Coastal and river engineering

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1 Introduction

Coastal engineering as part of geotechnical engineering with focus on hydraulic engineering considers the following tasks (see also Fig. 1.1):

- Protection measures at the coast line against flooding created by tsunamis, storms, tides etc.
- Preservation of natural landscape
- Protection against shoreline erosion
- Protection and development of navigation channels, ports etc.
- Development of structures along the coastline

In principle river engineering persues similar tasks, however in detail there are also significant differences. Also the impact of the tides on the estuaries has to be considered in addition.

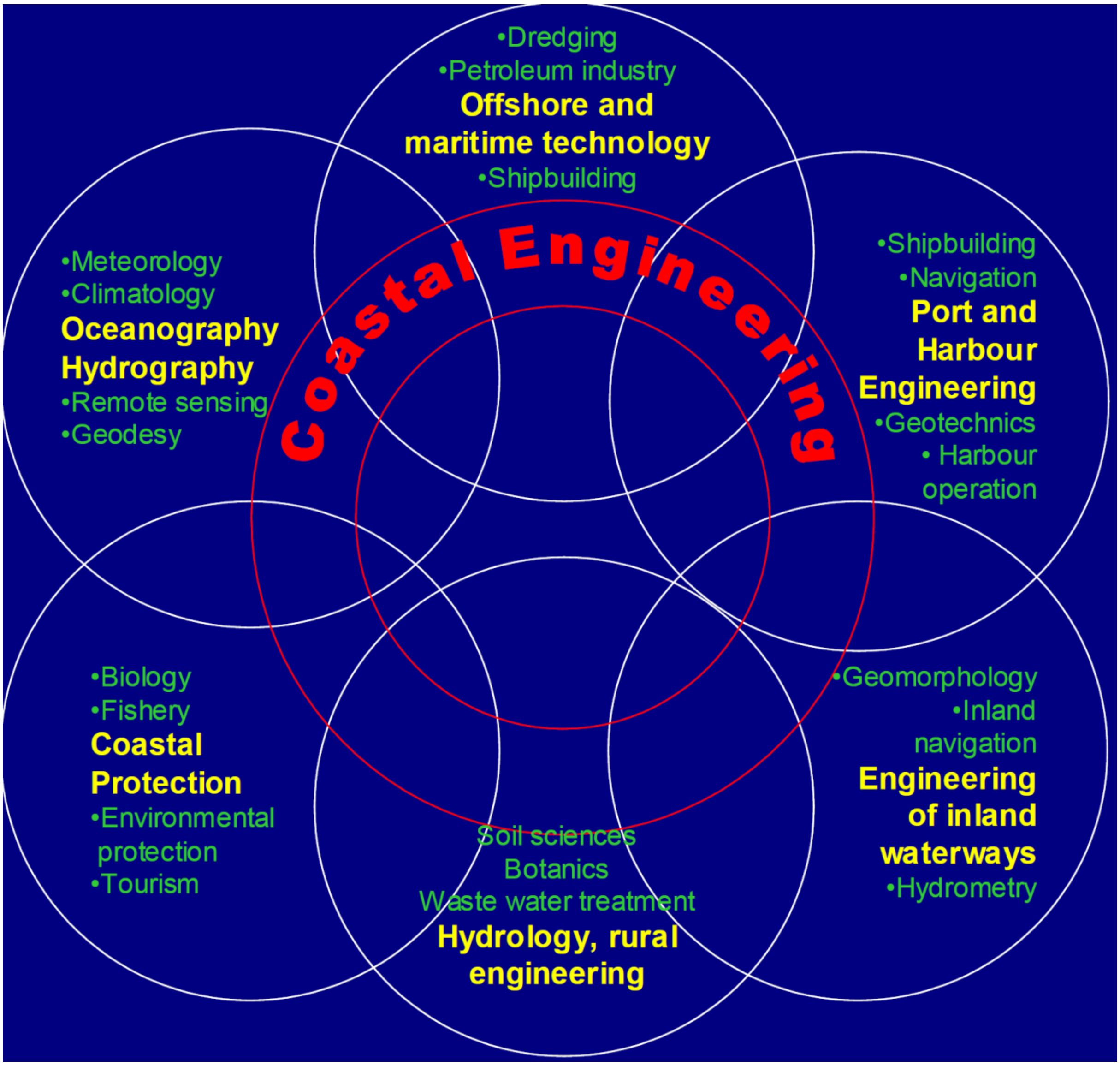

Fig. 1.1: Coastal engineering and fields involved (Fröhle & Kohlhase, 2004).

Fig. 1.2 illustrates terms and elements, respectively, important to describe geotechnical systems at the coastline. The following chapters mention basic terms in respect to coastal and river engineering in general, but special emphasis is paid on an introduction into rock mechanical aspects (cliffs and rip-rap revetments).

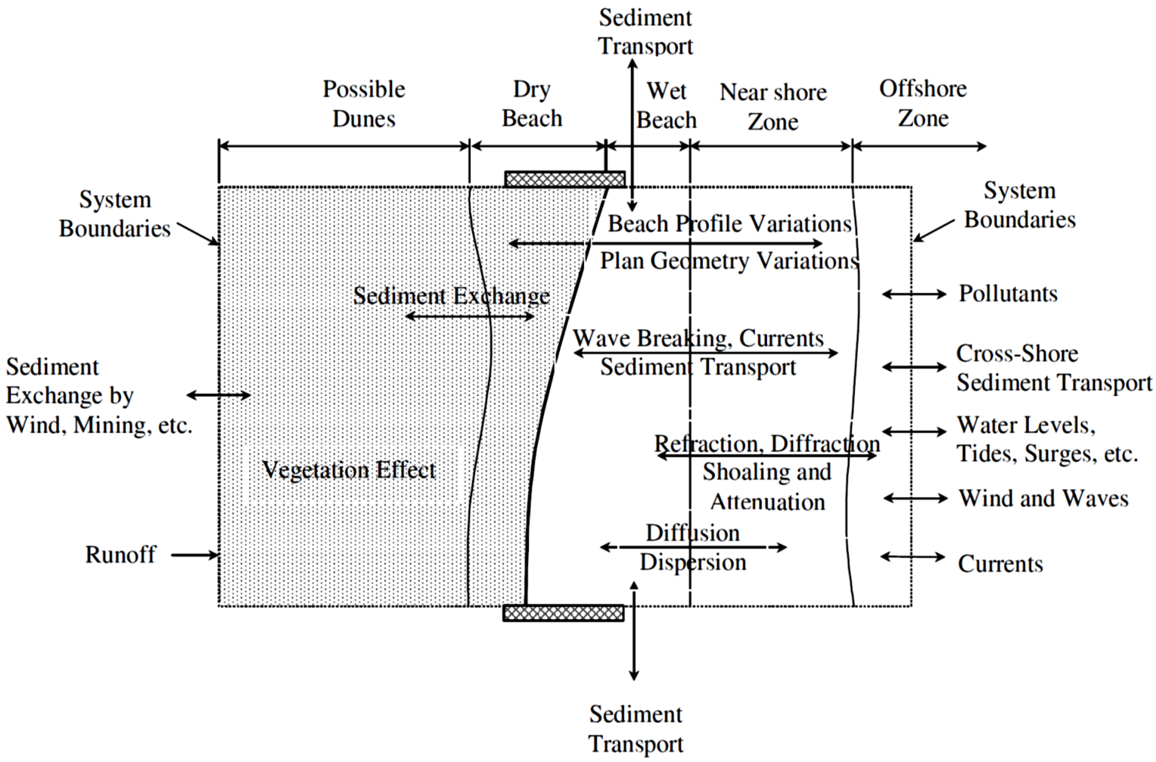

Fig. 1.2: Geotechnical elements of a coastal system (Kamphuis, 2010).

2 Influencing factors (costal engineering)

Fig. 2.1 gives an overview about the most important data (factors), which may have to be taken into account, when solving coastal engineering tasks.

1. Wave Data
   - Short-term wave spectra (measured or hindcast)
   - Long-term distributions of wave height, period and direction (usually hindcast)
2. Meteorological Data
   - Wind (speed, direction and frequency of occurrence)
   - Barometric pressure
   - Storms (tracks, frequencies)
   - Extreme values
3. Water Level Data
   - Tides
   - Seasonal and annual fluctuations
   - Longer term fluctuations (decades)
   - Fluctuations on a geologic time scale (sea level rise, isostatic rebound)
   - Water level fluctuations due to climate change
   - Potential storm surge and seiche (from extreme storm events)
   - Potential tsunamis (from tectonic activity))
4. Current Data
   - Tidal, wind-driven and wave-driven currents
5. Hydrographic Data
   - Sufficient resolution in time and space
   - Above water, through the breaker zone and in deeper water
6. Sediment Transport and Morphology Data
   - Rates
   - Directions
   - Erosion - accretion
7. Environmental Data
   - Water quality
   - Habitat
8. Sociological Data
   - Land use
   - Economic impact
9. Historical Data
   - Extreme water levels (high and low)
   - Major erosion and accretion events
   - Old charts and paintings, maps, photographs and air photos.
10. Materials Data
    - Availability, quality and cost

Fig. 2.1: List of influencing factors (Kamphuis, 2010)

The most important factor is the water wave. Wave generation depends on wind conditions (speed, direction, duration), water depth in the wind generation region and fetch of the wind field. One can distinguish sea waves and swell waves. Sea (also called wind or storm) waves propagate with lower velocity than the local wind velocity, while swell wave propagate with higher speed. Swell waves are generated far away from the considered coastal area. Sea waves are relatively high and short. They are destructive due to erosion of sediments resulting in flat shoreface and steep foreshore. Swell waves are normally relatively long and of moderate height. They tend to build up the coastal profile to a steep shoreface (Mangor, 2017). Water waves can be characterized by the following parameters (Frigaard et al., 1997; USACE, 2012):

- Maximum wave height
- Mean wave period
- Mean wave direction
- Significant wave height = mean of the highest 1/3 of the waves in a representative time series
- Significant wave period = mean period of the highest 1/3 wave heights in a wave train

If the time-series of the water waves are transformed into the frequency domain, the following parameters are typically determined:

- Significant wave height
- Peak period
- Significant wave period
- Mean wave period
- Mean wave direction
- Peak wave direction

Exemplary, Fig. 2.2 shows a time series of water wave parameters at the west coast of Denmark over a period of about 18 years. Fig. 2.3 shows a so-called wave Rose-diagram, which documents wind direction and wave magnitude. Fig. 2.4 summarizes parameters, which have to be considered (and collected) for planning and design of coastline and river protection measures. The hydraulics of water waves are explained in detail in (CIRIA, 2007).

