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Damage to Rock Groynes from Long-Period Ship Waves: Towards a Probabilistic Design Method

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Abstract: Over the past two decades, the increase in typical and maximum vessel size has significantly affected the loading regime in German estuaries, resulting in a much greater relevance of ship-induced waves for structure design. Rock structures, designed for physical conditions and with equations that do not reflect this present-day wave loading regime are showing significant signs of deterioration. Since no applicable guidance for ship-related load cases is currently available, research into process-based understanding and characterisation of ship wave-structure-interaction was conducted. In the course of this research, hydraulically optimised groyne designs were developed, which were subsequently trialled at prototype scale. A monitoring programme was devised in which the wave loading and structural response was recorded over several years. Based on this data, a probabilistic design approach is to be developed, facilitating the appropriate dimensioning of groynes and the rock armour layer as well as cost-optimised groyne designs.

Keywords: rock groyne, recessed groyne, rock armour, primary ship waves, long-period ship waves, probabilistic design, Juelssand, Elbe

1 Background

Over the last 20 years, the structure of the shipping fleet in major German estuaries has changed significantly. This is reflected in the ever-increasing dimensions of container vessels, with associated implications for passing distances and wave making potential, and has led to a significant increase in the intensity of ship-induced loads on estuary infrastructure. As a result, existing rock structures have proven to be under-designed for the now prevalent load intensities and significant deterioration of rock structures such as groynes, training walls and revetments (cf. Fig. 1) have been observed in certain areas of German estuaries (e.g. Ohle and Zimmermann, 2003; WSA Bhv, 2009; BAW, 2010a; WSA HH, 2010; BAW, 2012).

An early investigation into the cause of the observed damages by BAW (2010a) concluded that structure deterioration could in large part be attributed to long-period primary ship waves, which have in recent years become the most relevant hydraulic loading in some parts of the estuary. While several approaches for the calculation of rock armour size in response to wave action exist (e.g. Hansen, 1985; EAK, 2002; CIRIA et al., 2007), BAW (2010a) and Gier and Schüttrumpf (2012) have concluded that these methods are not applicable for this load case. To address the lack of design guidance, BAW, in cooperation with several university partners, devised a multi-faceted research framework in which the wave-structure interaction was investigated in significant detail. The early research focused on the description and process-based understanding of the damage mechanisms (BAW, 2012; Gier and Schüttrumpf, 2012), followed by quantification and parameterisation of the relevant hydrodynamic load parameters for long-period ship waves (Oumeraci and Brühl, 2013). The overtopping conditions and weir coefficients for various groyne cross-sections and porosities, as well as experiments relating to armour stability in response to a surge-like wave were investigated in 2D flume tests (Wöffler et al., 2015; Oetjen et al., 2017). An attempt was made to replicate these experiments in a numerical CFD/CSD model (Oumeraci et al., 2014). To develop groynes which are more resilient to long-period ship waves, BAW (2015a) conducted 3D physical model tests in a wave basin with a number of different structure designs. Based on the optimisations identified in this study two strongly deteriorated groynes (cf. Fig. 1, right) at Juelssand (Elbe Estuary), were reconstructed with innovative groyne root designs and shallower rock armour slope angles in cooperation with the Federal Waterways and Shipping Office Hamburg (WSA HH). A monitoring programme was implemented in order to evaluate the performance of groynes and collect sufficient data for performance analysis and the development of a design method. The monitoring programme has resulted in a unique dataset which allows for detailed examination of the wave-structure-interaction at prototype scale. This dataset will be used to develop a probabilistic design approach for the sizing of rock armour on groynes with respect to long-period primary ship wave attack.

Fig. 1. Examples of ship-induced damage to rock structures: deterioration at training wall Langlütjen, Weser Estuary (left), damaged groyne roots at Juelssand, Elbe Estuary (right).

