Monitoring, maintenance and repair of coastal rock structures

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Two main classes of maintenance are defined: corrective and preventive maintenance. In the preventive maintenance subclass, which seems most appropriate for coastal and harbor structures, repair takes place at specified intervals before failure occurs. The optimal cycle of inspection and repair is found by minimizing the present value of all costs. Coastal and harbor engineers can give attention to the design equations that predict failure Ultimate Limit State (ULS) or structural deterioration over time Serviceability Limit State (SLS). Both types provide a good basis for the optimization of the maintenance of coastal and harbor structures.

تستخدم حواجز الأمواج الكومية عالمياً علي نطاق واسع، سواء كان في إنشاء الموانئ أو في حماية الشواطئ من النحر والترسيب وتقليل ومنع الإطماء في الممرات الملاحية. ويرجع ذلك لإنخفاض تكلفتها الإقتصادية بالإضافة إلي كونها صديقة للبيئة حيث إنها تقلل طاقة الأمواج المهاجمة وفي نفس الوقت تسمح للأمواج طويلة المدي بالعبور من خلال الفجوات الموجودة بين أحجارها، مما يؤدي إلي تجدد المياه في المنطقة التي يحميها الحاجز، وبالتالي تقليل التأثير الضار الذي يحدث للبيئة في هذه المنطقة. ونظراً لما يتعرض له مثل هذا النوع من منشآت لقوي هائلة قد تؤدي إلي أضرار كبيرة وربما إنهيارات ببعض أجزائها، فإنه يلزم ملاحظة ومراقبة هذه الحواجز بصفة مستمرة وتسجيل ما قد يحدث لها من أضرار وتحديد أساليب إصلاحها وصيانتها. يهدف هذا البحث إلي إستعراض الطرق المختلفة المستخدمة في مراقبة وصيانة المنشآت البحرية والتي تستخدم الأحجار في تنفيذها وبالذات حواجز الأمواج الكومية مما يؤدي إلي خفض تكاليف الصيانة وتجنب الإنهيارات المفاجئة الناتجة عن عدم المتابعة الدورية لهذا النوع من المنشآت. وقد إعتمد البحث علي وضع نماذج رياضية يمكن عن طريقها تقدير الزمن المتوقع لإنهيار المنشأ أو التدهور الذي قد يحدث له قبل الإنهيار وذلك بهدف تقليل تكاليف الصيانة إلي أدني حد لها. هذا وقد أوضح التطبيق العملي للإسلوب المقترح إمكانية الوصول إلي نتائج طيبة وبطريقة مبسطة وبالتالي إمكانية تعميمة.

Keywords: Coastal and harbor structures, Corrective, Maintenance, Preventive, Costal rock structure

1. Introduction

Maintenance consists of two activities: inspection and repair. Two main classes of maintenance are discerned: corrective and preventive maintenance. The latter subclass contains inspection as well as repair. When a corrective maintenance strategy is selected, the structure will be repaired after damage. In a preventive maintenance subclass the structure will be repaired at specified intervals before damage occurs. The structure is inspected regularly. On the basis of the inspection the decision to repair is taken. The optimal cycle of inspection and repair is found by minimizing the sum of the damage, inspection and repair costs.

Coastal and port engineers do not have large numbers of failed structures as a way to provide reliable statistical data to construct failure rate data base. They must concentrate on the design equations that predict failure Ultimate Limit State (ULS) or structural deterioration over time Serviceability Limit State (SLS). SLS provides good bases for maintenance optimization.

2. Problem statement

Maintenance of coastal and harbor structures compromise all the activities required to be carried out on a periodic bases to ensure that the structure performance is accepted. A good maintenance program includes:-

1. Monitoring and inspection of environmental conditions and structural state.
2. Analysis of the collected data to predict structural deterioration and to ensure compliance with pre-determined standards.
3. Repair or replacement of the parts whose life or performance is expected to be less than that of the overall structure.

The activities to be carried out are based on the maintenance policy developed during the design stage. A successful maintenance policy requires minimizing the overall cost of the structure during its expected life, that is;

$$MINIMIZE \{I + f_1(M) + f_2(R) + f_3(p_t, c_t)\}$$

Where,
I is the investment in the structure,
M is the cost of monitoring,
R is the cost of repair or replacement,
p_t is the probability of failure per year,
c_t is the cost of failure, and, and
f_1 is the present value operator.

Several methods are available to carry out the maintenance, [1-8]. In the case of failure based maintenance repair is only undertaken if the structure, or a part, has failed. This type of maintenance is advisable if the consequences of failure (risk) are very limited, fig. 1. Time based maintenance assumes that the structural state deteriorates according to a known function of time. Repair is due after a certain time has elapsed, fig. 2.