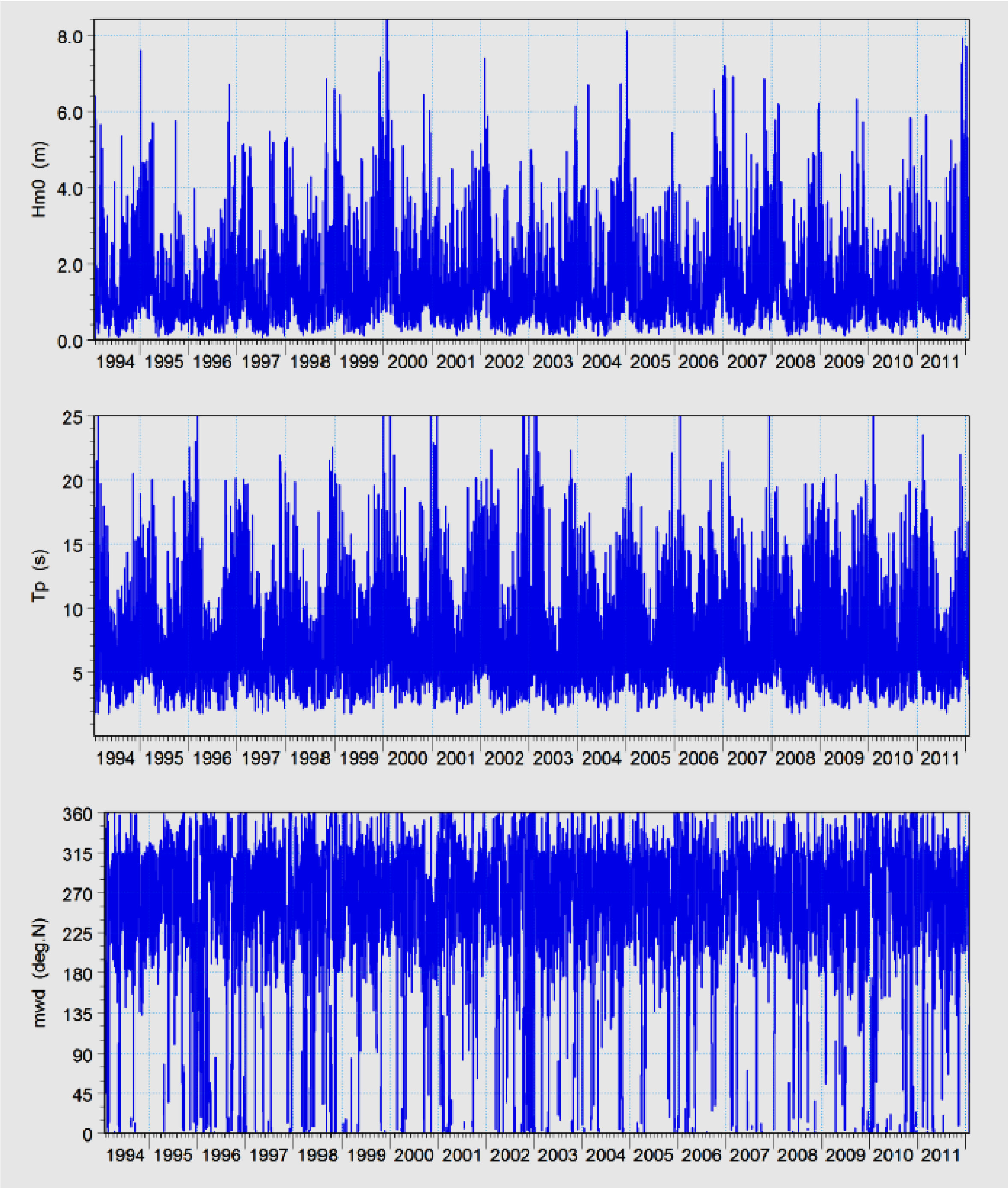

Fig. 2.2: Time series of significant wave height (top), peak wave period (middle) and mean wave direction (bottom) (Mangor et al., 2017)

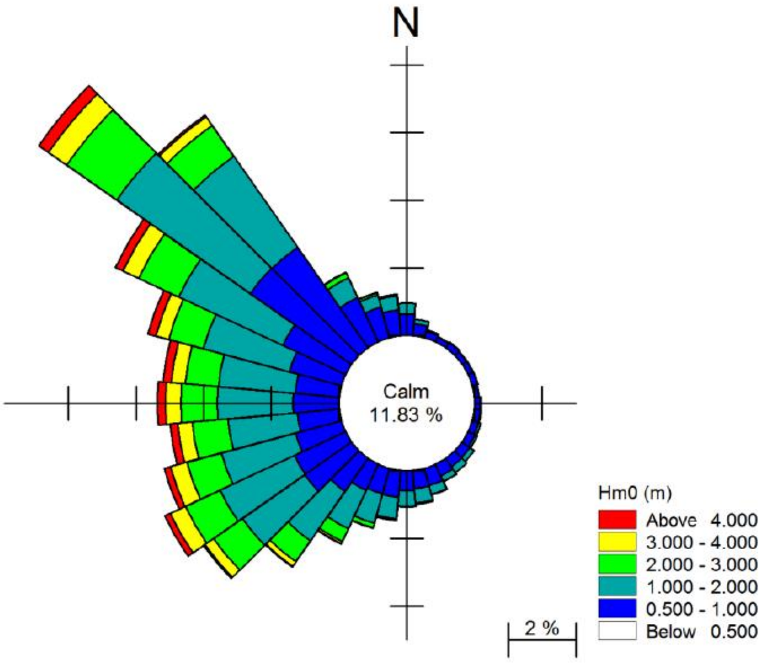

Fig. 2.3: Wave height directional distribution at the west coast of Danmark (Mangor et al., 2017)

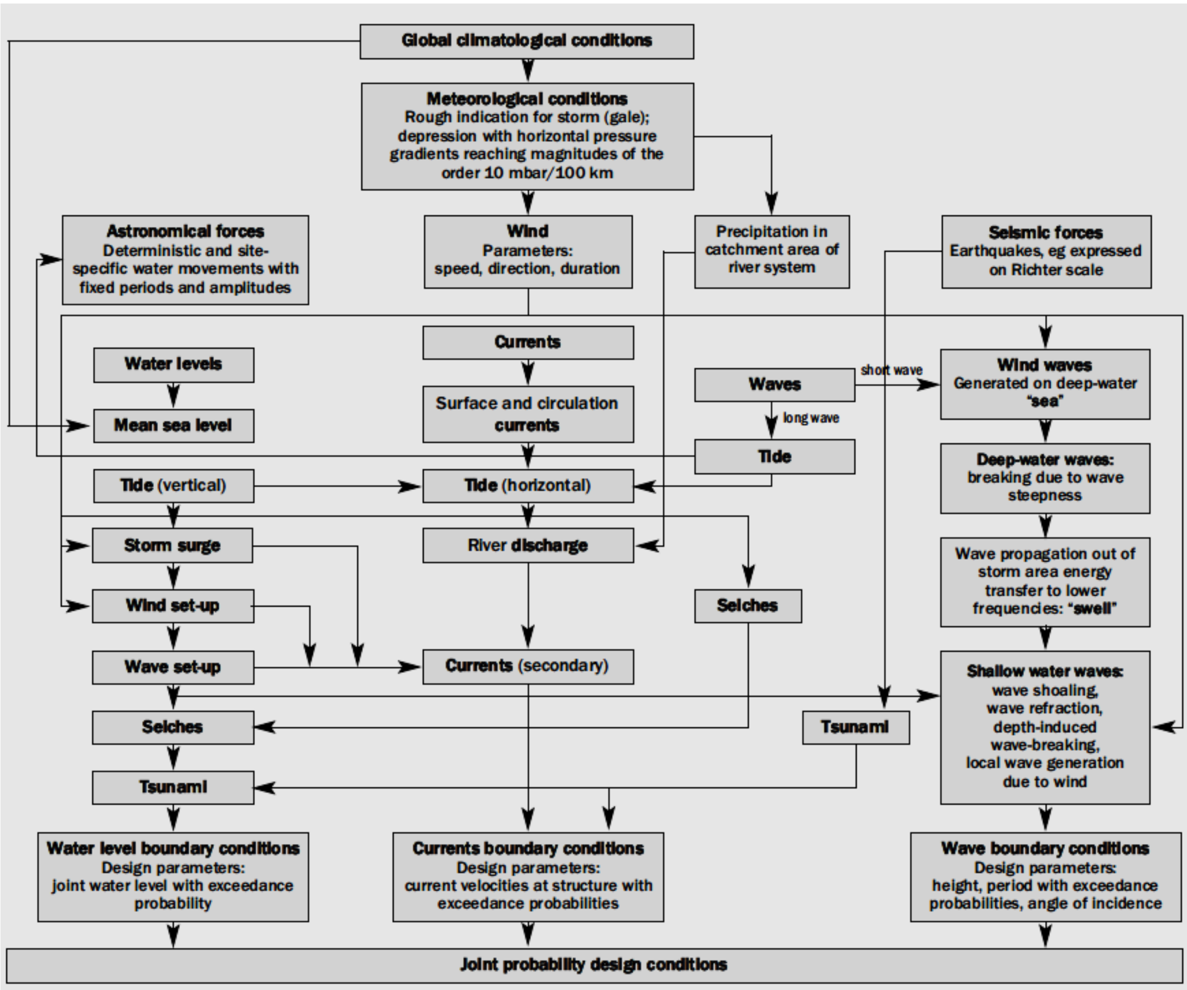

Fig. 2.4: Parameters influencing coastline and river engineering projects (CIRIA, 2007)

