaboration between three countries in the European Union: France, Netherlands and United Kingdom.

The new manual is more than a revision of existing documents. It is based on two full years of effort by an unique team of international experts. They have put together a extensive summary of good practice on the use of rock in engineering works for our rivers, coasts and seas and have incorporated all the significant advances in knowledge that have occurred over the past 10–15 years. It is our belief that application of the guidance in this manual will help to achieve a long-term improvement in the use of armourstone and will promote conservation of natural systems in balance with the proper protection of human life and property.

We therefore have pleasure in commending this document to all those interested in the subject including public authorities commissioning work, designers and construction contractors.

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Minister of State, Department for Environment, Food and Rural Affairs, United Kingdom	Director of Institute for Maritime and Inland Waterways, France	Director-General for Public Works and Water Management, Netherlands

Summary

In 1991 CIRIA/CUR produced the *Manual on the use of rock in coastal and shoreline engineering*, commonly referred to as "**The Rock Manual**" (CIRIA, 1991). CUR/RWS updated the book in 1995 to include the use of rock in dams, fluvial engineering and construction (CUR, 1995). Two French reference books were produced in the late 1980s: *Le dimensionnement des digues à talus* (EDF R&D, 1987) and *Les Enrochements* (LCPC/CETMEF, 1989). Since publication of these earlier reference texts significant research has been done to improve understanding of rock behaviour and to determine improved practices for hydraulic engineering. Consequently, this manual has been developed to bring the earlier publications up to date and has been given a broader scope that increases the focus on environmental and sustainability concerns.

New information incorporated in this edition includes:

- extended scope of the manual (from the 1991 edition) to cover coastal, inland waterway and closure structures
- guidance on design and construction using concrete armour units
- updated guidance on armourstone specification and model construction specification for rock structures
- cross-referencing to the new European armourstone specification EN 13383, which supersedes sections of the previous manuals
- extensive cross-referencing to the Eurocodes for geotechnical considerations
- new research on block integrity, packing and placement, predicting quarry yield and block size distributions
- a new risk assessment template
- updated guidance on wave overtopping, wave run-up and wave transmission
- updated guidance on wave climate description and representative wave parameters including wave height distribution in shallow waters
- updated guidance on the selection of hydraulic design conditions, including design with joint probabilities of, for example, waves and water levels
- updated guidance on river hydraulics and design conditions for river structures
- updated guidance on the performance of falling aprons
- updated guidance on stability of low-crested structures, toe protection to vertical breakwaters, calculating wave forces on crown elements and on the stability of rock-armoured slopes with shallow foreshores
- new guidance on rear-side stability of rock structures, on the stability of near-bed rockfill structures, on design and construction of statically stable berm breakwaters and on the structural response to ice loads
- a new section on design of rock protection works in ports
- a completely revised chapter on monitoring, inspection, maintenance and repair.

The following changes or omissions from the earlier versions have been made in this update:

- gravel beaches have been omitted, as these are covered in other reference texts on beach design
- detailed guidance on scour is omitted, as this subject is well covered in other reference texts and manuals
- appendices on rock measurement, hydraulic and geotechnical data collection have been omitted.

The chapter on construction provides reference to recent research on safety and construction risk. Chapter 10 on monitoring, inspection, maintenance and repair concentrates on practical experiences and approaches to post-construction monitoring and to upgrading and repair of structures.

This publication is available in English and French language as both a book and a CD-Rom. The material can also be downloaded from the CIRIA and CETMEF websites (<www.ciria.org/><www.cetmef.equipement.gouv.fr>). A large number of equations from this manual are included in the software package CRESS, which is free to download from the website <www.cress.nl>.

More than 100 experts from Europe and across the world have been involved in the project to update *The Rock Manual*, ensuring the updated edition will retain its place as the number one reference guide worldwide for the use of rock in hydraulic engineering.

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Three national backing groups were established to guide the project and represent the stakeholders of the partner countries.

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Contents

Glossary

Abutment That part of the valley side against which a **dam** is constructed or, in the case of bridges, the approach embankment, which may intrude some distance into the waterway.

Accretion Process by which particles carried by the flow of water are deposited and accumulate (the opposite of **erosion**).

All-in A material that includes everything that passes through a spacing of a grizzly or a screen aperture.

Alternative granular materials Granular materials excluding rock sourced from quarries and natural deposits. They include secondary and recycled materials.

Alternative materials Materials, such as plastic and rubber, that are not usually considered to be traditional construction materials.

Apron Layer of stone, concrete or other material to protect a structure's toe against **scour**.

Armour layer Outer layer of larger and/or more durable material used as protection against waves and/or currents and/or ice loads.

Armourstone Coarse aggregates used in hydraulic structures and other civil engineering works.

Armourstone quality designation (AQD) A numerical value of the overall quality of an armourstone source between 1 (poor) and 4 (excellent).

Armour stone or unit A relatively large quarry stone or concrete block that is selected to fit specified requirements of mass and shape; it is placed in a **cover layer**.

Attrition Degradation mechanism related to shear movement of particles.

Back-rush The seaward return of the water following the **up-rush** of a wave.

Backwater curve The longitudinal profile of the water surface in an open channel where the depth of flow has been increased by an obstruction such as a **weir** or a **dam** across the channel, by an increase in channel roughness, by a reduction of channel width or by a lessening of the bed gradient.

Barrage Structure built in an **estuary** with the specific intention of preventing, or in some way modifying, tidal propagation.

Barrier The function of a barrier is to control the water level. It consists of a combination of a concrete or a steel structure with or without adjacent **rockfill dams**.

Bastion A massive **groyne** or a projecting section of seawall, normally constructed with its crest above water level.

Bathymetry Underwater topography of sea, estuary or lake bed.

Bedload Sediment transport mode in which individual particles either roll or slide along the bed as a shallow, mobile layer a few particle diameters deep; the part of the load that is not continuously in suspension.

Bed protection A (rock) structure on the bed intended to protect the underlying bed against erosion by current and/or wave action.

Bed shear stress Stress acting tangentially to the bed and represent wave and current energy transfer to the bed.

Berm

1. Relative small mound to support or key-in an **armour layer**.
2. A horizontal step in the sloping profile of an **embankment** or **breakwater**.

Berm breakwater	Rubble mound structure with a horizontal **berm** of **armour stones** at about design water level, which is allowed to be (re)shaped by the waves.
Bifurcation	The point where a river separates into two or more reaches or branches (the opposite of a **confluence**).
Blanket	A layer or layers of graded fine stones underlying a breakwater, rock **embankment** or **groyne**. Its purpose is to prevent the natural bed material from being washed away.
Block size distribution	Sizes of armourstone pieces represented mathematically to reflect the relative proportions of smaller and larger pieces.
Braided river	A river type with multiple channels separated by shoals, bars and islands.
Breakage	Degradation of **armourstone** or **armour units** that can be categorised either as major breakage (or loss of integrity) or minor breakage.
Breaker zone	The zone within which waves approaching the coastline begin **wave breaking**, typically in water depths of between 5 m and 10 m.
Breakwater	A structure projecting into the sea that shelters vessels from waves and currents, prevents siltation of a navigation channel, protects a shore area or prevents thermal mixing (eg cooling water intakes).
Bulk density	Mass of **armourstone** placed in the works per unit volume; see **Placed packing density**.
Bund	Mound of material, such as rock, gravel, sand, clay, gabions etc.
Caisson	Concrete box-type structure.
Canal	A large artificial channel, generally of trapezoidal cross-section, designed for low-velocity flow.
Catchment area	The area that drains naturally to a particular river, thus contributing to its natural discharge.
Channel	1 A natural or artificial waterway of perceptible extent that either periodically or continuously contains moving water, or that forms a connecting link between two bodies of water. 2 The part of a body of water deep enough to be used for navigation through an area otherwise too shallow for navigation. 3 A large strait, such as the English Channel. 4 The deepest part of a stream, bay or strait through which the main volume or current of water flows.
Coastal defence(s), coastal works	Collective terms covering protection provided to the coastline. These include **coast protection** and **sea defences**.
Coastal processes	The action of natural forces on the coastline and adjoining sea bed.
Coastal regime	The overall system resulting from the interaction on the coast and sea bed of the various **coastal processes**.
Coast protection	Works to protect land against **erosion** or encroachment by the sea.
Cofferdam	A temporary watertight structure enclosing all or part of the construction area so that construction can proceed in the dry.
Combined closure method	Construction of a **dam** partly by means of the **horizontal closure method** and partly by the **vertical closure method**.
Confluence	The junction of two or more river reaches or branches (the opposite of a **bifurcation**).
Co-ordination number	The average number of points of contact that each armour unit makes with its neighbouring units in an armour layer.

