

Optimal inspection strategy for rubble-mound breakwaters with time-dependent reliability analysis

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ABSTRACT: This paper presents a comprehensive maintenance strategy with optimal inspection planning and its application to rubble mound breakwaters. In order to fulfil designated functions, a breakwater has to be inspected during its lifetime and has to be repaired if necessary. Actions of inspecting and repairing form a maintenance strategy. In the paper rational maintenance decision-making approaches are discussed. The proposed maintenance strategy combines time-dependent and condition-dependent maintenance with event-dependent inspection. Optimal inspection planning is obtained by cost optimization with a safety constraint. In practical cases, it is possible to achieve an optimal inspection plan when relevant parameters of strength and load are existing and available.

1 INTRODUCTION

Structural systems in general and breakwater systems in particular are subject to deterioration in time due to various factors such as the cumulative loading, the environmental effects or the ageing of materials. Selecting a rational maintenance strategy, which is formed by a combination of inspecting and repairing actions, is of main concern for engineering operation management.

Over the past decade, optimal maintenance strategies following probabilistic and reliability approaches has been developed widely. Faber (2002) and Straub & Faber (2005) introduced and discussed the concepts and applications of reliability-based and risk-based inspection planning for structural system (RBI). In the field of coastal and hydraulic engineering, several researches on the maintenance model have also been presented. van Noortwijk & van Gelder (1996) proposed an optimal maintenance decision model for berm breakwaters that dealt with breakwaters' breaching processes. Vrijling (2003) developed a framework for the maintenance of water defense systems which focused on distinguishing different maintenance strategies. Recently a thorough discussion on the monitoring, inspecting and repairing procedures of flood defence systems was presented by Buijs (2007).

This paper proposes a comprehensive maintenance strategy for breakwater systems that includes the time, load and state dependencies. With this strategy the optimal inspection planning is derived.

In this paper the functional system, functional failures, failure modes and reliability analysis of a breakwater system are presented. Rational maintenance optimisation approaches are discussed.

Then a maintenance strategy applied to rubble mound breakwater is developed based on the reliability analysis of breakwater systems. The optimisation problem is formulated with cost component quantification. Optimal inspection plan is found when a minimum total expected cost of maintenance is achieved with a minimum reliability constraint.

The paper is structured as follows. A brief introduction on reliability analysis of rubble mound breakwaters is presented in Section 2. Discussion on maintenance strategies is given in Section 3. In Section 4, the optimisation problem is formulated. Finally, conclusions are presented in Section 5.

2 RELIABILITY ANALYSIS OF BREAKWATER SYSTEMS

2.1 *Introduction to reliability analysis of rubble-mound breakwaters*

Several concepts in the context of reliability analysis should be mentioned including system, failure and fault tree. A structure can be modelled by a system including subsystems and components. A failure is defined as a condition in which a structure or a structural component loses its designated functionalities. Interaction (or correlation) between failure modes and the contribution of each one to the system failure can be defined in a fault tree. A fault tree gives a logical succession of all events that leads to one unwanted top event. The probability of failure of the whole system, equal to the probability that the top event occurs, can be calculated based on probabilities of failure of components and their correlations.

The main objective of a breakwater in this study is to protect the harbour basin against unacceptable wave actions. Within this objective, the top event in the fault tree of a breakwater system is the port downtime, i.e. the stoppage of the port operations due to malfunction of the breakwater system. Three major mechanisms causing this top event can be distinguished: i) collapse of the breakwater; ii) excessive wave height in the basin; iii) obstruction of the entrance channel. Various failure modes exist in each failure mechanism. Each failure mode is described by a formula. Fault tree of a breakwater describing the major mechanisms is illustrated in Figure 1.

The first failure mechanism is the collapse of the breakwater which is called the Ultimate Limit State (ULS). As a result of collapse, the protective function of the breakwater fails.

The second failure mechanism is the excessive wave height inside the harbour basin during normal weather condition. The port operations at the lee side, e.g., ship manoeuvring, berthing, loading and unloading, can only be carried out within an allowable wave height in the harbour. Whenever the wave height exceeds the maximum allowable height, the breakwater system can be considered to fail. This failure mechanism occurs without severe collapse, and can be regarded as Serviceability Limit State (SLS).