3 Influencing factors (river engineering)

The water flow in rivers is influenced by several factors (see also Fig. 2.4) like:

- Riverbed morphology
- Flow velocity
- Water depth
- Discharge distribution
- Type of soil or rock in the river bed and at the river slopes
- Climate conditions (wind, precipitation, freezing etc.)
- Vegetation along the river
- Transport of sediments
- Meandering
- River slope topography

The flow regimes of rivers are often altered by human activities and constructions, respectively:

- Dam constructions
- Groundwater pumping
- Water diversion
- Channelisation
- Sealing

The aim of such structures can be quiet diverse:

- Use of water for drinking, industry or agriculture
- Energy generation and storage
- Protection against natural disasters
- Protection against erosion
- Protection against pollution
- Usage for fishing, transport and recreation

4 Hydro-mechanical processes at the coastline

Fig. 4.2 summarises the most important hydro-mechanical coupled processes at the coastline according to their location (zone) as described in Fig. 4.1. If water waves reach the coastal area several phenomena can be observed, like:

Wave breaking: wave breaks, whenever wave height exceeds a specific water depth

Wave shoaling: amplitude increase due to wave speed change in shallow water

Wave refraction: change of wave propagation direction due to seabed morphology

Wave reflection: wave is reflected by obstacles (e.g. structures) according to the reflection coefficient

Wave diffraction: spreading wave energy into areas behind structures

Wave swash: propagation of the wave onto the beach slope Geotechnical damage or failure phenomena are:

Overtopping: overtopping of structures by water waves

Transmission: transmission of water through permeable structures

Piping: creation of flow channels

Erosion: degradation of soil and rock at the coastline

Sliding: slope failure due to violation of shear strength

Main geotechnical problems at the coastline are related to erosion incl. cliff destabilisation, rockfall, slope instabilities up to triggering of landslides as well as flooding, piping and devastation of infrastructural elements due to water wave impact. At certain locations erosion rates can reach high values between 20 and nearly 80 m/year (for instance at certain areas along the coastline of Vietnam, India or China). Fig. 4.2 and 4.3 illustrate typical processes.

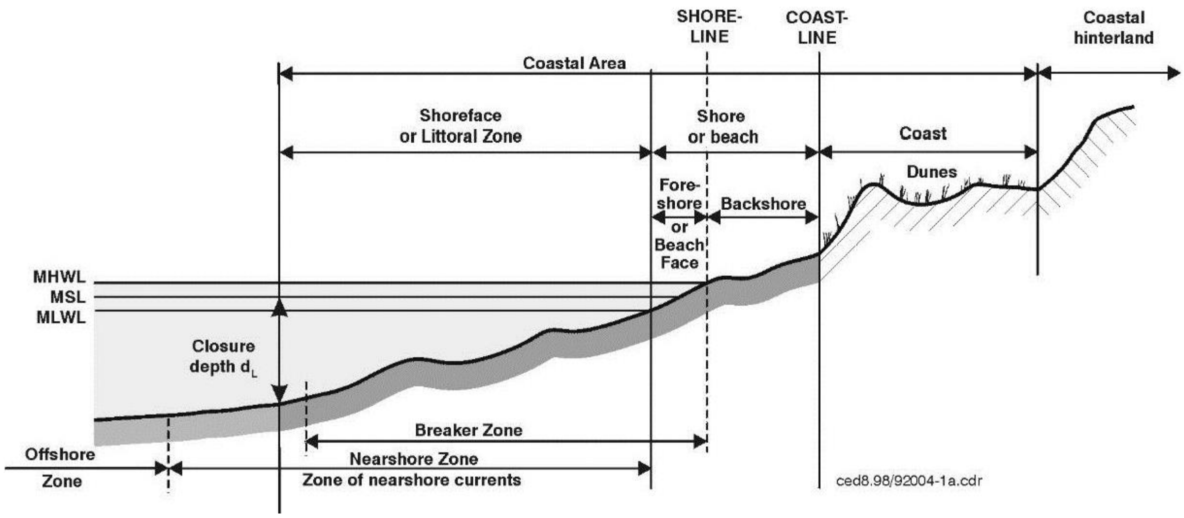

Fig. 4.1: Morphology and areas at the coastline (Mangor et al., 2017)

	Feed Backward	Feed backward				
	Feed Forward	Feed forward				
Feed forward Feed backward	Process Zone	Waves	Currents	Sediment Transport	Morphology	Intervention
Feed backward / Feed forward	Offshore	Generation Interaction Grouping White capping ...	Tidal currents Wind generated currents ...	Combined wave-current boundary layer	Tidal ridges Sand waves ...	Wind mill farm Breakwater Dredging Mining
	Shoreface	Shoaling Refraction Groups Breaking Surf Beat Wave-wave ... Storm surges Seasons ...	Longshore Cross-shore 3D circulation Tidal current ...	Bead load Suspended load Longshore Undertow Wave asymmetry Wave groups Grain sorting ...	Mean profile Erosion profile Summer profile Bars/troughs Rip channels Crescentic bars ...	Breakwater Groyne Nourishment Headland ...
	Beach	Swash Run-up Run-down Storm surge ...	...	Cross-shore zig-zag motion Wind ...	Shoreline Undulations Beach profile Berm ...	Breakwater Revetment Headland ...
	Coast	Run-up Overtopping Storm surge ...	Overflow	Dune erosion Vegetation Wind	Cliffs Dunes Erosion 3D breaches Dune build up ...	Dike Revetment Dune foot protection ...
	Hinterland	Overtopping Storm surge ...	Flooding	Flushes	Sediment tongues	

Fig. 4.2: Typical processes at the coastline and intervention measures (Mangor et al., 2017)

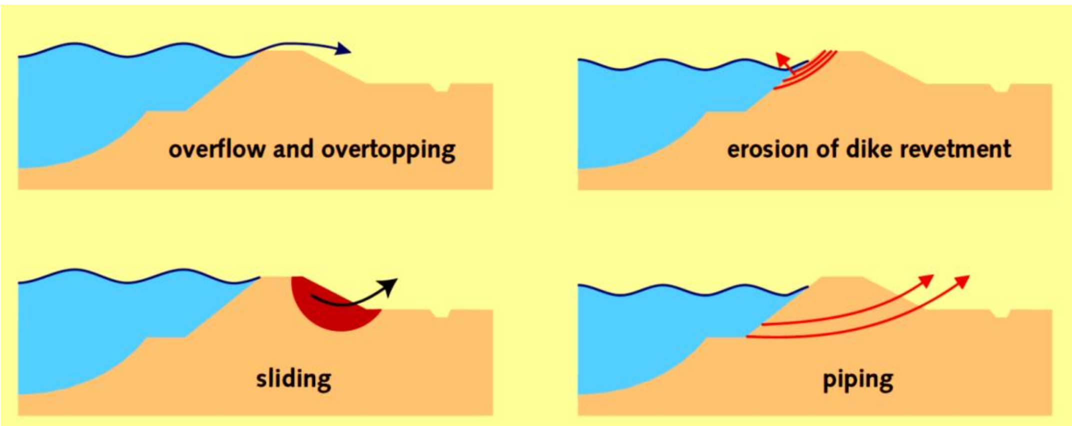

Fig. 4.3: Typical failure mechanisms at the coastline (van Westen, 2005)

5 Hydro-mechanical processes at rivers

The characteristic zoning along a river course is illustrated in Fig. 5.1. The main corresponding hydro-mechanical coupled processes are:

- Erosion
- Transport of sediments
- Deposition of sediments
- Indentation of the riverbed
- River slope destabilisation and triggering of landslides
- Rockfall and cliff destabilisation
- Piping

River hydraulics are explained in detail by de Vriend et al. (2011).