2 Wave-structure interaction

2.1 Long-period primary ship waves

For large vessels in relatively narrow waterways, the long-period wave can present the most relevant hydraulic load for shoreline infrastructure. Fig. 2 illustrates the primary and secondary wave systems associated with a ship travelling in confined and shallow water. For a stationary observer at the estuary bank, the passing of a ship at subcritical velocity will manifest itself in a primary wave system that consists of a bow wave followed by a depression in the water level, caused by a pressure drop around the vessel hull, and a transverse stern wave. Following the passing of the stern wave, which travels at a speed equivalent to that of the wave-inducing vessel, the water level drawdown is compensated with the slope supply flow which restores the ambient water level. The period T of the primary wave is determined by vessel length and its speed over ground; for the fleet structure in the Elbe Estuary values of approximately 60 s < T < 240 s are common.

The interaction of a primary wave (T = 65 s) with a groyne at approximately mean water level (freeboard $R_c \approx 0$) is illustrated by time-lapse photographs in Fig. 3. The interaction begins with the bow wave (Fig. 3a) which is typically small (here 0.1 m) and its impact negligible. This is followed by the drawdown (z_A = 0.7 m) which causes a water level drop in the upstream groyne field. The resulting water level gradient results in compensatory flow over the groyne opposite to the direction of travel (Fig. 3b, c). This flow state weakens as the drawdown gradually moves into the downstream groyne field and the original water level in the upstream groyne field is restored (Fig. 3d). This is associated with the arrival of the transverse stern wave and the slope supply flow. The drawdown in the downstream groyne field acts to reverse the water level gradient and results in flow over the groyne in the direction of travel (Fig. 3e). Due to wave focussing, reflection and transformation effects which lead to a concentration of energy in the root area, the overflow is typically initiated here and spreads along the groyne towards the head. The large gradient and the swell-like action of the transverse stern wave (H_p = 0.71 m), which travels at the same speed as the vessel, results in a high-velocity shallow-depth skimming flow that is characterised by strong turbulence and fluctuating hydrodynamic pressures; flow aeration on the lee side is also common, the extent varies with the hydraulic configuration of the overflow and boundary effects (Fig. 3f). The described processes are representative of the load case for freeboards in the approximate range $R_c \leq 0$. For positive freeboard heights overflow phenomena may be weaker, restricted to lower parts of the groyne or replaced by stronger flows around the head of the groyne; in this case wave run-up, wave breaking and overtopping processes are prevalent (cf. Tab. 1).