The last failure mechanism is not closely related to the protective function of the breakwater. Obstruction of the entrance channel can be the consequence of a bad breakwater layout. Ships that run aground in the navigational channel cause traffic obstructions and affect the port operations. This failure mechanism falls beyond the scope of this paper.

2.2 Ultimate limit state of a breakwater

A breakwater structure is composed of many parts, e.g., armour layers, concrete caps, toe structures. Collapse of one of these parts will weaken the resistance of other parts and, eventually, the whole structure. ULS failures occur under an extreme condition, in this case a typhoon.

Failure modes in cross-section of a rubble mound breakwater can be the instability of the primary

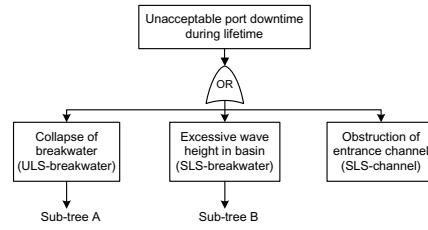


Figure 1. Fault tree with top event and intermediate events.

armour layer, the erosion of the toe, the excessive wave overtopping, the slip circle, the excessive settlement, etc. Details on failure modes of breakwater can be found in, for instance, d'Angremond & van Roode (2004), Burcharth (2006), Nguyen et al. (2008a), Nguyen et al. (2008b). The first two failure modes are illustratively presented in this paper.

Some relevant parameters involving in the ultimate limit state functions (ULSFs) are shown in Table 1.

To calculate the hydraulic stability of a Tetrapod armour layer, the following van der Meer's formula is applied, see Burcharth (2006):

$$\frac{H_s}{\Delta \cdot D_n} = f_i \left(3.75 \frac{N_{od}^{0.5}}{N^{0.25}} + 0.85 \right) s_{om}^{-0.2} \quad (1)$$

D_n and Δ are calculated as follows:

$$D_n = \sqrt[3]{V} = \sqrt[3]{\frac{M}{\rho_c}} \quad (2)$$

$$\Delta = \rho_c / \rho_w - 1 \quad (3)$$

The following ULSF can then be derived:

$$Z = f_i \left(3.75 \frac{N_{od}^{0.5}}{N^{0.25}} + 0.85 \right) s_{om}^{-0.2} \cdot \left(\frac{\rho_c}{\rho_w} - 1 \right) D_n - H_s \quad (4)$$

Table 1. Relevant parameters in ULSFs.

Parameter	Meaning	Units
D_n	characteristic diameter of armour elements	m
D_{n50}	median of nominal diameter of rocks for design condition	m
H_s	significant wave height	m
M	mass of a block	ton
N	number of wave	—
N_{od}	number of displaced units within a strip with width D_n	—
V	volume of a block	m^3
Δ	relative density of material	—
f_i	coefficient denoting the difference between slope angle of the tested model and the real design	—
s_{om}	wave steepness	—
ρ_c	density of concrete	ton/m ³
ρ_r	density of rock	ton/m ³
ρ_w	density of water	ton/m ³

The erosion of the toe is one of the major failure mechanisms. According to van der Meer et al. (1995), the following equation is valid:

$$\frac{H_s}{\Delta \cdot D_{n50}} = \left(0.24 \frac{h_t}{D_{n50}} + 1.6 \right) N_{od}^{0.15} \quad (5)$$

This equation is then reformulated to a ULSF as the following:

$$Z = \left(0.24 \frac{h_t}{D_{n50}} + 1.6 \right) N_{od}^{0.15} \cdot \left(\frac{\rho_r}{\rho_w} - 1 \right) D_{n50} - H_s \quad (6)$$

2.3 Serviceability limit state of a breakwater

The SLS of a breakwater relates to the tranquillity of the port basin. During normal conditions, the breakwater system can be considered as failure if the wave height inside the basin exceeds a maximal allowable height.

The wave inside the port basin is a combination of wave refraction-diffraction via the entrance, wave transmission through and overtopping the breakwater, and locally generated wave. The locally wave generated by wind or ship can be considered as minor and negligible.

According to CUR/RWS (1995), the wave height in the port basin can be calculated by the following formula:

$$H_{basin} = (K_{dif} + K_t) H_{sea} \quad (7)$$

where H_{sea} is the wave height outside the basin, K_{dif} is the diffraction coefficient and K_t is the transmission coefficient.