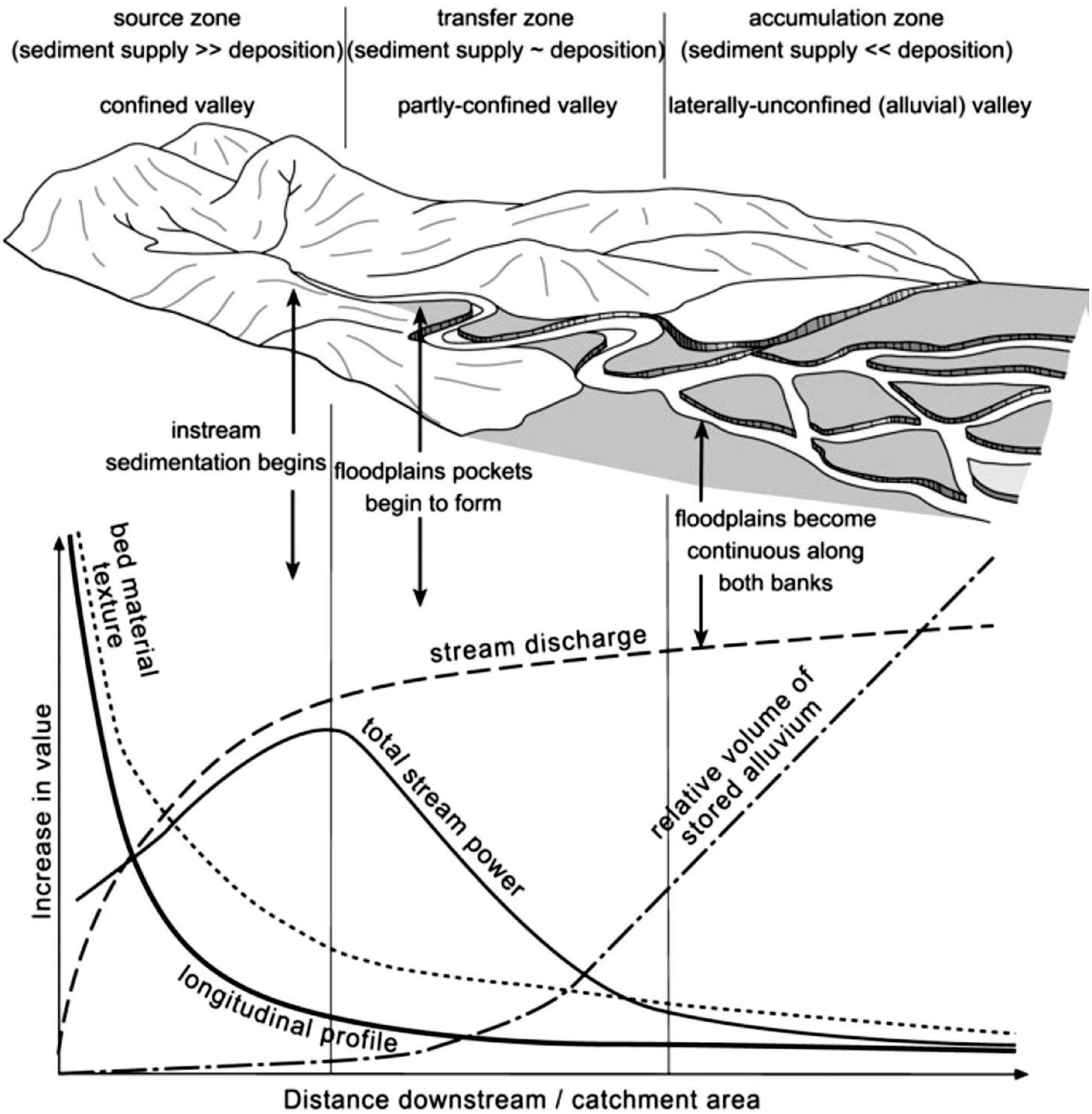

Fig. 5.1: River channel characteristics along the river course (Hohensinner et al., 2018)

6 Typical coastline protection measures

Coastline protection can be performed by several methods (see for instance Masria et al., 2015). These methods can be distinguished between hard and soft structures as well as biological concepts. The following structures are common (sometime they are used in combination):

Seawalls: These are stiff massive barriers parallel to the coastline in the shore area against flooding and erosion.

Revetments: These are shore-parallel structures directly placed at the coastline.

Breakwaters / moles: These structures are either detached shore-parallel structures or structures connected to the coast to break water waves.

Dykes: These are onshore structures to protect low-lying areas against flooding.

Groyns: These are linear structures perpendicular to the coastline erected in certain distances to each other to break waves and reduce erosion.

Bulkheads: These are vertical walls at the coastline parallel to the coastline with the aim to prevent land sliding and erosion.

Jetties/moles: These are heavy constructions for harbours or river channels connection the sea to stabilise boat navigation channels.

Beach fills: This means deposition of additional sand on eroded beach areas.

Dredging: This comprises hydraulic or mechanical movement of sand from the area of accretion to the area of erosion.

Geotextiles: This means installation of geotextiles to stabilise the coastline area.

Beach Drainage System (BDS): Lowering the groundwater level along beaches to reduce back-swash.

Biological based measures to protect the coastline comprise the following actions:

- Sand dune stabilisation by vegetation in combination with fences.
- Artificial reefs to break water waves offshore.
- Artificial mangrove root systems to reduce erosion.

7 Typical river protection measures

Various structures are applied to manage an environmental and economic useful water flow in rivers. Most popular structures and their main functions are:

Dykes: These are structures parallel to the river to reduce flooding risks.

River groynes: These structures are orthogonal or inclined to the river bed and redirect the water flow. They also reduce erosion at the river banks.

Revetments: These are structures along the river banks to avoid or reduce erosion.

Locks / Dams: These structures are used to regulate the water flow and to avoid flooding or drying-up.

Besides protection measures, also the renaturation of rivers is an important geotechnical task, which helps to reduce the risks of flooding.

Interest	Geography	Revetment	Hydrology
Safety against floods	Summer dikes Winter dikess Groynes	"Hard" structures Stone	Maintaining design flood levels and discharge distributions
Navigation	Summer dikes Deep low water bed	"Hard" structures Stone	To 4.0 m water depth: All discharge through the low water bed
Agriculture	Summer dikes Transverse dikes Grass, no natural vegetation	"Hard" structures	No inundation of floodplains
Ecology	No summer dikes or summer dikes with flow gaps Secondary channels Natural vegetation	"Soft" revetments No stone	Often inundation of floodplains

Fig. 7.1: Typical protection measures (de Vriend et al., 2011)

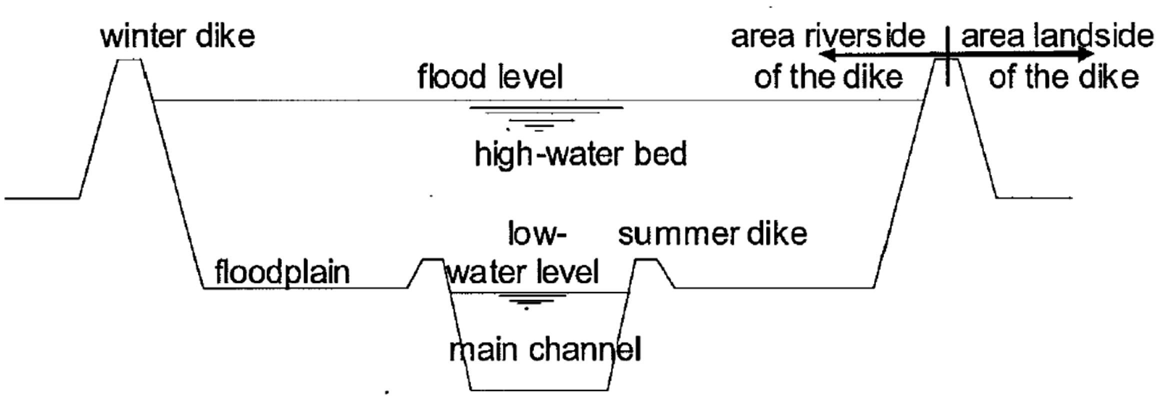

Fig.7.2: Protection measures along the lower part of the river Rhine (de Vriend et al., 2011)

8 Rock mechanical issues at coastlines and rivers

A significant part of the coastline consists of rock masses, as exemplary illustrated in Fig. 8.1 and 8.2 for the continental European Atlantic coast lines. Hampton & Griggs (2004) provide an overview about cliff evolution and corresponding processes. According to Gómez-Pujol et al. (2014), the cliff retreat rates can locally reach values up to about several m/year. Typical average values are between 3 mm/year and 0.5 m/year. The cliff recession process is illustrated in Fig. 8.3 and consists of 4 phases: detachment, transport, deposition and removal. Fig. 8.4 shows typical cliff failure pattern and Fig. 8.5 summarises the process of cliff failure.