Core	An inner, often much less permeable, portion of a **rubble mound structure**.
Core materials	Materials used primarily for the function of volume filling. Their fines content and upper sizes may be controlled, but there is normally no constraint on their median mass or size.
Cover layer	The outer layer used in a **rubble mound structure** as protection against external hydraulic loads.
Crest	Highest part of a breakwater, seawall, **sill** or **dam**.
Crown wall	Concrete superstructure on a **rubble mound structure**.
Crusher run	Material that includes everything passing through the primary crusher. The top size is therefore restricted by crusher aperture settings.
Dam	Structure built in rivers or estuaries to separate water on either side and/or to retain water at one side (in the estuarine environment the term **barrage** is also used).
Damage level	A scale for assigning the degree of damage of an armour layer with respect to an undamaged layer, usually based upon the cross-sectional area of armour layer removed by hydraulic action and normalised in relation to armour unit size.
Datum	Any permanent line, plane or surface used as a reference datum to which elevations are referred.
Deep water	Water so deep that surface waves are little affected by the sea bed. Generally, water deeper than one half the surface **wavelength** is considered deep water.
Design storm	A hypothetical extreme storm whose waves coastal structures will often be designed to withstand. The severity of the storm (ie **return period**) is chosen in view of the acceptable level of risk of damage or failure. A design storm consists of a design wave condition, a design water level and a duration.
Detached breakwater	A breakwater without any constructed connection to the shore.
Diffraction	Process by which energy is transmitted laterally along a wave crest. Propagation of waves into the sheltered region behind a **barrier** such as a breakwater.
Dike	Earth structure along sea or river constructed to protect low lands from flooding by high water (the term dike is often also used for **embankments**; **dikes** along rivers are sometimes called **levees**).
Dimension stone quarry	A quarry producing ornamental and building stone in which orthogonal blocks are cut out or split from the rock mass, in contrast to aggregate quarries, in which explosives are used to fragment the rock.
Discontinuity	A zone or plane of weakness within a rock mass or in a rock block.
Diversion channel	A **waterway** used to divert water from its natural course. The term is often applied to a temporary arrangement, eg to take water around a **dam** site during construction.
Downdrift	The direction of predominant movement of littoral drift along the shore.
Drowned flow	See **subcritical flow**.
Durability	The ability of a material to retain its physical and mechanical properties when exposed to actual loading during the service life.
Ebb	Period when tide level is falling; often taken to mean the **ebb current** that occurs during this period.
Ebb current	Tidal current away from shore or down a tidal stream.
Eddy	A vortex-type motion of fluid flowing partly opposite to the main current.
Embankment	Fill material, usually earth or **rock**, placed with sloping sides and with a length greater than its height (the term embankment is often also used for **dikes**).

Erosion — Process by which particles are removed by the action of wind, flowing water or waves (the opposite of **accretion**).

Estuary

1. The part of a river that is affected by tides.
2. The region near a river mouth in which the fresh water of the river mixes with the salt water of the sea and that receives both fluvial and littoral sediment influx.

Facing — A coating of a different material, masonry or brick, for architectural or protection purposes, eg stonework facing, brickwork facing (concrete dam) or an impervious coating on the upstream slope of the **dam**.

Factory production control (FPC) — A system for monitoring, with feedback and adjustment where necessary, performed by periodically testing samples, equipment and procedures to ensure the production process continues to generate materials of expected properties.

Fascine mattress — A blanket constructed from willow branches or bamboo poles, **geotextile** and reed lashed together to protect a shoreline, **embankment** or river bed or sea bed against **erosion**.

Fetch (length) — Relative to a particular point (on the sea), the area of sea over which the wind can blow to generate waves at the point. The fetch length depends on the shape and dimensions of the fetch area and upon the relative wind direction.

Filter — Intermediate layer, preventing the fine materials of an underlayer from being washed through the voids of an upper layer.

Fictitious wave steepness — The ratio of the local wave height - in shallow water - and the theoretical deep-water wavelength, expressed in terms of the local wave height and the wave period accompanied with a factor.

Flood

1. Period when tide level is rising; often taken to mean the **flood current** that occurs during this period.
2. A flow beyond the carrying capacity of a channel.

Flood current — Tidal current towards the shore or up a tidal stream.

Floodplain — The low-lying area adjacent to a river, often contained within flood **embankments**.

Flood routing — The attenuating effect of storage on a flood passing through a valley, a **channel** or **reservoir** by reason of a feature acting as a control, eg a reservoir with a spillway capacity less than the flood inflow or the widening or narrowing of a valley.

Flood wall, splash wall — Wall, set back from the seaward edge of the seawall crest, to prevent water from flowing on to the land behind.

Flow regime — Combinations of river discharge and corresponding water levels and their respective yearly or seasonally averaged values and characteristic fluctuations around these values.

Foreshore — The part of the shore lying between mean high water (spring) and mean low water level (spring).

Fractile — The variable value below which a given fraction of the cumulative frequency lies.

Freeboard — The height of a structure above **still water level**.

Gabion — Generic name given to a revetment system consisting of stone contained in steel or polymer mesh. Types include box gabions, gabion mattresses and sack gabions.

Geotextile — A synthetic fabric, woven or non-woven, used as a **filter** or separation layer.

Gradation — Parameter that characterises the width of a mass distribution or size distribution.

Grading — Distribution defined by nominal and extreme limits, with regard to size or mass of individual stones. Heavy, light and coarse gradings are distinguished.

Granular filter	A band of granular material incorporated in an **embankment** dam and graded so as to allow **seepage** to flow across or down the filter zone without causing the migration of the material from zones adjacent to the **filter**.
Grouted materials	Loose granular materials that have been treated with a grout – usually of bituminous or cementitious origin – such that the particles are less able to move because of the binding action of the grout.
Groyne	A structure generally perpendicular to the shoreline built to control the movement of beach material.
Head	End of a **breakwater** or **dam**.
Headwater level	The level of water in the **reservoir**.
Horizontal closure method	Construction of a **dam** by dumping the materials from one or both banks, thereby progressively constricting the **waterway** laterally until the gap is closed. The method is also known as end dumping, and point tipping (the opposite of vertical closure method).
Hydraulics	Science of the motion, flow and mass behaviour of water.
Hydrology	Science of the hydrological cycle, including precipitation, runoff and fluvial flooding.
Incident wave	A wave moving landward.
In-service degradation model (armourstone)	A model under research and development that attempts to predict yearly mass losses from the **armourstone**, taking account of rock properties and site conditions.
***In situ* block size distribution (ISBD)**	The block size distribution consisting of all the distinct pieces of rock bounded by discontinuities located within the rock mass before excavation.
Intact fabric strength	Strength of rock derived from the strength and fabric of the rock's minerals.
Integrity	The ability of a piece of **armourstone** to remain in one piece during construction and service that is controlled by geological or production-induced discontinuities.
Internal erosion	The formation of voids within soil or soft rock caused by the mechanical or chemical removal of material by **seepage**.
Intertidal	The zone between the high and low water marks.
Irregular waves	Waves with random wave periods (and in practice, also heights), which are typical for natural wind-induced waves.
Length-to-thickness ratio	Shape description of a piece of **armourstone** calculated by dividing its maximum length by its minimum thickness.
Levee	Flood **embankment**.
Limit states	Conditions under which a structure can no longer perform its intended functions. Ultimate limit states (ULSs) are related to the safety of the structure and they define the limits for its total or partial collapse. Serviceability limit states (SLSs) represent those conditions that adversely affect the expected performance of the structure under normal service loads.
Lining	A coating of asphaltic concrete, concrete or reinforced concrete to provide watertightness, to prevent **erosion** or to reduce friction of a canal, tunnel or shaft.
Littoral zone	Beach and **surf zone**.
Longshore	Parallel to and near the shoreline.
Longshore transport	Wave-induced movement of sediment, stones or gravel along a beach (but also along sloping rock structures).
Low-lying	Used to describe land or infrastructure located below sea level or in a floodplain that is at risk from flooding.