K_t can be calculated as follows:

$$K_t = 0.46 - 0.3 \frac{R_c}{H_s} \quad (8)$$

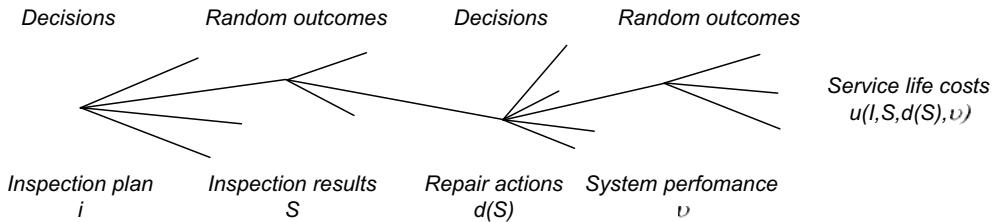


Figure 2. Bayesian decision-making context, from Faber (2002).

where R_c is the crest freeboard and H_s is the incident wave height.

The limit state function for the excessive wave height is the following:

$$Z = H_{allow} - H_{basin} \quad (9)$$

where H_{allow} is the allowable wave height inside the port basin.

3 RATIONAL MAINTENANCE DECISION-MAKING

3.1 Rational maintenance optimisation models

The combination of a proper maintenance optimisation method and a certain maintenance strategy for a specific type of structure forms a rational maintenance optimisation model. Maintenance optimisation methods deal with the system description, system functional failures and failure modes analysis, and maintenance tasks. A maintenance strategy considers triggers that prompt a maintenance operation.

There are three maintenance optimisation methods: fully quantitative, fully qualitative and mixture of qualitative and quantitative methods. The quantitative maintenance optimisation approach is illustrated with a framework which has been developed for risk-based inspection (RBI) planning, see for instance Faber (2002), Straub & Faber (2005). This illustration shows where a time-dependent reliability contribution is required and in which form. Quantitative maintenance approach in hydraulic engineering is further discussed in Buijs (2007). It has been shown in Buijs (2007) that for time-dependent processes, a Bayesian approach is preferred over a Markovian approach in case of flood defence structures. An example of the Bayesian decision-making model is described in Figure 2.

Disadvantages of the quantitative maintenance approach are the information-dependent and computationally intensive attributes. The qualitative maintenance optimisation approach overcomes these disadvantages by concentrating

only on important failure modes and on rational maintenance actions. The qualitative method analyses the prioritisation of failure modes and carries out only applicable and effective maintenance tasks. The redundancy in failure modes analysis and in maintenance actions results in a reduction of intensive computation, although the subjective prioritisation often relates to quantitative approaches. A mixture of quantitative and qualitative approaches combines the computationally feasible qualitative decision-making with quantitative objective prioritisation. It is shown in Buijs (2007) that the combined approach is better applicable to the maintenance of coastal and hydraulic structures.

All aforementioned maintenance optimisation approaches require describing the system function, identifying the functional failures and corresponding failure modes, and selecting a proper maintenance strategy. The functional and reliability analysis of breakwater systems is described in Section 2. Maintenance strategies in mechanical engineering relates to types of triggers that prompt a maintenance operation. These strategies are discussed in Vrijling (2003) and can be illustrated by a flow chart in Figure 3. As seen in Figure 3, curative maintenance and preventive maintenance are clearly distinguished. Curative or fault-dependent maintenance repairs or replaces structural components when they can no longer fulfil their functions and the lifetimes of the components are fully exploited. Preventive maintenance can be either use-dependent or condition-dependent maintenance. Use-dependent maintenance can be further broken down into load-dependent or time-dependent maintenance. In case of load-dependent maintenance, loads which cause deterioration need to be registered and a maintenance operation takes place after an extreme large load or after a certain cumulative amount of load. Time-dependent maintenance discretises the lifetime of a

structural components into time intervals between two subsequent maintenance operations. With condition-dependent maintenance the state of the structural components is determined at an optimal frequency by means of inspections. The decision whether or not to repair depends on observations. Graphical illustrations of these maintenance strategies are demonstrated in Vrijling (2003).