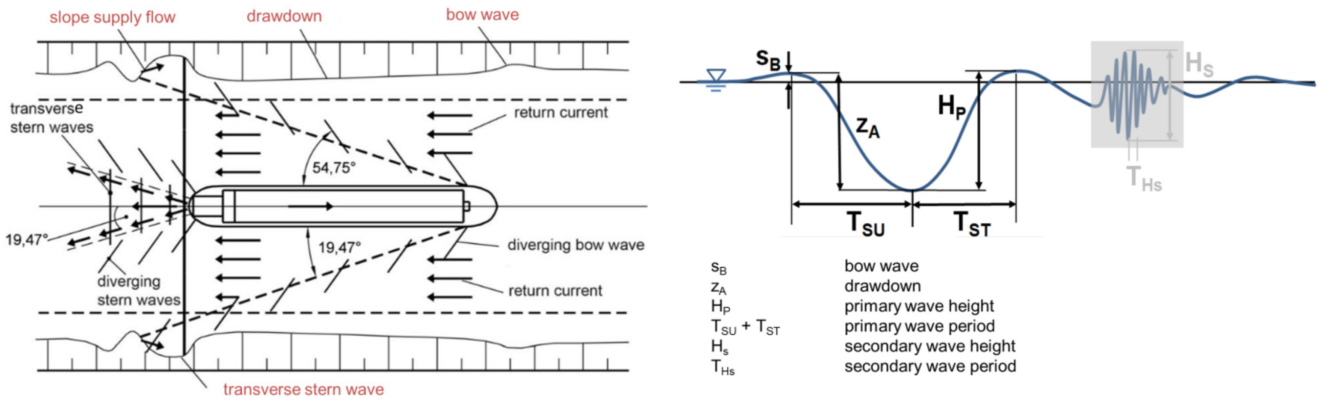


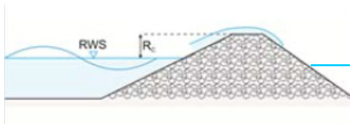
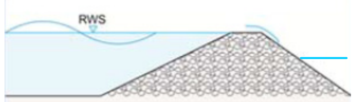
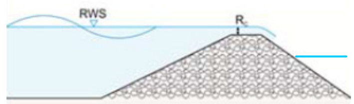
Fig. 2. Illustration of the ship-generated wave system in confined shallow water with components of the primary wave highlighted in red (left), modified from BAW (2010b), and idealised ship wave record with definition of relevant parameters (right).

Fig. 3. Interaction of long-period ship-wave with groyne at Juelssand during passage of seaward-travelling PostPanMax vessel (length 368 m, width 51 m) at approximately mean water level. Passage with draught of 12,5 m, 13 kn speed through water and passing distance of 228 m to groyne head.

2.2 Structural response

The structural response of groynes under long-period ship wave attack is described in detail in BAW (2010) and BAW (2012). At the study site, the groynes exhibit a characteristic pattern of damage that features the deterioration of the groyne root to the point of complete destruction (cf. Fig. 1) and a deformation of the crest, particularly on the lee side w.r.t. the incident wave (cf. Fig. 6). As described above, the wave-structure interaction differs depending on freeboard height. A differentiation for the load cases $R_c > 0$ and $R_c \lesssim 0$ is useful, as the processes and damage mechanisms are distinct and typically also affect different areas of the groyne, as illustrated conceptually in Tab. 1. For positive R_c, wave impact processes are prevalent, affecting mostly the upstream slope, although low-impact overtopping and wave run-down on the lee side is possible, depending on structure parameters such as crest height and permeability. For negative R_c the destabilising forces are related primarily to overtopping and overflowing of the groyne. In this case the structural response to supercritical loading is expected in the root and crest areas and predominantly on the lee side. Gier and Schüttrumpf (2012) conclude that the long-period wave is particularly damaging due to the fast-flowing and highly-turbulent overflowing of the groyne. The high-energy surge-like overflow, in which the groyne is at least partially submerged, is particularly erosive. It follows that the hydraulic load case for $R_c \lesssim 0$ is the most acute, and thus informs the design conditions.

Tab. 1. Conceptual model for load cases and damage due to long-period primary ship waves in relation to freeboard. Modified from Gier and Schüttrumpf (2012).

freeboard R_c	$R_c > 0$	$R_c = 0$	$R_c < 0$
			
load case	wave run-up overtopping / overflow wave run-down wave breaking	instationary overtopping / overflow	quasi-stationary overtopping / overflow
expected damage	displacement of rock armour on head / crest / root area on both sides of groyne	displacement of rock armour on crest and root area predominantly on lee-side	displacement of rock armour on crest and root area on lee-side

The initiation and progression of damage is likely damage attributable to the repeated erosion and dislocation of individual rocks from the armour layer. The role of other mechanisms such as sliding along the filter/armour interface and disruption of the armour layer due to longitudinal and uplift forces cannot be determined conclusively from prototype observations alone. Initial loading can lead to an improvement in rock armour stability owing to the rearrangement of rocks into a more stable position and orientation of the flow. With further and more severe load cycles that exceed threshold flow, the deterioration of the armour layer begins; once the integrity of the armour layer is compromised, resistance is locally reduced due to a decrease in frictional forces and interlocking effects with neighbouring rocks. Associated with erosion of the crest is an increasing groyne footprint as dislodged rocks gradually move downslope to accumulate in the foot area.