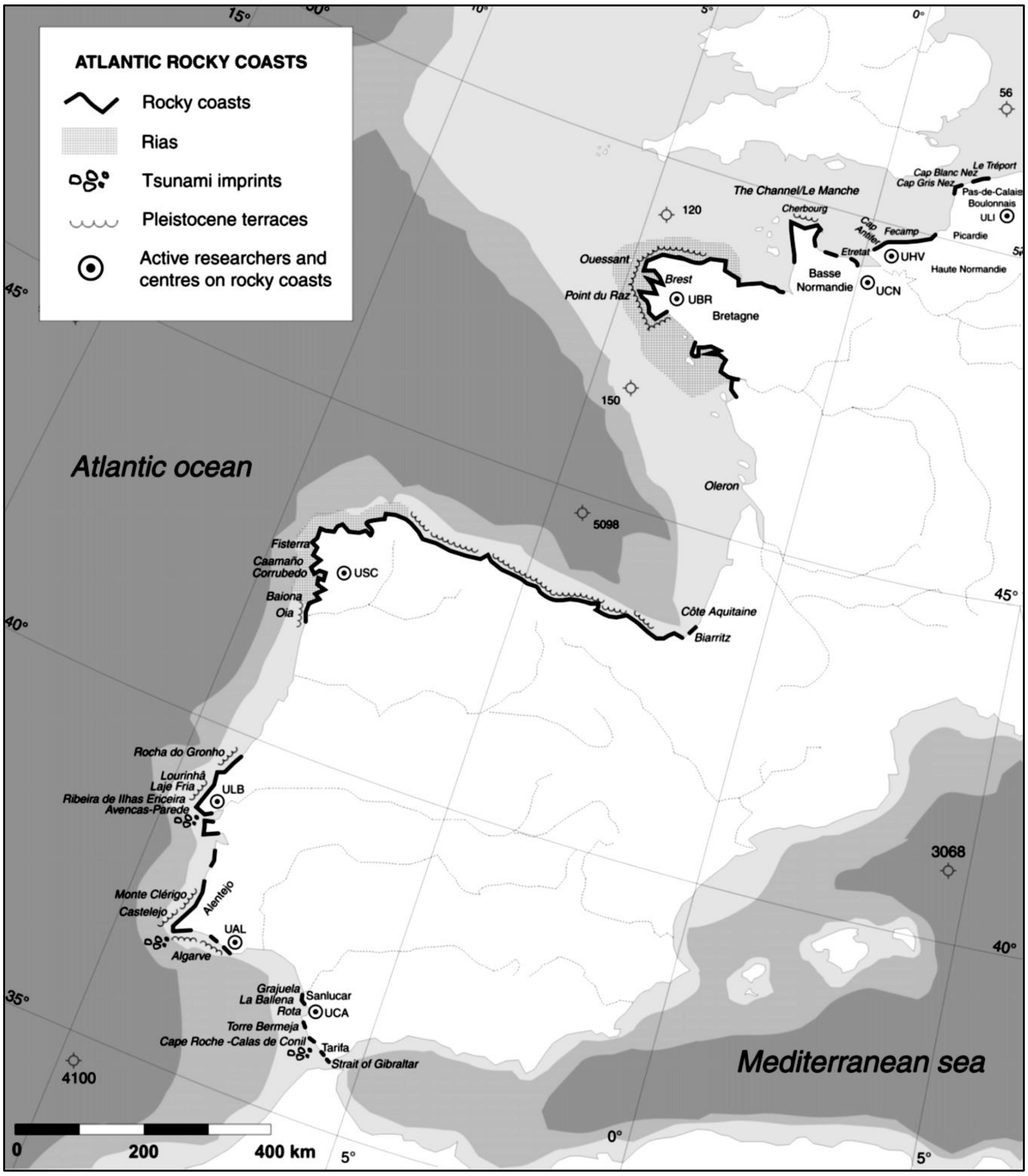

Fig. 8.1: Continental europen atlantic rocky coast (Gomez-Pujol et al., 2014)

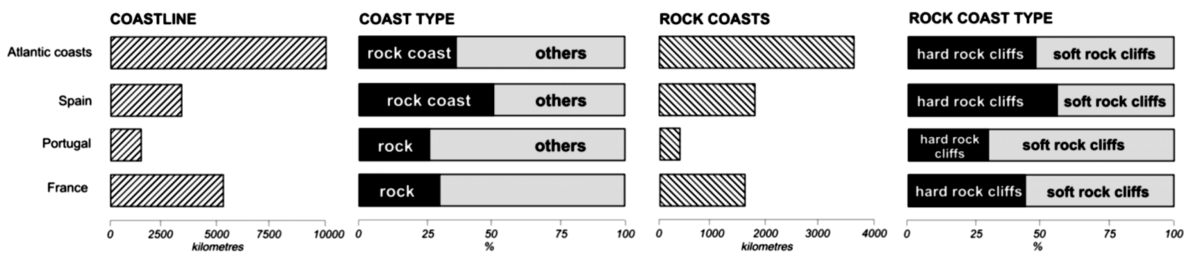

Fig. 8.2: Statistics of rocky coast along continental european atlantic coast (Gomez-Pujol et al., 2014)

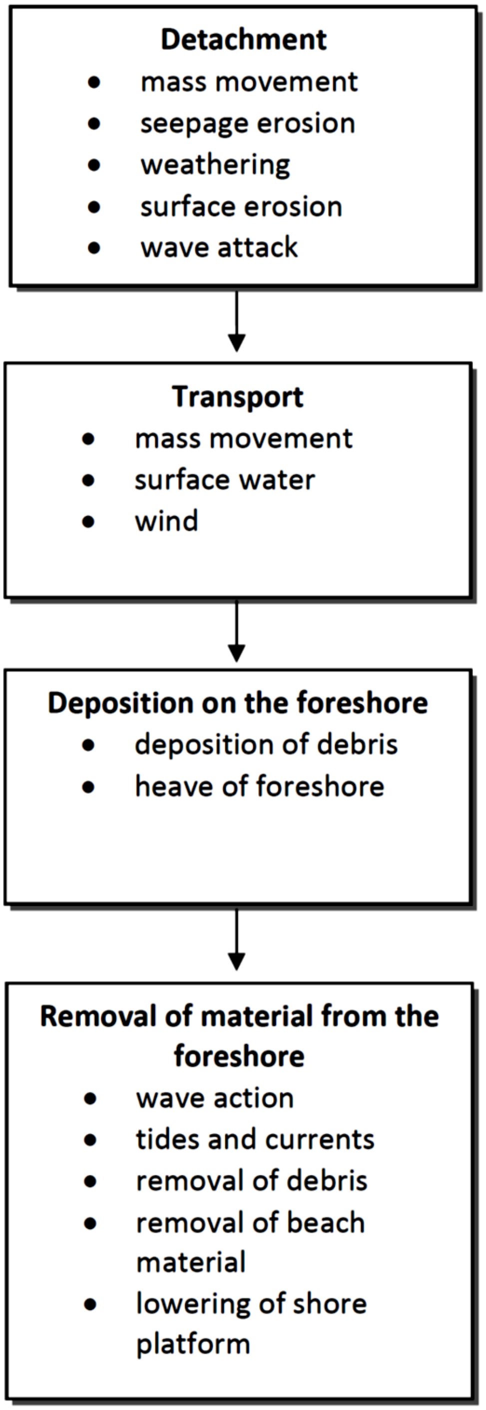

Fig. 8.3: Cliff recession process (EA, 2010)

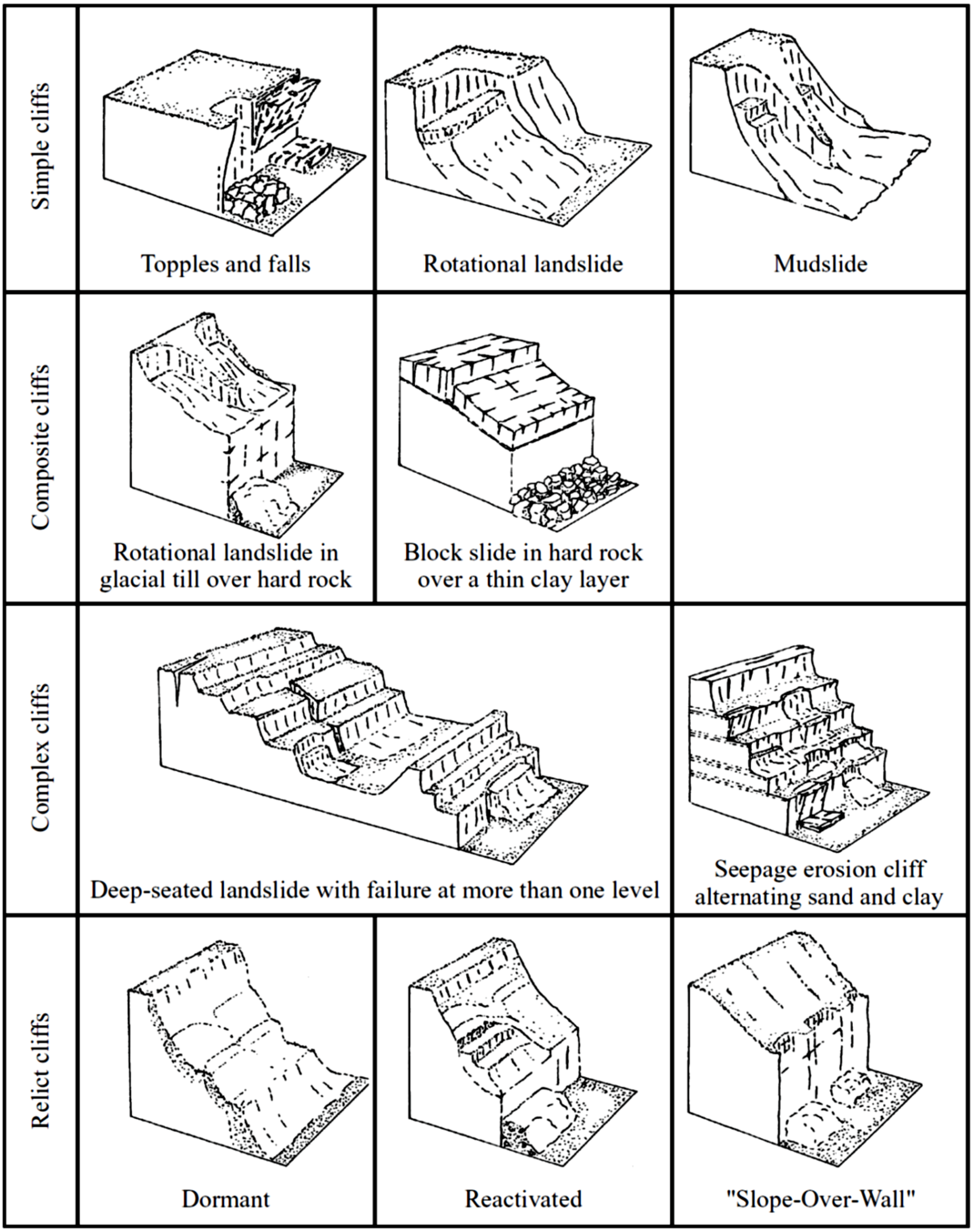

Fig. 8.4: Main failure types of cliffs (Lee, 2002)