Mach-stem wave	Higher-than-normal wave generated when waves strike a structure at an oblique angle.
Maintenance	**Repair** or replacement of components of a structure whose life is less than that of the overall structure, or of a localised area that has failed.
Major breakage	Breakage of pieces of **armourstone** resulting from failure along pre-existing geological or production-induced **discontinuities**, usually resulting in particle mass reductions of greater than 10 per cent.
Manufactured armourstone	**Armourstone** resulting from an industrial process involving thermal or other modification (excluding concrete armour units).
Maximum water level	The maximum water level, including flood surcharge, that the **dam** has been designed to withstand.
Meandering	A single channel characterised by a pattern of successive deviations in alignment that results in a more or less sinusoidal course.
Mean wave period	The mean period of the wave defined by zero-crossing analysis of a wave record.
Minor breakage	Breakage of pieces of **armourstone** resulting from crushing, shearing, spalling and splitting through the mineral fabric, usually resulting in particle mass reductions of less than 10 per cent.
Modular flow	See **supercritical flow**.
Monochromatic waves	See **regular waves**.
Morphology	River, estuary, lake or seabed form and its change with time.
Numerical model	Mathematical equations that describe reality and permit prediction of the behaviour of flows, sediment and structures.
Offshore	1 In beach terminology, the comparatively flat zone of variable width, extending from the shoreface to the edge of the continental shelf. It is continually submerged. 2 The direction seaward from the shore. 3 The zone beyond the nearshore zone where sediment motion induced by waves alone effectively ceases and where the influence of the sea bed on wave action is small in comparison with the effect of wind. 4 The breaker zone directly seaward of the low tide line.
One-dimensional (1D) model	A **numerical model** in which all the flow parameters are assumed to be constant over the cross-section normal to the flow. There is only a velocity gradient in the flow direction.
Orthogonal wave ray	In a wave refraction or diffraction diagram, a line drawn perpendicular to the wave crest.
Outlet	An opening through which water can be freely discharged from a **reservoir** to a river for a particular purpose.
Outflanking	**Erosion** or **scour** behind or around the land-based end of a structure that may threaten to compromise the stability or integrity of the structure and its function.
Overtopping	Passing of water over the top of a structure as a result of wave **run-up** or surge action.
Parapet	Solid wall at the crest of a **seawall** projecting above deck level.
Parapet wall	See **crown wall**.
Peak period	The wave period determined by the inverse of the frequency at which the wave energy spectrum reaches a maximum.
Permeability	The property of bulk material (sand, crushed rock, soft rock *in situ*) that permits movement of water through its pores.

Physical model See **scale model**.

Pitched stone Squared masonry, precast blocks or embedded stones laid in regular fashion with dry or filled joints (to increase friction forces). It is often placed on **dikes**, **revetments**, the upstream slope of an **embankment** dam or on a **reservoir** shore as a protection against wave and ice action.

Placed packing density Mass per unit volume of **armourstone** placed in the works. The value obtained is very sensitive to the type of placement (ie loose, dense, random, standard); the **grading**, shape and density of the rock materials; the method used to survey the volume; and whether the element is thin-layered or bulk-filled.

Packing (density) The number of armour units per unit area, equal to the ratio of the part of the armour layer thickness occupied by material to the volume of the armour unit (which ratio is also equal to the ratio of the **packing density coefficient** to the squared nominal diameter of the armour unit). The value obtained is sensitive to the method of placement, the grading in the case of armourstone and the shape of the armourstone or the concrete armour unit.

Packing density coefficient The **packing density** times the squared nominal diameter of the armour unit, equal to the ratio of the part of the armour layer thickness occupied by material to the nominal diameter of the armour unit.

Pore pressure The interstitial pressure of fluid (air or water) within a mass of soil, rock or concrete.

Porosity Property of a **material** or **armour layer** expressed as the percentage of the total volume occupied by air and water rather than solid particles.

Porous For **revetments** and **armour layer**, the permitting of rapid through movement of water, such as during wave action. Many **geotextiles** and sand asphalt can be non-porous under the action of waves but are porous in soil mechanics terms.

Primary materials Materials whose production has involved extraction from virgin natural reserves.

Prototype The actual structure or condition being simulated in a model.

Quality control A system of procedures, including documentation, based on repeated monitoring and feedback with adjustment as necessary, with the purpose of maintaining a target performance or property.

Quasi-three-dimensional (3D) model A **numerical model** in which the flow parameters vary in two dimensions, but which allows determination of the flow parameter in the third dimension.

Quarry run **Materials** with no fines control and including all granular material found in the quarry blastpile that can be picked up in a typical loading shovel; ie only blocks too large for easy digging and loading are left behind.

Random waves The laboratory simulation of irregular sea-states which occur in nature.

Reach

1. An arm of the ocean extending into the land, eg an **estuary**.
2. A straight section of restricted waterway that is uniform with respect to discharge, slope and cross-section.

Recycled material Material that has been collected and separated from the waste stream and that has undergone some form of processing so that it can be used again.

Reef breakwater **Rubble mound** of single-sized stones with a crest at or below sea level that is allowed to be (re)shaped by the waves.

Reflected wave That part of an incident wave that is returned seaward when a wave impinges on a beach, seawall or other reflecting surface.

Reflection The process by which (part of) the energy of the wave is returned seaward.

Refraction (of water waves)	The process by which the direction of a wave moving in **shallow water** at an angle to the depth contours is changed so that the wave crests tend to become more aligned with those contours.
Regime theory	Empirical method for predicting river characteristics.
Regular waves or monochromatic waves	Waves with a single height, period and direction.
Regulating reservoir	A **reservoir** from which water is released so as to regulate the flow in the river.
Rehabilitation	Restoring to good condition, operation or capacity. This implies that steps are taken to correct problems before the structure's functionality is significantly degraded. Rehabilitation can also be thought of as preventative **maintenance**.
Repair	Restoring to good condition after damage has occurred and a structure's functionality has been greatly reduced. Repair can also be thought of as corrective **maintenance**.
Replacement	Process of demolition and reconstruction.
Reservoir	An artificial lake, basin or tank in which a large quantity of water can be stored.
Retention water level	For a **reservoir** with a fixed overflow **sill**, the lowest crest level of that sill. For an outflow controlled wholly or partly by movable gates, syphons or other means, the retention water level is the maximum level at the **dam** to which water may rise under normal operating conditions, exclusive of any provision for flood surcharge.
Return period	Inverse of the probability that a given event will occur in any one year. It can also be considered as the statistical average period of time between occurrences of the event.
Reuse	The use of materials recovered from waste materials without further processing.
Revetment	A sloping surface of stone, concrete or other material used to protect an embankment, natural coast or shoreline against erosion.
Rip-rap	Wide-graded quarry stone normally bulk-placed as a protective layer to prevent **erosion** of the sea bed and/or river bed, riverbanks or other slopes (possibly including the adjoining crest) by current and/or wave action.
River regime	Combinations of river discharge and water levels characteristic for a prescribed period (usually a year or a season). The river regime determines the overall **morphology** of the river.
River training structure	Any configuration constructed in a stream or placed on, adjacent to or in the vicinity of a streambank that is intended to deflect currents, induce sediment deposition, induce **scour** or otherwise alter the flow and sediment **regimes** of a river.
Rock	Natural accumulation of minerals bound together by geological processes to produce a compact solid.
Rockfill closure dam	Structure primarily designed to stop water flow. It is composed of loose stone (usually dumped) in place and characterised by high flows in the final stages of the closure.
Rock weathering	Physical and mineralogical decay processes in rock brought about by exposure to climatic conditions either at the present time or in the geological past.
Roundhead	Circular-shaped head of a breakwater, often reinforced by using larger armour units, higher-density armour units and/or a reduced slope.
Rubble mound structure	A mound of random-shaped and random-placed stones protected by a cover layer of selected **armour stones** or specially shaped concrete **armour units**. The **armour layer** may be placed in an orderly manner or dumped at random.