3.2 Maintenance strategy in application to rubble mound breakwaters

Vrijling (2003) briefly discussed the selection of maintenance strategies. A fault-dependent maintenance can only be accepted for non-integral parts of structures. Fully time-dependent maintenance is applied if inspection is not possible or if inspection is expensive. Fully condition-dependent maintenance is carried out if it is not possible to make a prognosis of the strength in time or if inspection is cheap.

In practical hydraulic engineering it is not possible to apply a single maintenance strategy. Complex structures like breakwater systems include various components, which subject to degradation and failure in different ways. The reliability analysis of breakwater systems presented in Section 2 shows that the system failure is the consequence of regular normal conditions or of a sudden extreme condition. The occurrences of extreme events, i.e. storms, are quite uncertain. Thus the fully time-dependent maintenance is not applicable. Regarding to structural condition inspection, the inspection methods applied to breakwater systems are ranging from a simple visual check to a thorough seabed and toe survey. A combination of all three strategies leads to a better result. The proposed model is as follows.

The maintenance planning is firstly drawn up using the time-dependent maintenance strategy, which based on the designed loads. The initiative

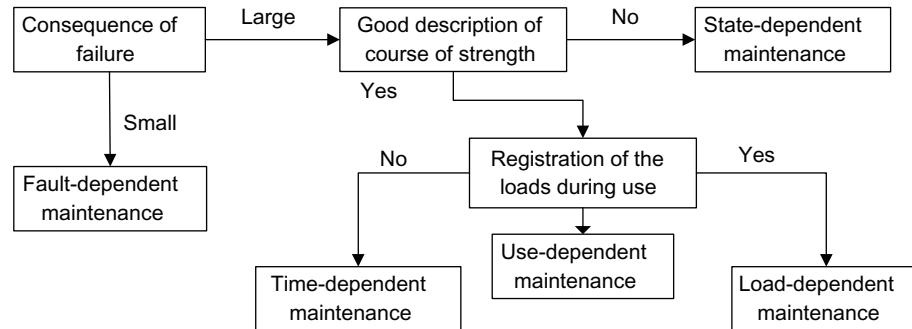


Figure 3. Global selection of the maintenance strategy, from Vrijling (2003).

to commence repair or replacement works depends on the strength according to inspection. The actual loads are monitored and the maintenance operation including inspection and repair is triggered when a single extreme load or a cumulative load threshold is exceeded. Having accepted that repair works bring structural components back to as good as new state, the maintenance routine is started over after a repair. This maintenance strategy draws up the following norms.

- A strength-based warning threshold: a limit state which leads to an increase of inspection frequency.
- A strength-based action threshold: a limit state which leads to carrying out repair works.
- Load-based action thresholds: limit states based on the registration of loads which also leads to carrying out repair works. Load-based action threshold can be further broken down into single or cumulative load threshold.

The proposed maintenance strategy is described in Figure 4. For a simpler illustrative purpose, only the cumulative load-based action threshold is displayed. In Figure 4, Δt denotes the planned (or designed) inspection intervals, and Δt^* denotes the updated inspection intervals. Changes in inspection intervals happen when either the strength falls below the warning threshold or the load exceeds the load-based action threshold.

In case of rubble-mound breakwaters, monitoring or registering all loads for every structural component at crucial places can hardly be possible. The monitoring procedure of loads, if being carried out, is also expensive. Therefore the load-based action threshold is dismissed. As mentioned in Section 2, ULS failures occur under extreme

loading conditions during storms, which can be called extreme events. Instead of using load-dependent maintenance, the event-dependent inspection is introduced. The event-dependent inspection means that an inspection is carried out immediately after an extreme event, i.e., a storm.

An alternative maintenance strategy applied for rubble-mound breakwater is proposed, which combines the time-dependent and condition-dependent maintenance. Inspections in this strategy are event-dependent or based on updated strength observations. This maintenance strategy is shown in Figure 5. In Figure 5, Δt denotes the planned (or designed) inspection intervals, and Δt^* denotes the updated inspection intervals. Changes in inspection intervals happen when either the strength falls below the warning threshold or an extreme event occurs.