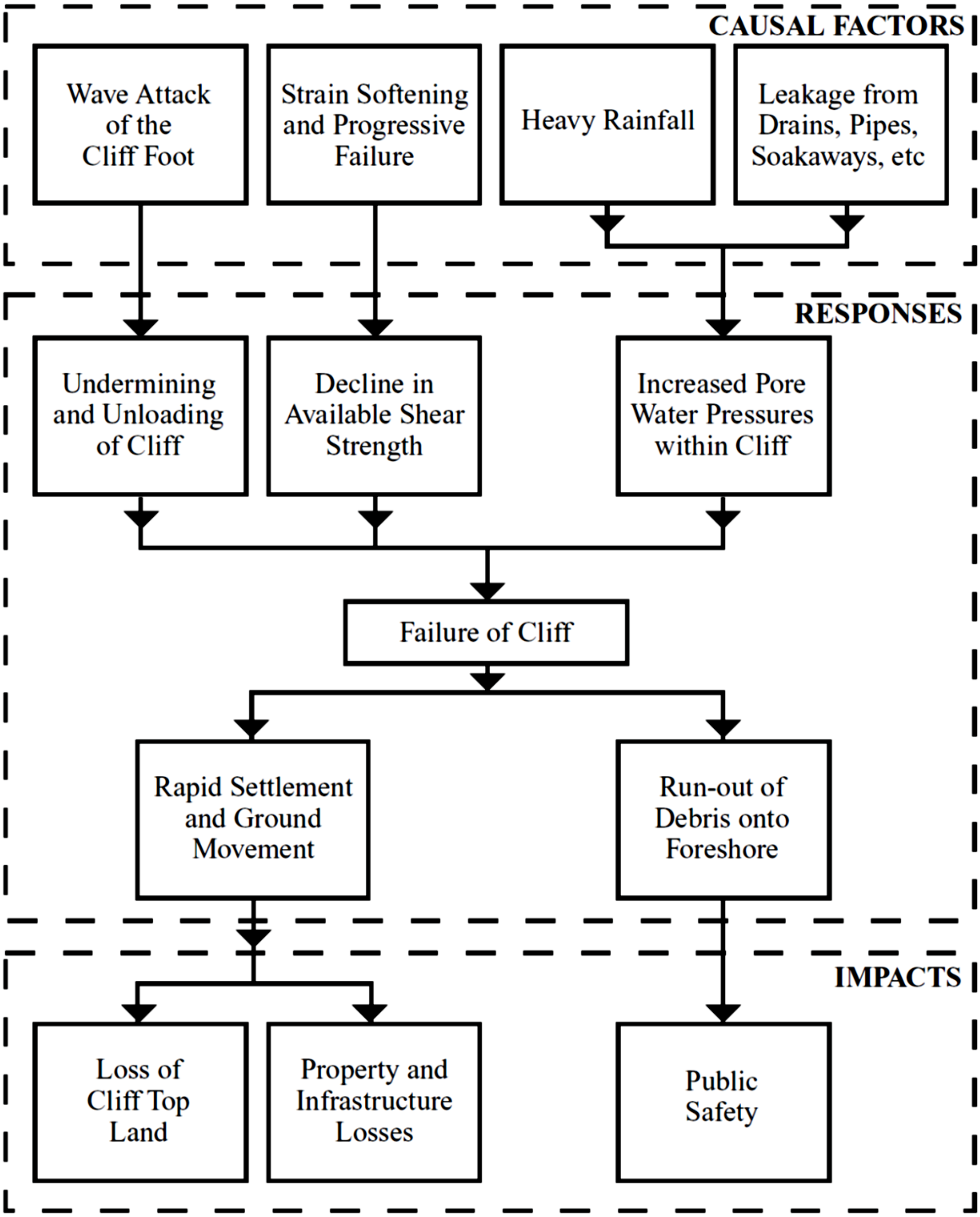

Fig. 8.5: Factors – Responses – Impact in respect to soft cliff failure (Lee, 2002)

Westoby et al. (2018) provide an overview about up-to-date survey methods to monitor coastal erosion at different scales in time and space:

- Cartographic mapping
- Aerial photogrammetry
- Satellite imaging
- GPS/GNNS data
- Airborne lidar
- Terrestrial lidar
- Stereo-photography

Coastline erosion and cliff failure are also important issues in Germany. An impressive example is the erosion at the chalk cliff Jasmund (Island Rügen, Baltic Sea). Günther & Thiel (2009) as well as Dietze et al. (2020) have investigated the cliff failure potential. By the turn of the year 2018/2019 app. 6.000 m^3 failed in several events (see Fig. 8.6 and 8.7) and in 2008 in a single event app. 10.000 m^3 failed. Fig. 8.7 illustrates slope failure event distribution along the Jasmund chalk cliff.

Another interesting example is the famous island Helgoland in the North Sea (Fig. 8.8). Massive protections measures (jetties, groynes, dune dams, embankment dams) were installed to avoid further erosion of this sandstone island with cliffs up to 60 m high as shown in Fig. 8.9 and 8.10.

Fig. 8.6: Failure at the chalk cliff Jasmund, island Rügen, Germany (Dietze, 2020)

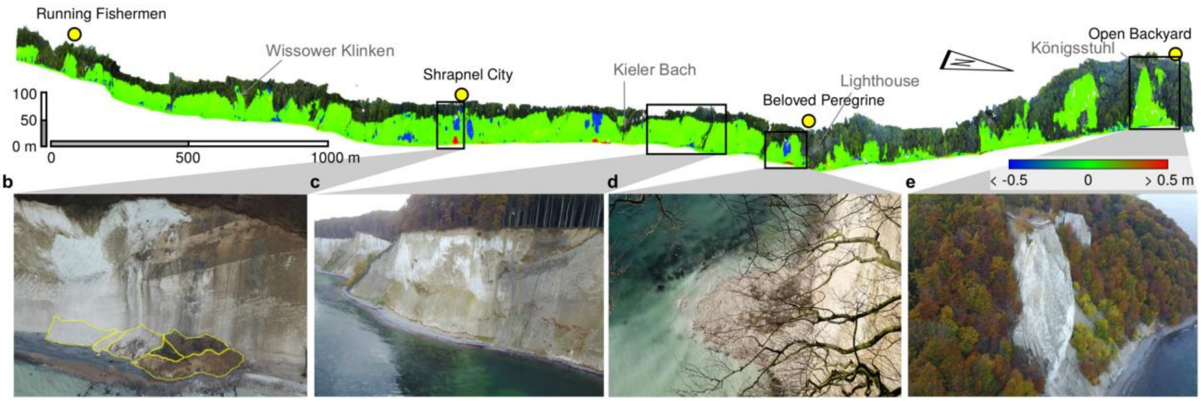

Fig. 8.7: Cliff failure regions along the chalk cliff Jasmund, island Rügen, Germany (Dietze et al., 2020)

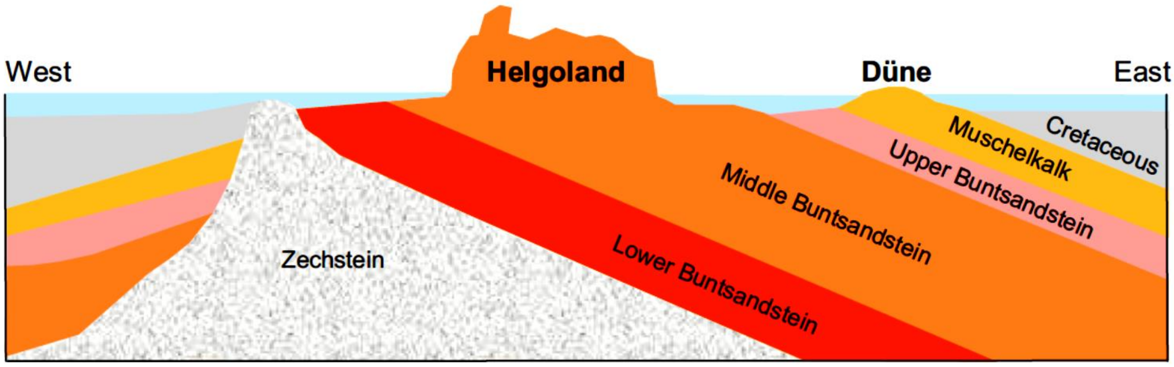

Fig. 8.8: Geological profile of island Helgoland, Germany (Bednarczyk et al., 2020)

Fig. 8.9: Cliff coast of island Helgoland, Germany, with coast proetction measures (Bednarczyk et al., 2008)

Fig. 8.10: Protection measures at the island Helgoland Düne, Germany (Bednarczyk et al., 2008)

9 Boulders as stabilisation measure

Rock blocks (boulders) or concrete blocks in form of rip-rap are often used to stabilise the coastline, but also river banks. Fig. 9.1 illustrates the hydromechanical coupled behaviour of such a structure (CIRIA, 2007). The most important application of boulders in river and coastal engineering is the use for revetments. Fig. 9.2 shows the potential failure mechanisms of revetments which have to be considered during the dimensioning. The used boulders have to fulfil certain requirements (often specified in national regulations), especially in respect to size distribution, shape and weather resistance. Fig. 9.3 to 9.6 show how boulders are used in coastal and river engineering. Fig. 9.7 shows a typical rip-rap revetment construction. Fig. 9.8 shows factors influencing the behaviour of rip-rap revetments, which should be considered in the corresponding design. Fig. 9.9 shows how the behaviour of revetments can be simulated by coupling a numerical DEM-based approach (considering the boulders) with a numerical continuum based approach (CFD) considering the water waves.