Based on an understanding of the structural response to the most relevant load cases, improved groyne designs were developed and evaluated in 3D physical model tests (BAW, 2015a). Subsequently, the designs were tested at prototype scale in a pilot study at Juelssand in the Elbe Estuary.

3 Study site and prototype groynes

Juelssand is located on the northern bank of the Lower Elbe estuary, between chainage km 651-653 (Fig. 4). Owing to the proximity of the fairway, this area is characterized by close passing distances and large ship-induced loads, especially in the case of seaward travelling vessels. Groynes B29 and

B31 were chosen for the prototype scale pilot study of the optimised groyne designs from BAW (2015a).

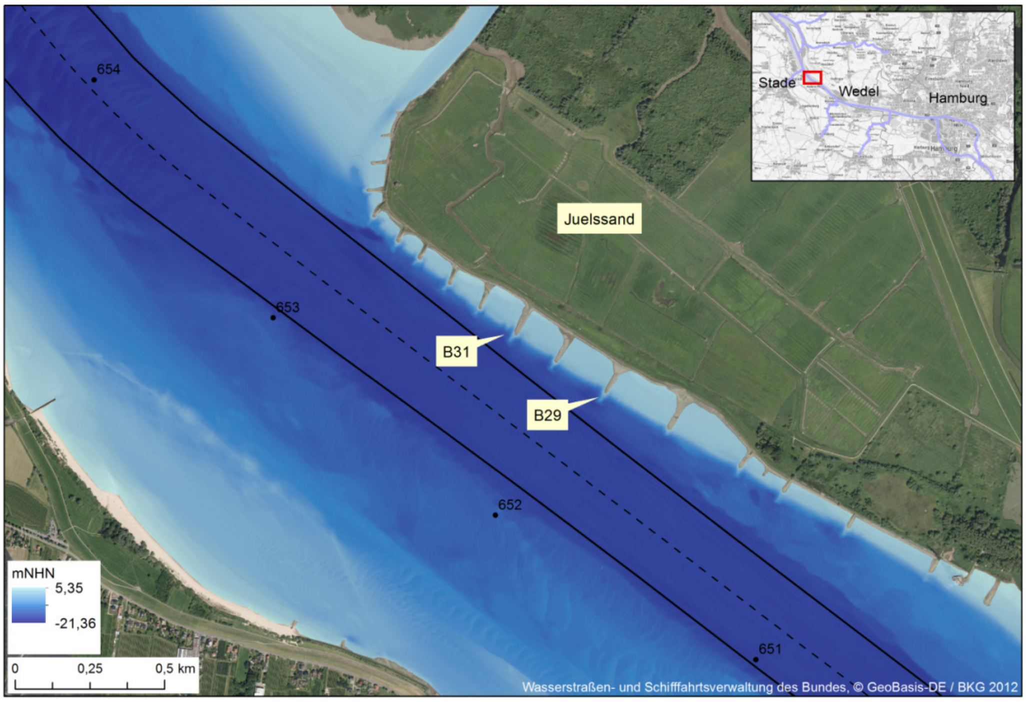


Fig. 4. Location of study site with prototype groynes, indicative bathymetry, chainage and location of navigational channel.

Taking cues from the observed pattern of damage, the design optimisations are related to the configuration of the groyne root (cf. Fig. 5). At groyne B31, the root was profiled to a larger diameter radius of 25 m with the intention of reducing wave focusing in this vulnerable area. At groyne B29 the root was not reconstructed; instead, in order to allow wave energy to bypass, a 25 m wide recess, secured with scour protection, was created. In this initial reconstruction in late 2014, the original rock grading of $CP_{90/250}$ was used. Apart from modifications to the root area, some smaller adaptations to the structure cross-section (shape and crest level) including a reduction of side and head slope angles were undertaken.