Run-up, run-down	The upper and lower levels reached by a wave on a beach or coastal structure, relative to still water level, measured vertically.
Sampling (rock)	Selection and assessment by test methods of a small proportion of a large collection of rock particles or rock mass.
Scale or physical model	Simulation of a structure and/or its (hydraulic) environment, usually in much smaller dimensions, to enable the consequences of future changes to be predicted. The model can be built with a fixed bed or a movable bed.
Scour	**Erosion** resulting from shear forces associated with flowing water and wave actions.
Scour protection	Works to prevent or mitigate **scour**.
Sea defences	Works to prevent or alleviate flooding by the sea.
Sea state	Description of the sea surface with regard to wave action.
Secondary materials	Materials used in construction that have already been used or are recovered from the waste stream of other activities.
Sediment load	The sediment carried through a **channel** by streamflow.
Seepage	The interstitial movement of water that may take place through a **dam**, its foundation or **abutments**.
Seiche	Standing wave oscillation of the water surface that may occur in a closed or semi-closed body of water with the natural frequency of oscillation for that water body.
Shallow water	Commonly, water of such depth that surface waves are noticeably affected by bottom topography. It is customary to consider water of depths less than half the surface wavelength as shallow water.
Shoulder	Horizontal transition between sloping sections of a structure, often used where there is a change in stone size.
Significant wave height	Average height of the highest one-third of the waves in a given **sea state**.
Significant wave period	Average of the periods associated with the highest one-third of wave heights in a given **sea-state**.
Sill	1 A submerged structure across a river to control the water level upstream. 2 The crest of a spillway.
Skewness	The phenomenon that as gravity waves become steeper their profile becomes distorted with a tendency towards sharper crests and flatter **troughs**, characteristic of the classical shape of the Stokes infinite wave train. Such a profile has a non-zero third moment, ie the skewness is greater than zero.
Slope	The inclined face of a cutting or canal or **embankment**.
Slope protection	The protection of **embankment** slope against wave action or **erosion**.
Soft defences	Usually refers to sand beaches (natural or designed), but may also refer to energy-absorbing structures including those consisting of gravel (or **shingle**).
Specification	Document detailing the materials, construction and/or measurement requirements for a contract, agreed by the contracted parties before they undertake the contract.
Spillway	A structure over or through which flood flows are discharged.
Spur (-dike) or groyne	A structure extending from a bank into a channel that is designed usually to protect the banks or to provide sufficient water depth for navigation purposes.
Stationary process	A process in which the mean statistical properties do not vary with time.
Stilling basin	A basin constructed to dissipate the energy of fast-flowing water, such as that from a **spillway** or bottom outlet, and to protect the river bed from erosion.

Still water level	The water level that would exist in the absence of waves.
Stochastic	Having random variation in statistics.
Stone	Piece of **rock**.
Storage reservoir	A **reservoir** operated with changing water level for the purpose of storing and releasing water.
Storm surge	A rise in water level in the open coast caused by the action of wind stress as well as atmospheric pressure on the sea surface.
Subcritical	The flow condition above a dam by which the **tailwater** level influences the upstream head. The discharge is a function of upstream and downstream head. Also called submerged flow, submodular flow or **drowned flow**.
Supercritical	The flow condition above a **dam** by which the upstream head is independent of the **tailwater** level. The discharge is a function of the upstream head only. Also called free flow, rapid flow or **modular flow**.
Supplier	Party from whom the purchaser takes materials in return for a fee. This may be the producer, a transport agent or a contractor.
Surf zone	The area between the outermost breaker and the limit of the wave **run-up**.
Suspended load	The material moving in suspension in a fluid, kept up by the upward components of turbulent currents or by colloidal suspension.
Swell (waves)	Wind-generated waves that have travelled out of their generating area. Swell characteristically exhibits a more regular and longer period and has flatter crests than waves within their **fetch**.
Tailwater level	The water level downstream of a **dam** or **sill**.
Thalweg	The locus of the deepest points in a valley at successive cross-sections.
Tides	Water movements that essentially are generated by the global response of oceans to astronomic effects. On the continental shelves and in coastal waters, particularly bays and estuaries, the effect is amplified by shallow water and coastal platforms.
Toe	The lowest part of a coastal or fluvial defence structure. Often it provides support for the slope protection.
Toe blanket	See **apron**.
Total load	The sum of **bed load** and **suspended load** in the river.
Tout venant	See **quarry run**.
Training wall	A wall built to confine or guide the flow of water over the downstream face of an overflow **dam** or in a **channel**.
Transmission	The process of wave energy passing over and through a (low) crested structure and generating waves behind the structure.
Tsunami	Gravity waves that originate from earthquakes below the ocean. Their **wavelengths** are in the order of minutes rather than seconds.
Two/three-dimensional (2D or 3D) model	A mathematical model in which the flow parameters vary in two or three dimensions.
Underlayer	Granular layer beneath an **armour layer** that serves either as a **filter** or to even-out the formation level.
Uniformity index	Parameter expressing the **gradation** in Rosin-Rammler distribution.
Upgrading	Improved performance against a particular criterion.
Uplift	Upward pressure in the pores of a material (interstitial pressure) or on the base of a structure.

Up-rush, down-rush	The flow of water up or down the face of a structure following **wave breaking**.
Vertical closure	Construction of a **dam** by dumping the materials over the full width. During this operation the dam crest is raised more or less uniformly over the entire gap until the channel is completely blocked. The method is also known as frontal dumping, **horizontal closure** and traverse dumping.
Vesicular	Used to describe basalt and other volcanic rocks containing many spherical or ellipsoidal cavities produced by bubbles of gas trapped during solidification.
Water level	Elevation of still water level relative to a **datum**.
Waterway	A navigable **channel**.
Wave breaking	Reduction in wave energy and height in the surf zone due to limited water depth.
Wave height	The vertical distance between a crest and the preceding trough.
Wavelength	The horizontal distance between two successive crests or troughs in a wave record.
Wave number	Inverse of the **wavelength** times 2π.
Wave period	The time for a wave crest to traverse a distance equal to one **wavelength**.
Wave return face	The face of a **crown wall** designed to throw back the waves.
Wave set-down	Drop in water level beyond the **breaker zone** to conserve momentum as wave particle velocities and pressures change before **wave breaking**.
Wave set-up	Superelevation of the water surface over the normal surge elevation attributable to onshore mass transport of the water by wave action alone.
Wave spectrum	A function that describes the distribution of wave energy over wave frequency.
Wave steepness	The ratio of **wave height** to **wavelength**.
Wear	Superficial degradation of a material that may be induced by **weathering** or **attrition**.
Weathering	Physical, chemical and biological action that leads to deterioration in strength of the rock mass or deterioration in strength of the pieces of produced **armourstone**.
Weir	A low dam or wall across a stream to raise the upstream water level. When uncontrolled, it is termed a fixed crest weir.
Yield curve	Cumulative plot of the blasted **block size distribution** of a quarry. It refers to a period of production and is often taken as the basis for calculating the relative proportions of available quarry materials. The yield curve may either be a prediction or an analysis of past production.