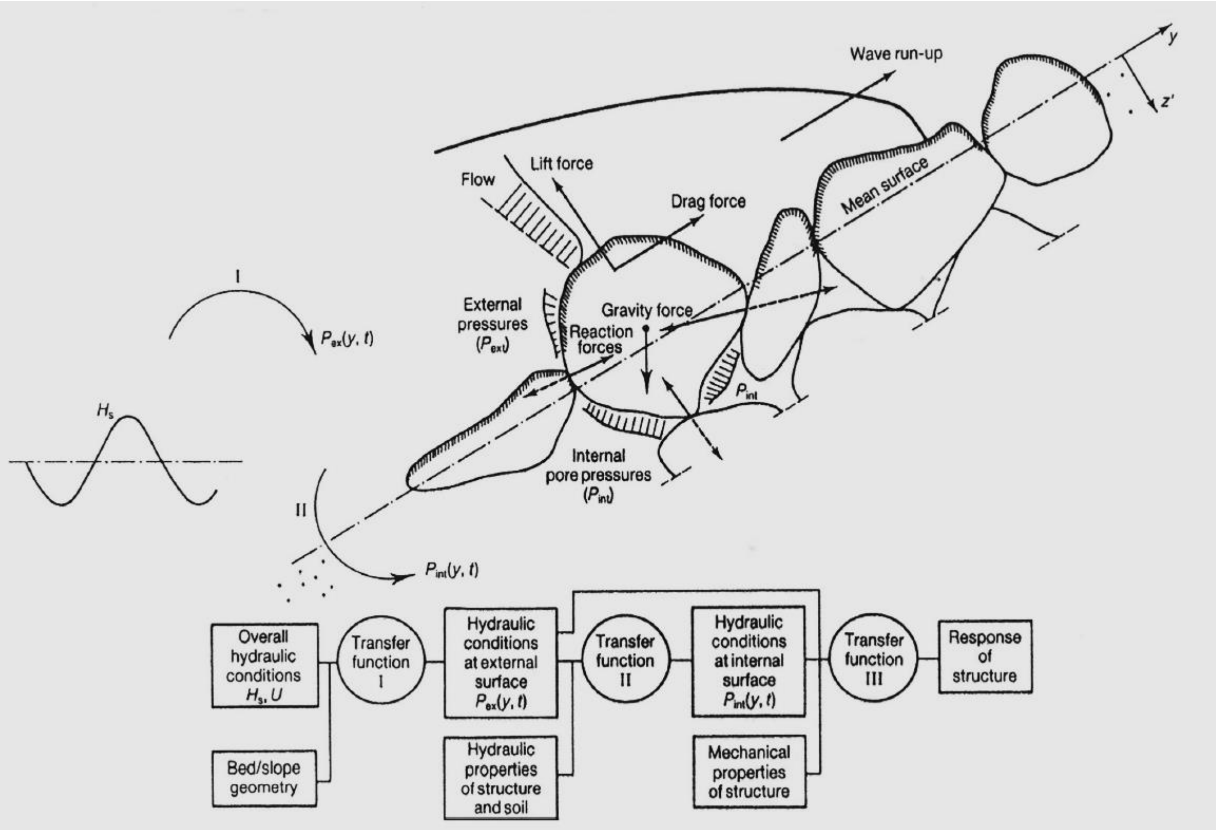

Fig. 9.1: Hydromechanical coupled behaviour of a rocky revetment (CIRIA, 2007)

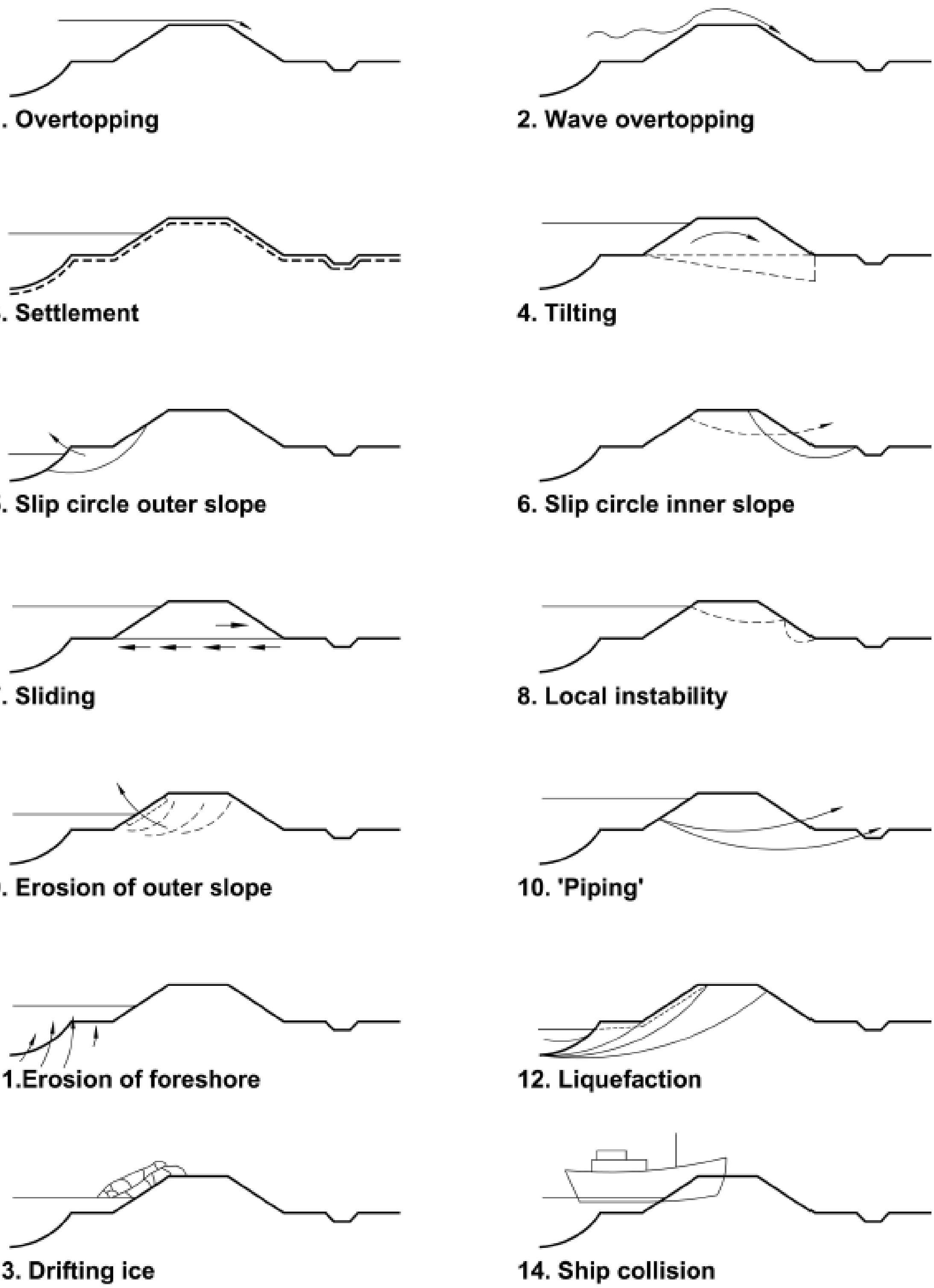

Fig. 9.2: Potential failure mechanisms of rip-rap revetments (CIRIA, 2007)

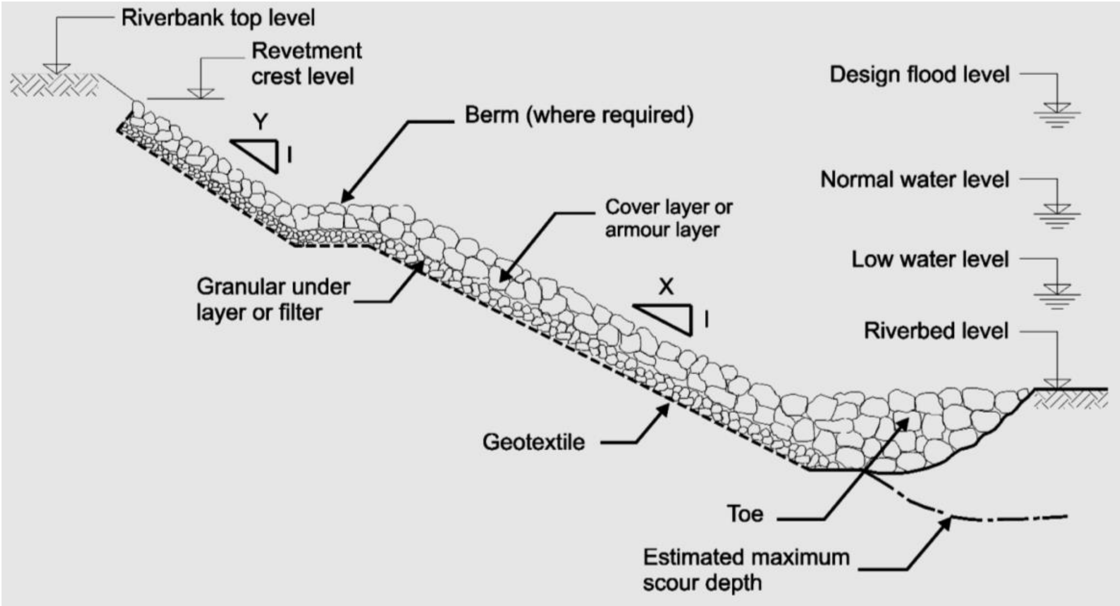

Fig. 9.3: Typical rip-rap based reventment (CIRIA, 2007)

Rubble mound breakwaters	Rock protection to port structures	Shoreline protection and beach control	Rockfill in offshore engineering
conventional rubble mound breakwaters composite and berm breakwaters	scour and slope protection for open piled jetties and vertical quay walls	revetments groynes offshore breakwaters submerged breakwaters	pipeline and cable protection scour protection for offshore structures