Fig. 5. Optimised groyne root designs: recessed groyne B29 (left), large-radius groyne root B31 (right).

An intermediate evaluation of damages in the summer of 2017 indicated that while the recessed groyne showed improved stability in the root area, significant damage to the crest was noted. It was concluded that optimisations of structure geometry alone are insufficient to withstand the prevalent loads. Subsequently, groyne B29 was re-profiled using the larger rock grading of $LMB_{5/40}$ and monitored for a further 1.5 years. Groyne B31 did not show favourable damage development and this design was not pursued any further, however, monitoring was continued.

4 Monitoring and data collection

A monitoring programme was devised to record the evolution of groyne damage and the incident ship-induced loads. Monitoring began in July 2015 and included the recording of the groyne topography at every low water by means of stationary mast-mounted laser scanners (Tschirschwitz et al., 2017). The hydraulic loads at the structure were measured with pressure sensors positioned at various locations in the head, foot, root and crest areas of the groynes. In November 2017, coinciding with the strengthening of groyne B29 and recognizing the significance of overtopping loads, a current meter was installed on the crest to measure overflow velocities. The monitoring programme completed in February 2019.

The monitoring programme resulted in a highly valuable dataset that allows for a detailed examination of the wave-structure-interaction at the prototype scale under real loading conditions. Owing to the extended record length, which contains in the order of 2000 scans and over 5000 ship passages per groyne, correlations of hydraulic loading and dynamic structural response as well as statistical analyses of load and resistance parameters and respective interdependencies is possible. Drawing on vessel traffic data (AIS), rock armour displacement can in some cases even be related to a specific wave event and, by extension, ship passage parameters such as vessel dimensions, draught, speed through water – the local tidal current was taken from an operational hindcast model – and passing distance. Surveys of the topography in the groyne field are also available, allowing the influence of the designs on the adjacent beach levels to be examined.

4.1 Ship-induced loads

In the Elbe Estuary, as the shipping channel to the port of Hamburg, the prevalent hydraulic loads on estuarine infrastructure result from the waves produced from displacement hulls of large container vessels. The magnitude of the incident primary wave height at the structure varies depending on measurement location, as the wave is subject to various transformation and reflection processes prior to incidence at the structure. Typically, the largest waves were measured in the groyne mid-section (B29) or in the root area (B31), depending on the structure. Here, the primary wave height H_p at the structure in isolated cases exceeds 2.5 m, albeit overwhelmingly H_p is less than 1.0 m. Data from the crest-mounted current meter reveal, however, that even these relatively moderate wave heights can generate overflow velocities in excess of 2.0 m/s; individual passages recorded overflow velocities greater than 3.5 m/s.

The measurements are processed and characteristic parameters are calculated for each data passage, allowing statistical analyses on the individual forcing variables, as well as their interdependence and correlation to e.g. ship passage parameters to be determined. A sufficiently long record of measured hydraulic loads is necessary in order to determine the appropriate statistical model for the loading variables.

4.2 Groyne development

A point cloud of the groyne topography is recorded at low water and the raw survey data is post-processed into a 1x1 m grid. The deformation of the rock armour over time can be visualised in difference plots as exemplified in Fig. 6. The previously described damage pattern with significant deformation of the crest area is recognisable. Rocks from the crest area are deposited at the foot of the groyne on the lee side leading to a flattening and widening of the structure.

This data can be analysed further to quantify rock armour deformation over individual profiles or specific sections of the groyne. In certain cases, particular damage can be related to specific loading events, i.e. ship passages.