Abbreviations

2DV	Two-dimensional, vertical averaged
AQD	Armourstone quality designation
BBSD	Blasted block size distribution
CLASH	Crest Level Assessment of coastal Structures by full-scale monitoring, neural network prediction and Hazard analysis on permissable wave overtopping
CWD	Composite Weibull distribution
DELOS	Environmental DEsign of LOw-crested coastal defence Structures
DGPS	Differential global positioning system
DSF	Directional spreading function
DT	Drop test
DTM	Digital terrain model
DWT	Deadweight tonnage
EDM	Electronic distance measurement
EIA	Environmental Impact Assessment
ELL	Extreme lower limit of armourstone grading
ES	Environmental Statement
EUL	Extreme upper limit of armourstone grading
FEM	Finite element method
FSCT	Full-scale crushing test
FSST	Full-scale splitting test
GPS	Global positioning system
HWL	High water level
IBSD	*In situ* block size distribution
ICOLD	International Commission on Large Dams
ITT	Initial type testing
JONSWAP	Joint Northsea Wave project
LAT	Lowest astronomical tide
LIDAR	Light detection and ranging
LWL	Low water level
LWS	Low water spring
MDE	Micro-Deval method
NLL	Nominal lower limit of armourstone grading
NUL	Nominal upper limit of armourstone grading
PIANC	Permanent International Association of Navigation Congresses (now called International Navigation Association)

PM	Pierson-Moskowitz (wave energy) spectrum
PMS	Principal mean spacing
POT	Peak over threshold
MCWI	Meterological Climate Weathering Intensity
MHWN	Mean high water neap
MHWS	Mean high water spring
MLWS	Mean low water spring
MLWN	Mean low water neapMSL Mean sea level
MWL	Mean water level
ROV	Remotely operated (underwater) vehicles
RQD	Rock quality designation
RTK	Real-time kinematic
SLS	Serviceability limit state
SWL	Still water level
TMA	Texel-Marsen-Arsloe project
UCS	Uniaxial compressive strength
ULS	Ultimate limit state

Notation

A	Area general; total surface area of armour layer panel parallel to slope	(m²)
A_a	Area covered by one armour unit, equal to: nA/N_a	(m²)
A_b	Area of basin	(m²)
A_c	Cross-sectional area of waterway	(m²)
A_{cs}	Cross-sectional area (of armour layer)	(m²)
A_e	Erosion area on rock profile	(m²)
A_t	Total area of structure cross-section	(m²)
A_S	Pipeline steel wall cross-sectional area, $= 2\pi R t$, where t = wall thickness	(m²)
AQD	Armourstone quality designation	(-)
a	Acceleration	(m/s²)
a	Coefficient used in various empirical formulae	(-)
a_o	Amplitude of horizontal (orbital) wave motion at bed	(m)
B	Structure width at crest, in horizontal direction normal to face	(m)
B	Channel width	(m)
B	Width of the constricted river in case of spur-dikes	(m)
BLc	Blockiness, the volume of a block divided by the volume of the enclosing *XYZ* orthogonal	(-)
B_B	Berm width	(m)
B_a	Width of armour berm at crest	(m)
B_n	Breakage rate	(%)
B_s	Beam width of ship	(m)
b	Width of closure gap	(m)
b	Width of fairway	(m)
b	Coefficient used in various empirical formulae	(-)
b_t	idem, at the bed (toe)	(m)
b_w	Width of waterway on waterline	(m)
b_0	Initial width of closure gap	(m)
C	Chezy coefficient	(m$^{1/2}$/s)
C_D	Drag coefficient	(-)
C_{FSST}	Characteristic integrity determined using FSST	(J/kg)
C_c	Compression index	(-)
C_r	Wave reflection coefficient	(-)
C_s	Recompression index	(-)
C_t	Wave transmission coefficient	(-)
C_U	Coefficient of uniformity, $= D_{60}/D_{10}$	(-)
c	Cohesion of soil	(N/m²)
c	Propagation celerity of waves	(m/s)
c_g	Group velocity	(m/s)
c_k	Creep coefficient	(-)
c_T	Turbulence coefficient (in Escarameia and May stability formula)	(-)
c_v	Consolidation coefficient	(m²/s)
D	Particle size, or typical dimension/block height of concrete armour unit	(m)
D_I	Indicative grain size diameter	(m)
D'	Basket or mattress thickness	(m)
D_f	Degree of fissuration	(-)
D_n	Nominal block diameter, or equivalent cube size, $D_n = (M/\rho_{app})^{1/3}$	(m)
D_{n50}	Median nominal diameter, or equivalent cube size, $D_{n50} = (M_{50}/\rho_{app})^{1/3}$	(m)
D_p	Diameter of ship propeller; diameter of pipe	(m)

D_s	Size of the equivalent volume sphere	(m)
D_z	Block size corresponding to sieve size z	(m)
D_{50}	Sieve diameter, diameter of stone that exceeds the 50% value of sieve curve	(m)
D_{85}	85% value of sieve curve	(m)
D_{15}	15% value of sieve curve	(m)
$D_{63.2}$	Location parameter in the Rosin-Rammler equation for sieve size distribution	(m)
D_*	Non-dimensional sediment grain diameter, $D_* = D_{50}(g\Delta/\nu^2)^{1/3}$	(-)
d	Structure (crest) height relative to bed level (breakwaters, dams etc)	(m)
d	Thickness or minimum axial breadth (given by the minimum distance between two parallel straight lines between which an armour block can just pass)	(m)
d_c	Crown wall height	(m)
d_{ca}	Difference of level between crown wall and armour crest, $d_{ca} = R_c - R_{ca}$	(m)
E	Young's Modulus	(N/m²)
E	Estuary number	(-)
E_c	Impact energy absorbance capacity	(kNm)
E_D	Total degradation energy applied to the material	(J)
E_i	Incident wave energy	(N/m)
E_r	Reflected wave energy	(N/m)
E_t	Transmitted wave energy	(N/m)
$E_{\eta\eta}$	Energy density of a wave spectrum	(m²s)
$E_{i;d}$	Design value of the effect of actions	(Unit of E)
$E_{i;k}$	Characteristic value of the effect of actions	(Unit of E)
e	Void ratio, $e = n_v/(1 - n_v)$	(-)
e_{sp}	Spur ratio, defined as the ratio of the head loss in a river between two successive spur-dikes, $U^2S_{sp}/(C^2h)$, and the velocity head, $U^2/(2g)$	(m)
F	Fetch length	(m)
F	Factor of safety (geotechnical), defined as ultimate resistance/required resistance	(-)
F^*	Non-dimensional freeboard parameter, $F^* = (R_c/H_s)^2 (s_{om}/2\pi)$	(-)
Fr	Froude number, $Fr = U/(gh)^{1/2}$	(-)
F_H	Horizontal force (on caisson or crown wall element)	(N/m)
F_U	Uplift force (on caisson or crown wall element)	(N/m)
$F_{j;d}$	Design value of an action or force	(N/m)
$F_{j;k}$	Characteristic value of an action or force	(N/m)
F_q	Discharge factor, ratio of critical discharge for bed protection and that of closure dam, $q_{cr\text{-}b}/q_{cr\text{-}d}$	(-)
F_o	Parameter expressing the amount of fines after minor breakage	(%)
F_s	Shape factor (of armour stone)	(-)
f	Friction factor	(-)
f	Frequency of waves, $f = 1/T$	(1/s)
f	Lacey's silt factor	(-)
f_c	Friction factor for currents	(-)
f_i	Stability increase factor for armourlayers with stepped or bermed slopes	(-)
f_p	*Peak* frequency of wave spectrum	(1/s)
f_w	Friction factor for waves	(-)
G	Shear modulus	(N/m²)
g	Gravitational acceleration	(m/s²)
H	Wave height, from trough to crest	(m)
H	Water level upstream of a dam or sill, relative to dam crest	(m)
$H_{1/10}$	Mean height of highest 1/10 fraction of waves	(m)
$H_{1/3}$	Significant wave height based on time domain analysis, average of highest 1/3 of all wave heights	(m)
$H_{2\%}$	Wave height exceeded by 2% of waves	(m)
Ho	Stability number, $Ho = N_s = H_s/(\Delta D_{n50})$	(-)
$HoTo$	Dynamic stability number, $HoTo = N_{sd} = N_sT_m(g/D_{n50})^{1/2}$	(-)
H_d	Drop height	(m)