Fig. 9.4: Marine structures using boulders (CIRIA, 2007)

River training works	Navigation and conveyance canals	Small rivers and streams	Special structures	Use of special materials
revetments, guide banks, spur dikes, flood protection	bed protection, bank protection	weirs and riffles, spur dikes, river restoration	fish passes, scour protection to bridge piers	grouted stone, gabions

Fig. 9.5: River structures using rip-rap (CIRIA, 2007)

Estuary closures	River closures	Reservoir dams	Flow control structures
horizontal, vertical, instantaneous and gradual closures	river closure bunds, cofferdams, horizontal and vertical closures	earthfill dams, rockfill dams	barriers, sills, weirs, barrages, diversion dams

Fig. 9.6: Closure structures using rip-rap (CIRIA, 2007)

Fig. 9.7: Typical rip-rap revetment along a river bank (Mittelbach et al., 2014)

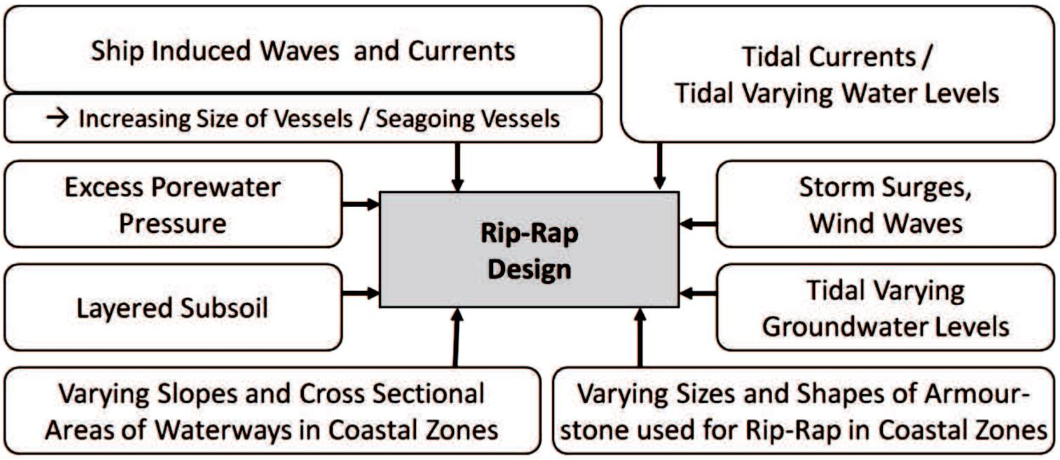

Fig. 9.8: Factors influencing rip-rap revetment design (Mittelbach et al., 2014)

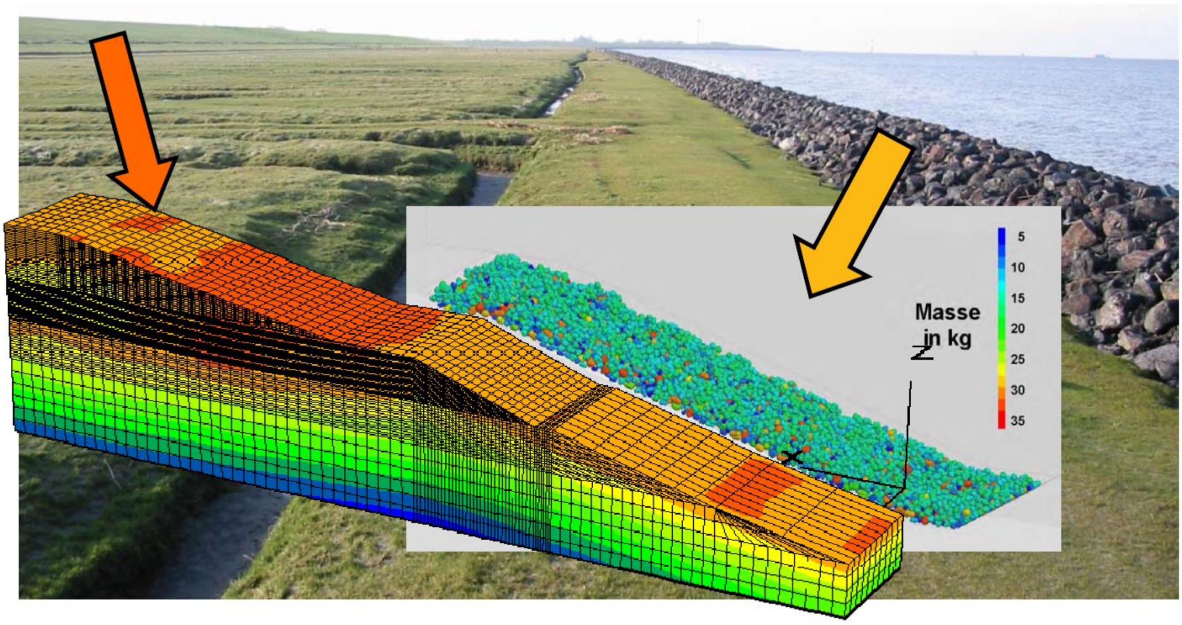

Fig. 9.9: Numerical simulation of rip-rap revetment (Herbst et al., 2010)

10 References

Bednarczyk, K.; Heeling, A.; Schaller, D. & Vierfuss, U. (2008): Coastal protection at the North and Baltic Sea: Helgoland island, *Die Küste*, 74: 143-157

CIRIA (2007): The rock manual: The use of rock in hydraulic engineering, CIRIA C683, 2nd edition 10 chapters, 1236 p.

Dietze, M.; Cook, K.L.; Illien, L.; Rach, O.; Puffpaff, S.; Stodian, I. & Hovius, N. (2020): Impact of nested moisture cycles on coastal chalk cliff failure revealed by multi seasonal seismic and topographic surveys, *J. Geophys. Res*. (in press)

EA National Coastal Team (2010): Assessment of coastal erosion and landslide for funding of coastal risk management projects – guidance notes, Environmental Agency, Bristol, GB, 23 p.

Frigaard, P.; Helm-Petersen, J.; Klopman, G.; Standsberg, C.T.; Benoit, M.; Briggs, M.J.; Miles, M.; Santas, J.; Schäffer, H.A. & Hawkes, P.J. (1997): IAHR List of Sea Parameters: an update for multidirectional waves, *Proc. of the 27th IAHR Congress*, IAHR Seminar : Multidirectional Waves and their Interaction with Structures, Canadian Government Publishing

Fröhle, P. & Kohlhase, S. (2004): The role of coastal engineering in integrated coastal zone management, *Coastline Reports*, 2: 167-173

Gómez-Pujol, L.; Pérez-Alberti, A.; Blanco-Chao, R.; Costa, S.; Neves, M. & Del Río, L. (2014): The rock coast of continental Europe in the Atlantic, *In: Rock Coast Geomorphology: A Global Synthesis*, The Geological Society of London, Memoirs 2014, 40: 77-88

Günther, A. & Thiel, C. (2009): Combined rock slope stability and shallow landslide susceptibility assessment of the Jasmund cliff area (Rügen Island, Germany), *Natural Hazards and Earth Systems Sciences*, 9: 687-698

Herbst, M., Pohl, M. & Konietzky, H. (2010): Numerische Simulation der Interaktion Wasser – Deckwerk im Tidegebiet, Proc. Dresdner Wasserbaukolloquium, *Dresdner Wasserbauliche Mitteilungen*, 40, p. 85-95

Hampton, M.A. & Griggs, G.B. (2004): Formation, evolution, and stability of coastal cliffs – status and trends, USGS professional paper 1693

Hohensinner, S.; Hauer, C. & Muhar, S. (2018): River morphology, channelization and habitat restoration, Riverine Ecosystem Management. In: Schmutz, S.; Sendzimir, J. (eds) Riverine Ecosystem Management. *Aquatic Ecology Series*, vol 8. Springer, Cham

Kamphuis, J.W. (2010): Introduction to coastal engineering and management, *Advanced Series on Ocean Engineering*, volume 30, World Scientific, 2nd edition 544 p.

Lee, E.M. (2002): Soft cliffs: Prediction of recession rates and erosion control techniques, DEFRA, Environmental Agency, UK, Project No. FD2403/1302, 122 p.

Mangor, K.; Drønen, N.K.; Kærgaard, K.H. & Kristensen, S.E. (2017): Shoreline management guidelines, DHI, 4th edition, 449 p.

Masria, A.; Iskander, M. & Negm, A. (2015): Coastal protection measures, case study (Mediterranean zone, Egypt), *J. Coastal Conservation*, 19: 281-294

Mittelbach, L., Pohl, M., Schulze, P. & Konietzky, H. (2014): Numerical simulation of rip-rap revetments in tidal areas, *Die Küste*, 81: 119-132

MLUV (2009): Regelwerk Küstenschutz Mecklenburg-Vorpommern, Übersichtsheft, Grundlagen, Grundsätze, Standortbestimmung und Ausblick. Ministerium für Landwirtschaft, Umwelt und Verbraucherschutz Mecklenburg-Vorpommern, Rostock, 102 p.

USACE (2012): Coastal Engineering Manual, US Army Corps of Engineers, Part I-V, EM 1110-2-1100

de Vriend, H.J.; Havinga, H.; van Prooijen, B.C.; Visser, P.J. & Wang, Z.B. (2011): River engineering, Delft University of Technology, CIE4345, 174 p.

van Westen, C.J. (2005): Flood risks and safety in the Netherlands, Floris Study – full report, Rijkswaterstaat, DWW

Westoby, M. J.; Lim, M.; Hogg, M.; Pound, M.J.; Dunlop, L. & Woodward, J. (2018): Cost-effective erosion monitoring of coastal cliffs, *Coastal Engineering*, 138: 152-164