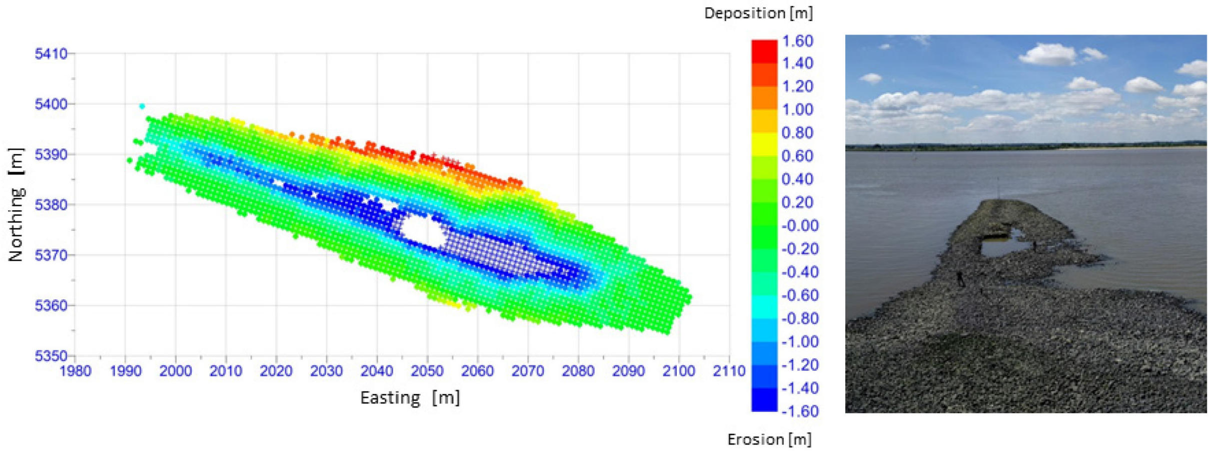


Fig. 6. Visualisation of damage as generated by postprocessing of laser scan data (left) and corresponding photographic image of groyne B31 at time of survey (right).

5 Design guidance for groynes under ship-wave loading

At this stage, drawing on the conducted research and from preliminary analyses of the prototype monitoring data, it is possible to make certain generalised statements about the design of groynes w.r.t. long-period ship wave loading:

i) Rock armour groynes designed in accordance with available engineering guidance are in many cases under-dimensioned to withstand the present-day ship-induced long-period waves, especially where the characteristics of the waterway and navigation exacerbate the loading situation. This results in increased frequency and cost of maintenance operations or destruction of the groynes.

ii) Available guidance does not account for the characteristic hydrodynamic processes associated with long-period ship waves. In the context of the present-day and future utilisation of estuarine waterways where, in many areas, ship-induced waves now dictate the parameters of design, existing guidance is not applicable.

iii) Rock armour stability can be improved by modifications to the groyne geometry. The recessed root reduces overtopping loads without forfeiting structure functionality. However, changes in geometry are, as sole measures, insufficient to significantly improve stability if the rock size is inadequate for the expected overtopping loads.

iv) The adequate rock grading at the study site appears to be $LMB_{5/40}$, however there is scope for optimisation with respect to structural parameters (e.g. slope angles, crest heights) and maintenance frequency.

v) A validated engineering approach for the dimensioning of rock groynes for long-period ship wave attack is needed. This dataset offers the rare opportunity to develop a design method based on prototype observations, as opposed to physical model tests.

In future work, the intention is to develop a probabilistic design approach. While numerous examples for the use of reliability-based methods in the context of coastal dikes, dunes and breakwaters exist (see e.g. listing in Kortenhaus et al. 2009), their adoption in coastal engineering is far from commonplace; the application to rock armour groynes for example is novel. Reasons are found in method complexity and the increased demands on process understanding and data availability (as compared to deterministic methods). However, the need to account for uncertainties stemming from the random nature of the input variables and uncertainties in the failure models provide a strong motivation to develop a probabilistic approach. Reliability-based methods permit the optimisation of design and maintenance plans over the life time of the structure, from construction to maintenance and decommissioning, facilitating cost-optimal and risk-appropriate design. The key concept here is the annual probability of failure P_f.