H_i	Wave height of secondary ship-induced waves	(m)
H_{m0}	Significant wave height calculated from the spectrum, $H_{m0} = 4\sqrt{m_0}$	(m)
H_{max}	Maximum wave height in a record	(m)
H_o	Offshore or deep-water wave height	(m)
H_{rms}	Root mean square wave height	(m)
H_s	Significant wave height, $H_s = H_{1/3}$	(m)
$H_{s,b}$	Breaking significant wave height	(m)
H_{so}	Deep-water significant wave height	(m)
h	Water depth; water depth at structure toe	(m)
$\hat{h}$	Maximum water depth of a channel	(m)
h_0	Water depth at critical section on closure dam during vertical closure	(m)
h_1	Water depth upstream of dam, relative to bed level	(m)
h_2	Water depth in closure gap, relative to bed level	(m)
h_3	Water depth downstream of dam, relative to bed level	(m)
h_B	Water depth above berm	(m)
h_b	Tailwater depth downstream of dam or sill, relative to dam crest	(m)
h_c	Water depth above structure crest	(m)
h_f	Depth of intersection point between original berm and reshaped berm	(m)
h_s	Water depth at a distance of l/2L or 5H_{max} seaward of structure toe	(m)
h_t	Water depth at structure toe, depth of the toe relative to SWL	(m)
h_t	Water depth above transition in composite slope	(m)
I_D	Density index, $I_D = (e_{max} - e)/(e_{max} - e_{min})$	(-)
I_{FSST50}	Full-scale splitting index	(-)
I_{Mx}	Relative decrease of characteristic percentage passing mass	(-)
I_c	Continuity index, equal to $V_p/V^* \times 100$	(%)
I_d	Normalised velocity anisotropy index	(-)
I_{d50}	Drop test breakage index	(-)
I_p	Plasticity index of soil	(-)
$I_{s(50)}$	Point load strength index	(N/m²)
I_s	Sinuosity index	(-)
i	Hydraulic gradient of (phreatic) water level	(-)
i_b	Gradient of river bed	(-)
i_{cr}	Critical hydraulic gradient	(-)
i_n	Transversal hydraulic gradient	(-)
i_p	Longitudinal hydraulic gradient	(-)
i_w	Wind-induced gradient of still water surface	(-)
K	Stability or velocity factor (rock stability), $K = \sqrt{(1/K')} = k_t \sqrt{k_w}$	(-)
K	Modulus of compressibility	(N/m²)
K'	Velocity loading factor (armourstone stability), $K' = k_w^{-1} k_t^{-2}$	(-)
K_D	Stability coefficient, Hudson formula	(-)
K_R	Refraction coefficient	(-)
K_S	Shoaling coefficient	(-)
K_d	Diffraction coefficient	(-)
K_{wa}	Modulus of compressibility for water with air	(N/m²)
K_r	Reflection coefficient	(-)
k	Permeability coefficient according to Darcy	(m/s)
k	Wave number, $k = 2\pi/L$	(-)
k_B	Influence factor for berm width	(-)
k_c	Modified layer coefficient for concrete armour units	(-)
k_d	Slope reduction factor for critical bed shear stress on a slope normal to the flow direction	(-)
k_h	Influence factor for berm level relative to SWL	(-)
k_h	Velocity profile factor	(-)

k_l	Slope reduction factor for critical bed shear stress on a slope along the flow direction	(-)
k_r , k_r'	Factor, similar to k_d , but for wave run-up/down	(-)
k_s	Bed roughness	(m)
k_s	Rock fabric strength	(-)
k_s	Shape coefficient for concrete armour units, $k_s = (D_n/D)^3$	(-)
k_{sl}	Slope reduction factor for critical bed shear stress, $k_{sl} = k_l\, k_d$	(-)
k_w	Wave amplification factor for bed shear stress	(-)
k_t	Layer thickness coefficient	(-)
k_t	Turbulence amplification factor for current velocity	(-)
L	Wavelength, in the direction of propagation	(m)
L	Characteristic response distance (geotechnics)	(m)
L	Panel chainage length	(m)
L	Length of the thalweg of a river between two inflection points	(m)
LT	Length-to-thickness ratio, $LT = l/d$	(-)
L_b	Basin length	(m)
L_i	Wavelength of secondary ship-induced waves	(m)
L_k	Seepage length	(m)
L_{om}	Offshore or deep-water wavelength of mean period, T_m	(m)
L_m	Relative loss of mass in destructive testing	(-)
L_o	Offshore or deep-water wavelength, $L_o = gT^2/2\pi$	(m)
L_{op}	Offshore or deep-water wavelength of peak period, T_p	(m)
L_m , L_p	Wavelength in (shallow) water at structure toe, based on T_m and T_p	(m)
L_s	Ship length	(m)
L_{sp}	Length of a spur-dike	(m)
l	Maximum axial length (given by the maximum distance between two points on the block)	(m)
M	Mass of an armour unit	(kg)
M	Overturning moment	(kNm/m)
M	Earthquake magnitude – Richter scale	(-)
M_I	Impactor mass	(kg)
M_0	Initial mass before degradation test	(kg)
M_{50}	Mass of particle for which 50% of the granular material is lighter	(kg)
M_{50max}	Maximum M_{50} calculated to exist when $M_{em} = M_{emul}$ for a given grading	(kg)
M_{50min}	Minimum M_{50} calculated to exist when $M_{em} = M_{emll}$ for a given grading	(kg)
M_{DE}	Micro-Deval test value	(-)
M_{em}	Effective mean mass (of a standard grading), ie the arithmetic average of all pieces excluding those that fall below ELL for the grading	(kg)
M_{emll}	Lower limit requirement for M_{em} given in EN 13383 system of gradings	(kg)
M_{emul}	Upper limit requirement for M_{em} given in EN 13383 system of gradings	(kg)
M_y	Mass for which a fraction or percentage y is lighter on the cumulative mass distribution curve (eg M_{15} , M_{50})	(kg)
$M_{x,f}$	Value of M_x after degradation	(kg)
$M_{x,i}$	Value of M_x before degradation	(kg)
$MCWI$	Meteorological climate weathering intensity	(° cm/days²)
m	Seabed slope (gradient)	(-)
m_0	Zeroth moment of wave spectrum	(m²s)
m_n	n-th moment of spectrum	($m^{2+n}s$)
m_v	Coefficient of volume change	(m²/N)
m_{ve}	idem, elastic	(m²/N)
N	Number of waves over the duration T_r of a storm, record, or test, $N = T_r/T_m$	(-)
N_a	Total number of armour units in area considered	(-)
N_b	Bulk number (cross-section of stones), $N_b = A_t/(D_{n50})^2$	(-)
N_d	Damage number, the number of armour units displaced in area considered	(-)