4 OPTIMISATION OF INSPECTION PLAN

An optimal inspection plan is defined as one that minimises the total cost of maintenance subject to a safety constraint. The decision variables can be the inspection time interval, the number of inspections in an inspection operation or a decision rule on actions to take depending upon inspection results. The objective function will be the total expected costs of maintenance including the inspection cost, the cost of repairs and the cost of failure. The reliability of the breakwater system is incorporated in the objective function through the expected cost of failure.

Based on the proposed maintenance strategy for breakwater systems (see Fig. 5), the following components of inspection plan are introduced.

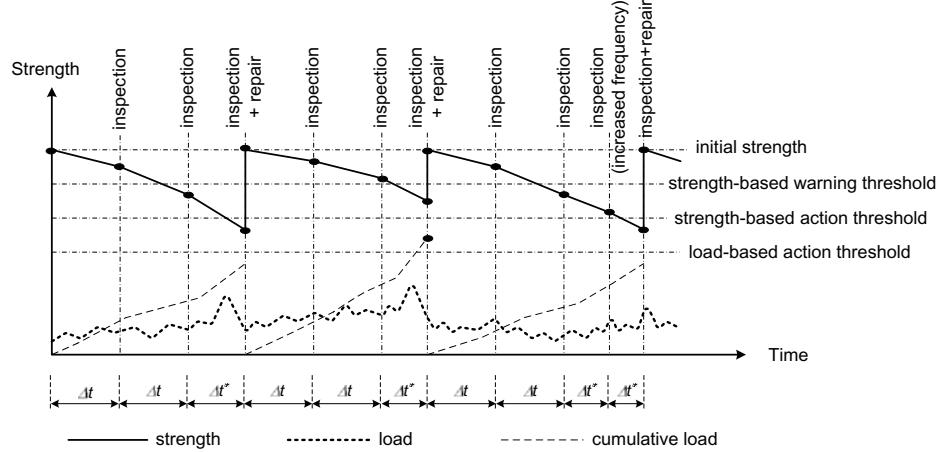


Figure 4. Comprehensive maintenance strategy in hydraulic engineering.

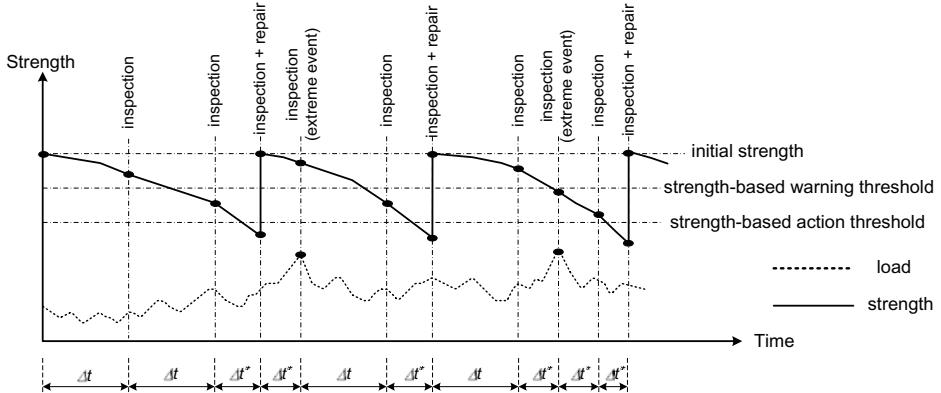


Figure 5. Maintenance strategy for rubble mound breakwaters.

$I(\Delta t, l, r)$ - the inspection plan I , consists of:

$\Delta t = (\Delta t_1, \dots, \Delta t_N)$ - the interval between the time t_i^{th} of N inspection operations

$l = (l(t_1), \dots, l(t_N))$ - the location to inspect at the inspection times

$l(t_i) = \{l_1, \dots, l_{M(t_i)}\}$ - the location to inspect at the t_i^{th} inspection

$r = (r_1, \dots, r_N)$ - the reliability or quality of the planned inspections (including the precision of inspection locations, the quality of the inspection method, etc.)