5.1 Development of probabilistic approach

The failure of a structure for design purposes is defined by the relative magnitudes of the loading S and resistance variables R. Conventionally, R and S are given discrete values and the probability of failure can only take the values 0 or 1. In probabilistic design, these variables are described by statistical distributions and, in simple terms, P_f is calculated by solving for the integral of R-S<0. To determine the statistical distribution functions, a detailed analysis of the load and resistance variables, as well as interdependencies with variables that influence the loading and response of the structure (e.g. ship and navigational parameters, structure characteristics) is performed. The most relevant parameters will be identified and treated statistically, resulting in probability distributions; the interdependence of variables can be treated in multivariate probability distributions. Each failure mechanism is described by a process-oriented failure model and its associated limit state equation; here, these models have to be developed drawing on the previous research. Due care is required in the described steps as the result can be very sensitive to the choice and robustness of the failure and probabilistic density models (Reis et al., 2006). The developed failure model is to be validated against observations. For the calculation of P_f, Monte Carlo simulation will be used, based on the developed load and resistance models. The joint probability distributions may be used to investigate the conditional probability of a particular damage configuration at certain load conditions. The criteria for acceptable groyne damage and target probability of failure P_f^T will be performed in consultation with stakeholders (e.g. WSV); this also relates to the optimisation of the structure, which concludes the design iteration (cf. Fig. 7).

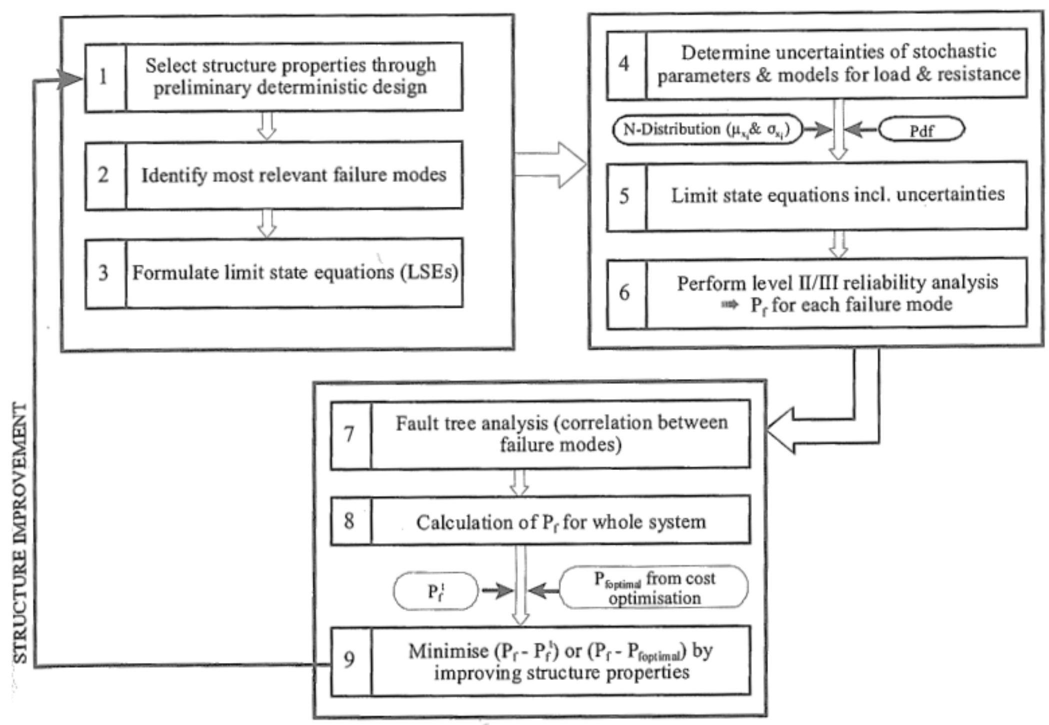


Fig. 7. Procedure for the development of a probabilistic design approach from Oumeraci et al. (2000).