N_e	Number of earthquake excitations	(-)
N_{od}	Damage number, the number of displaced units per width D_n across armour face	(-)
N_{ov}	Number of overtopping waves	(-)
N_s	Stability number, $N_s = H_s/(\Delta D_{n50})$	(-)
N_s^*	Spectral (or modified) stability number, $N_s^* = N_s (H_s/L_p)^{-1/3}$	(-)
N_{sd}	Dynamic stability number, $N_{sd} = N_s T_m (g/D_{n50})^{1/2}$	(-)
n	Number of layers	(-)
n	Manning's coefficient of bed roughness	(s/m$^{1/3}$)
n_{RRM}	Exponent (uniformity index) in Rosin-Rammler equation for mass distribution	(-)
n_{RRD}	Exponent (uniformity index) in Rosin-Rammler equation for size distribution, $n_{RRD} = 3n_{RRM}$	(-)
n_{RRDp}, $D_{63.2p}$, D_p	Values for the Rosin-Rammler segment length distribution used in association with the photo-scanline method for block-size assessment; uniformity index, characteristic segment length and segment length respectively	(-), (m), (m)
n_X	Scale factor of parameter X, $n_X = X_p/X_m$	(-)
n_v	Porosity of granular material within the component of the structure in question, equal to the volume of voids as a proportion of the total volume; the volumetric porosity, referred to as *armour layer porosity* for layered components and *bulk porosity* for bulk or volume-filling components	(-)
O, O_i	Opening size in geotextile, i%	(μm)
P	Notional permeability factor, defined by van der Meer	(-)
P	Wetted perimeter	(m)
P	Installed power of ship screw	(W)
$P(x)$	Probability function	(-) or (1/year)
P_R	Fourier asperity roughness based on the 11th to 20th harmonic amplitudes	(-)
p	Porosity of the rock	(-)
p	Pore water pressure; wave (-induced) or ice-crushing pressure	(N/m²)
$p(x)$	Probability density function	(1/x)
p_a	Atmospheric pressure at sea level	(N/m²)
p_i	Wave impact pressure	(N/m²)
p_p	Wave pulsating pressure	(N/m²)
p_u	Wave uplift pressure	(N/m²)
Q	Discharge	(m³/s)
Q/V	Specific charge of blasting	(kg/m³)
q	Time-averaged overtopping discharge per metre run of crest	(m³/s/m)
Q^*	Non-dimensional specific overtopping discharge, $Q^* = q/(T_m\, gH_s)$	(-)
q	Specific discharge	(m³/s/m)
R	Radius hydraulic, $R = A_c/P$	(m)
R	Radius	(m)
R_m	Mean hydraulic radius of voids in rockfill	(m)
Re	Reynolds number, $Re = 4RU/\nu$	(-)
Re_v	Reynolds number for flow through voids of rockfill	(-)
Re_*	Reynolds number with regard to shear velocity u_*	(-)
Rec	Recession of berm of berm breakwater	(m)
R'	Equivalent rock roughness	(-)
R^*	Non-dimensional freeboard, $R^* = R_c/(T_m\sqrt{(gH_s)})$	(-)
R_c	Crest freeboard, level of crest relative to still water level	(m)
R_{ca}	Crest freeboard, level of rock armour crest relative to still water level	(m)
R_d	Run-down level, relative to still-water level	(m)
$R_{d2\%}$	Run-down level, below which only 2% pass	(m)
$R_{i;d}$	Design value of a resistance	(N/m)
$R_{i;k}$	Characteristic value of a resistance	(N/m)
R_u	Run-up level, relative to still-water level	(m)
R_u'	Run-up level, due to ship-induced waves	(m)

$R_{u2\%}$	Run-up level exceed by only 2% of run-up tongues	(m)
r	Relative intensity of turbulence	(-)
r	Centre-line radius of river bend	(m)
S	Sediment transport	(m^3/s)
$S(f,\theta)$	Directional wave spectrum	(m^2s)
S'	Equivalent rock strength	(N/m^2)
S_d	Non-dimensional damage parameter, $S_d = A_e/D_{n50}^2$ calculated from mean profiles or separately for each profile line, then averaged	(-)
S_r	Degree of saturation of the rock	(-)
S_{sp}	Spacing between spur-dikes	(m)
s	Wave steepness, $s = H/L$	(-)
s_o	Fictitious wave steepness, defined as $H_s/L_o = 2\pi H_s/(gT_m^2)$	
s_{om}	Fictitious wave steepness for mean period wave, $s_{om} = 2\pi H_s/(gT_m^2)$	(-)
s_{op}	Fictitious wave steepness for peak period wave, $s_{op} = 2\pi H_s/(gT_p^2)$	(-)
s_p	Wave steepness at toe for peak period wave, $s_p = H_s/L_p$	(-)
$s_{m-1,0}$	Fictitious wave steepness for mean energy period, $s_{m-1,0} = 2\pi H_{m0}/(gT_{m-1,0}^2)$	(-)
$s_{s-1,0}$	Fictitious wave steepness for mean energy period, $s_{s-1,0} = 2\pi H_s/(gT_{m-1,0}^2)$	(-)
T	Wave period	(s)
T	Tidal period	(s)
T	Typical (geotechnical) response period	(s)
To	Wave period parameter for dynamic stability number $HoTo$, $To = T_m(g/D_{n50})^{1/2}$	(-)
T_E	Mean energy wave period or spectral wave period, $T_E = T_{m-1,0} = T_{-10}$	(s)
T_R	Return period, or recurrence interval	(years)
T_m	Mean wave period	(s)
$T_{m-1,0}$	Mean energy wave period or spectral wave period, $T_{m-1,0} = T_E = T_{-10} = m_{-1}/m_0$	(s)
T_p	Spectral peak period, inverse of peak frequency	(s)
T_r	Duration of wave record, test or sea state	(s)
T_s	Significant wave period	(s)
T_s	Draught of loaded ship	(m)
t	Time, variable, pipe wall thickness	(s)
t_d	Theoretical orthogonal thickness	(m)
t_a , t_u , t_f	Thickness of armour and underlayer or filter layer in direction normal face	(m)
U	Horizontal depth-mean current velocity	(m/s)
	Horizontal cross-sectional mean current velocity in rivers	(m/s)
U	Ursell number	(-)
U_{cr}	Depth-averaged critical current velocity	(m/s)
U_g	Velocity in gap of closure dam (horizontal closure)	(m/s)
U_p	Propeller thrust velocity	(m/s)
U_r	Return current	(m/s)
U_v	Velocity through the voids, equal to seepage flow velocity	(m/s)
U_w	Wind speed	(m/s)
U_z	Wind speed at a height of z (m) above sea surface	(m/s)
U_0	Depth-averaged velocity over closure dam during vertical closure	(m/s)
U_1	Critical depth-averaged current velocity in water depth of 1 m	(m/s)
U_{10}	Wind speed at 10 m above sea surface	(m/s)
u, v, w	Local velocities, usually defined in x, y, z directions	(m/s)
u'	Fluctuating velocity component	(m/s)
u_*	Shear velocity, $u_* = \sqrt{(\tau_b/\rho_w)}$	(m/s)
u_b	Near-bed velocity	(m/s)
u_o	Maximum wave-induced orbital velocity near the bed	(m/s)
$\hat{u}_\delta$	Peak bottom velocity	(m/s)
V	Volume	(m^3)
V	Volume ratio number of an estuary, $V = Q_{river}\ T/V_f$	(-)
V	Individual overtopping volume per metre run of crest	(m^3/m)