$M(t_i)$ - the total number of inspection at time t_i

$d(t_i)$ - random vector defining the action to take depending on the inspection t_i^{th} , whereby the individual components refer to the results obtained from inspection actions at location $l(t_i)$

The optimisation problem is formulated as follows:

$$\begin{aligned} \min_i C_T(I, M(t_i), d(t_i)) &= C_I(I, M(t_i), d(t_i)) \\ \text{s.t. } \beta(T_L) &\geq \beta_{\min} + C_R(I, M(t_i), d(t_i)) \\ &\quad + C_F(I, M(t_i), d(t_i)) \end{aligned} \quad (10)$$

where C_T is the total expected maintenance cost, C_I is the expected inspection cost, C_R is the expected cost of repairs and C_F is the expected failure cost. C_L is the expected lifetime.

The generalised safety index $\beta(T)$ at reference time T is defined by:

$$\beta(T) = -\Phi^{-1}(P_f(T)) \quad (11)$$

in which $P_f(T)$ is the failure probability in the time interval $[0, T]$ and Φ is the standardized normal distribution function.

Equation 10 is a fully probabilistic problem with most of parameters can be considered random

variables. In practice assumptions and simplifications should be made in order to solve Equation 10.

Due to the fact that there are some locations along a breakwater which are more vulnerable to wave attack than other locations, these crucial locations can be set as inspecting locations. Thus the total number of inspection at time t_i^{th} can be assumed constant. It is also assumed that inspections are made with the same reliability r at any location and time.

Then the definitions of C_I , C_R and C_F are expressed in the following equations:

$$C_I = \sum_{i=1}^N M.C_H(r)[1 - P_f(t_i)] \frac{1}{(1+\gamma)^{t_i}} \quad (12)$$

where $C_H(r)$ is the cost of inspection i th with inspection reliability r , γ is the discount factor and $P_f(t_i)$ denotes the probability of system failure between 0 and t_i .

$$C_R = \sum_{i=1}^N \sum_{j=1}^M C_{R,i,j} P_{R,i,j} [1 - P_f(t_i)] \frac{1}{(1+\gamma)^{t_i}} \quad (13)$$

In Equation 13, $C_{R,i,j}$ is the cost of repair at location j of the i th inspection and $P_{R,i,j}$ is the probability of performing a repair at location j after the i th inspection given that failure has not occurred earlier. $P_{R,i,j}$ is a combination between the probability that the strength-based action threshold is exceeded and the success of the repair.

$$\begin{aligned} C_F &= \sum_{i=1}^{N+1} \sum_{j=1}^M C_F(t_i) [(1 - P_{R,i,j}) \\ &\quad \cdot [P_f(t_i) - P_f(t_{i-1})]] \\ &\quad + P_{R,i,j} [P_{f,R}(t_i) - P_{f,R}(t_{i-1})] \frac{1}{(1+\gamma)^{t_i}} \end{aligned} \quad (14)$$

In Equation 14, $C_F(t_i)$ is the cost of system failure at time t_i and $P_{f,R}(t_i)$ is the probability that the system fails after a repair has taken place. $C_F(t_i)$ includes the costs of repair and the economic losses caused by the suspension of harbour operation.

Equations 12, 13 and 14 formulate the cost components of an inspection plan. The probability of system failure P_f is calculated following the reliability analysis presented in Section 2, and can be seen in more detail in Burcharth 2006, Nguyen et al. (2008a), Nguyen et al. (2008b). In a practical case when all the parameters, including the breakwater's geometry, the wave condition and the costs of materials, etc., are available, the optimisation problem can be solved by iteration until a minimum total expected cost of maintenance is achieved with a minimum reliability constraint.

5 CONCLUSIONS

A comprehensive maintenance strategy for rubble mound breakwater is demonstrated in this paper. The general strategy bases on a mixture of qualitative and quantitative maintenance decision-making approaches. This mixed approach utilises the advantage of a rational computationally feasible qualitative approach with that of a quantitative objective prioritisation. In dealing with time-dependent processes, the Bayesian approach is used for posterior analysis.

Within the mixed maintenance decision-making approach, the maintenance strategy for rubble-mound breakwater systems is derived. This maintenance strategy combines time-dependent and condition-dependent maintenance. Inspections in the proposed maintenance strategy are event-dependent or based on updating from previous observations.

The optimisation of inspection plan is also formulated in this paper. Optimal inspection planning is obtained by cost optimisation with a safety constraint. The cost components are quantified according to the proposed maintenance strategy. In practical cases, it is possible to achieve an optimal inspection plan when relevant parameters of strength and load are existing and available.

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