5.2 Optimisation of design

The economic optimisation of the design over the structure lifetime is possible within the bounds of a risk- and cost-appropriate target (i.e. acceptable) probability of failure P_f^T. For groynes that consist of multiple layers of protective rock armour, a certain level of erosion may be tolerable, so long as the functionality of the structure is maintained. The choice of P_f^T is thus informed by balancing the structure's functional requirements with the associated capital expenditure for initial construction and maintenance. This relationship is illustrated conceptually in Fig. 8. Structures designed for a high design load, i.e. a low probability of failure, will incur higher initial costs yet are likely to require less maintenance. First analyses of maintenance costs for different design loads on inland waterways by

BAW (2015b) suggest that expenditure rises disproportionately for structures devised for lower design loads. More data on and analysis of the life-cycle costs of rock groyne structures from the estuarine environment will be needed in order to determine the cost-optimal structure reliability level. As groynes tend to deteriorate as a result of repeated loading (catastrophic failure, at least in response to intermittent ship waves, can be ruled out) failure-associated risk, which typically plays a role in the determination of P_f^T, is of secondary importance in this particular case.

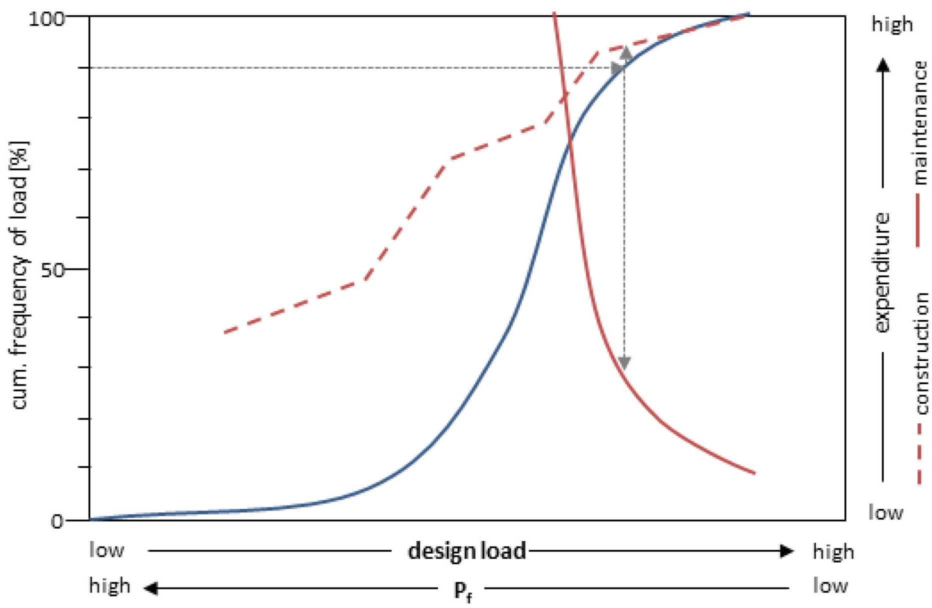


Fig. 8. Conceptual illustration of the relationship between design load, probability of failure and expenditure for construction and maintenance. Modified from BAW (2015b).

5.3 Outlook

The continued development efforts on this topic will be directed towards the aim of a practical, validated method, based on probabilistic principles, for the practising design engineer. In first instance, a methodological framework shall be provided which represents the initial step for the assessment of the impact of individual design decisions on failure probability. To assess the validity of the method, ground-truthing of the results based on prototype observations will be necessary. It is likely, that the method can be improved upon in the future as more data and observations are collected and the underlying mechanics are updated to reduce uncertainty in the underlying models. This includes the creation of baseline data for groyne life-cycle costs which are required for economic design optimisation.

From collaboration on the method development with the Department of Hydraulic Engineering at TU Delft, further impulses for the acceptance, development and use of probability-based tools in applied coastal engineering are anticipated.

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