V_{I50}	Velocity index for geotextiles according to EN ISO 11058	(m/s)
V_b	Bulk volume of armour layer	(m^3)
$V_{b,d}$, $V_{b,s}$	Designed and surveyed bulk volume of armour layer	(m^3)
V_e	Equilibrium fall velocity of an object in water	(m/s)
V_f	Volume of sea water entering the estuary during flood	(m^3)
V_L	Maximum (or limit) sailing speed	(m/s)
V_{max}	Maximum individual overtopping volume	(m^3/m)
V_P	Volume of pores in the rock	(m^3)
V_p	P-wave velocity in rock	(m/s)
V^*	Theoretical sonic velocity of the mineral fabric	(m/s)
V_r	Volume of rock	(m^3)
V_s	Ship sailing speed	(m/s)
W	Blast energy	(kWh/t)
WA	Water absorption, $WA = (\rho_w/\rho_{rock})\, p/(1-p)$	(-)
w	Sediment fall velocity	(m/s)
X, Y, Z	Block dimensions of enclosing rectanguloid box with minimum volume, as used in blockiness calculation	(m)
X	Equivalent wear time factor in the in-service degradation model equal to the number of years in service divided by the equivalent number of revolutions in the reference abrasion test	(-)
X_1, X_2…X_9	Parameters that are given rating values in the in-service degradation model	(-)
$X_{j;k}$	Characteristic value of a material property	(Unit of x)
$X_{j;d}$	Design value of a material property	(Unit of x)
x, y, z	Distances along orthogonal axes	(m)
y_s	Scour depth relative to the original bed	(m)
y_{max}	Maximum depth of scour hole	(m)
z_a	Static rise in water level due to storm surge	(m)
z_{max}	Stern wave height (ship-induced water movements)	(m)
z_s	Internal set-up in a mound above still-water level	(m)
z_0	Reference level of vertical velocity profile, also called *bed roughness length*	(m)
α	Structure slope angle	(rad) or (°)
α_s	Slope angle of the foreshore	(rad) or (°)
β	Angle of wave attack with respect to the structure	(rad) or (°)
β	Horizontal slope of the bed	(rad) or (°)
γ	Unit weight or weight density, $\gamma = \rho g$	(N/m^3)
γ'	Submerged unit weight, $\gamma = \gamma - \gamma_w = g(\rho - \rho_w)$	(N/m^3)
γ_E	Partial factor on the effect of an action	(-)
γ_F	Partial factor to determine the design value of an action	(-)
γ_R	Partial factor on a resistance	(-)
γ_X	Partial factor to determine the design value of a material property	(-)
γ_{br}	Breaker index or depth-limited relative maximum wave height, $\gamma_{br} = [H/h]_{max}$	(-)
γ_b	Reduction factor for berm influence (wave run-up, wave overtopping)	(-)
γ_f	Reduction factor for slope roughness (wave run-up, wave overtopping)	(-)
γ_h	Reduction factor for shallow foreshores (wave run-up)	(-)
γ_β	Reduction factor for oblique waves (wave run-up, wave overtopping)	(-)
Δ	Relative buoyant density of material, ie for rock $\Delta = \rho_{app}/\rho_w - 1 = \rho_r/\rho_w - 1$	(-)
Δx	Difference or increase/decrease of x	(Unit of x)
Δh	Water level depression (ship-induced water movements)	(m)
Δh_f	Front wave height (ship-induced water movements)	(m)
δ	Friction angle between two materials	(-)
δA_M	Effect of major breakage on grading curve	(kg)
δA_m	Effect of minor breakage on grading curve	(kg)
δT	Temperature change	(°C)

δm	Shift in grading curve after minor breakage	(kg)
ε	Strain, relative displacement	(-)
η	Instantaneous surface elevation relative to MWL	(m)
η	Wave set-up	(m)
θ	Mobility parameter for near-bed structures, $\theta = u^2/(g\Delta D_{n50})$	(-)
θ	Mean direction of waves, usually to grid north	(rad) or (°)
Λ_h	Depth or velocity profile factor	(-)
Λ_w	Depth factor for hydraulic resistance in wave-induced flow	(-)
λ	Leakage length	(m)
λ	Wavelength of river bends	(m)
μ	Discharge coefficient	(-)
μ_x	Mean value of x	(Unit of x)
ν	Coefficient of kinematic viscosity	(m^2/s)
ν_p	Poisson's ratio	(-)
ξ	Surf similarity parameter or Iribarren number, $\xi = \tan\alpha /\sqrt{s_o}$	(-)
ξ_m	Surf similarity parameter or Iribarren number for mean wave period T_m	(-)
$\xi_{m-1,0}$	Surf similarity parameter or Iribarren number for spectral wave period $T_{m-1,0}$ and spectral significant wave height H_{m0}	(-)
ξ_p	Surf similarity parameter or Iribarren number for peak wave period T_p	(-)
$\xi_{s-1,0}$	Surf similarity parameter or Iribarren number for spectral wave period $T_{m-1,0}$ and significant wave height $H_s = H_{1/3}$ from record	(-)
ρ	Mass density, usually of fresh water; mass density of soil or rockfill including water if fully saturated: $\rho = \rho_b + n_v\, \rho_w$	(kg/m^3)
ρ_{app}	Apparent mass density of rock that may have water in its pores, the value depends on the degree of saturation, often also called ρ_r	(kg/m^3)
ρ_b	Placed packing density or dry bulk density, $\rho_b = \rho_r\,(1 - n_v)$	(kg/m^3)
ρ_{rock}	Density of rock with zero saturation	(kg/m^3)
ρ_r, ρ_c, ρ_a	Mass density of rock ($\rho_r = \rho_{app}$), concrete and armour, respectively	(kg/m^3)
ρ_w	Mass density of water	(kg/m^3)
ρ'	Submerged mass density, $\rho' = \rho - \rho_w$	(kg/m^3)
σ	Stress; strength	(N/m^2)
σ'	Effective stress in soil or rubble, $\sigma' = \sigma - p$	(N/m^2)
σ_c	Uni-axial compressive strength	(N/m^2)
σ_x	Standard deviation of x	(Unit of x)
τ	Shear strength of rubble or soil	(N/m^2)
τ_c	Bed shear stress exerted by a steady current	(N/m^2)
τ_{cr}	Critical bed shear stress (hydraulic stability)	(N/m^2)
τ_w	Bed shear stress due to wave-induced orbital water motion	(N/m^2)
τ_{cw}	Bed shear stress due to combined current and waves	(N/m^2)
ϕ	Packing density coefficient, packing factor, $= n\, k_t (1 - n_v)$	(-)
Φ_p	Packing factor (Knauss)	(-)
ϕ	Angle of repose	(rad) or (°)
ϕ_{sc}	Stability correction factor for current-exposed stones	(-)
ϕ_{sw}	Stability correction factor for wave-exposed stones	(-)
ϕ_u	Stability upgrading factor (depending on system)	(-)
φ, φ'	Angle of internal friction of soil or stone	(rad) or (°)
φ_m	Mobilised angle of internal friction in plane parallel to slope	(rad) or (°)
ϕ_w	Angle of wind direction in wind wave-generation calculations	(rad) or (°)
ψ	Angle made by the flow to the upslope direction	(rad) or (°)
ψ	Non-dimensional shear stress parameter or Shields number	(-)
ψ_{cr}	Critical value of the Shields number (hydraulic stability)	(-)
ω	Angular frequency of waves, $\omega = 2\pi/T$	(1/s)

Commonly used indices

A	air
a	armour layer
app	apparent
b	bed; base; bulk; blasted
br	breaking; breaker
c	cover layer; crest; current; concrete
cr	critical
d	design
el	elastic
f	filter layer; final; friction; front
g	geotextile; gap
H	horizontal
i	*in situ*; incident; initial
M	mass; minerals; major breakage
m	mean value; moment (wave spectrum); model; minor breakage
max	maximum
min	minimum
o	offshore (= deep water); orbital
P	pores
p	peak; prototype
ph	phreatic
pl	plastic
R	strength (or resistance) descriptor; return
r	rock; return; reflection
S	loading descriptor
s	ship; significant; soil; stability; steel
T	total; test
t	top layer, time, toe, transition, total
V	vertical
W	water
w	water (usually sea water), waves
0	initial