The use based maintenance reckons that the structural state deteriorates as a known function of the number of times the structure is used (e.g. spillway), [5]. Usage has to be monitored and repair is due after a certain number of times that the structure has operated, fig. 3. Load based maintenance attributes the structural deterioration to heavy loading (e.g. storms). Loading has to be monitored and repair is due after a certain number of heavy loadings taking place, fig. 4.

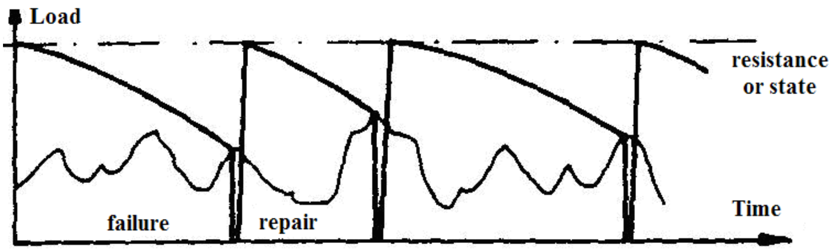

Fig. 1. Failure based maintenance.

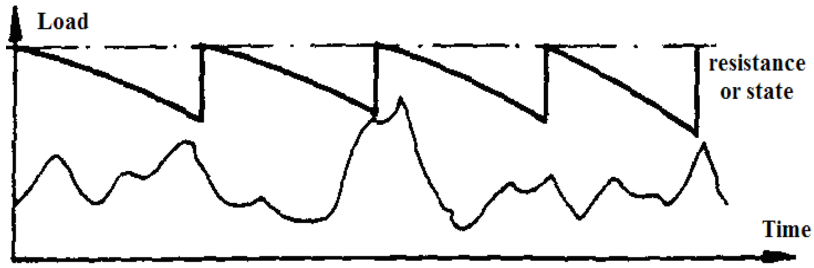

Fig. 2. Time based maintenance.

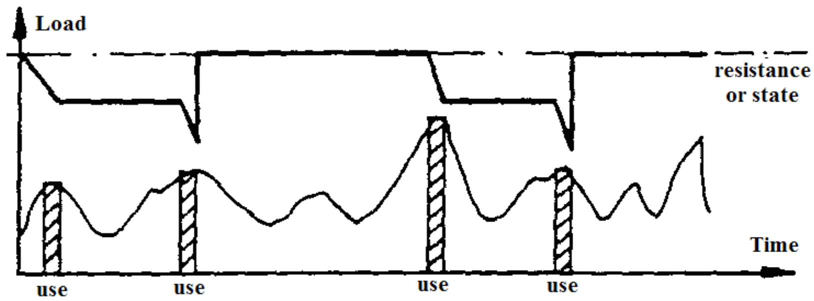

Fig. 3. Use based maintenance.

State based maintenance depends on the inspection of the structural state of the structure. If the structural state seems no longer adequate, repair is necessary, fig. 5.

From this classification, it may be clear that the choice of the maintenance strategy depends on; predictability of the structural deterioration SLS, cost of inspection and monitoring, cost of repair, consequences of failure, availability of methods to measure the structural state accurately.

Due to the poor underwater visibility and the huge volume, inspection of underwater parts, becomes so costly that an inspection strategy similar to those mentioned above should be developed, [6]. The decision to inspect the structure thoroughly is based on the observation of variables that indicate the functionality and the state of the structure. The monitoring of time, usage, load or state precedes an in-depth inspection of the true state. Fig. 6 shows the sequence of monitoring, inspection and repair strategy.

The maintenance policy chosen and developed at the design/construction stage should be recorded in a maintenance manual. If the structure has been designed to minimize maintenance, the manual may be very simple. The manual must contain an indication of the adopted maintenance strategy and the necessary guidance on techniques and criteria for the three basic elements of the maintenance program given in fig. 6. It should give the interrelations of the various activities involved in the maintenance processes, a guide to which is given in the flow chart in fig. 7.

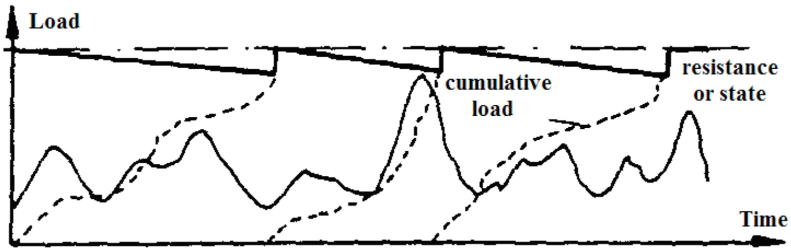

Fig. 4. Load based maintenance.

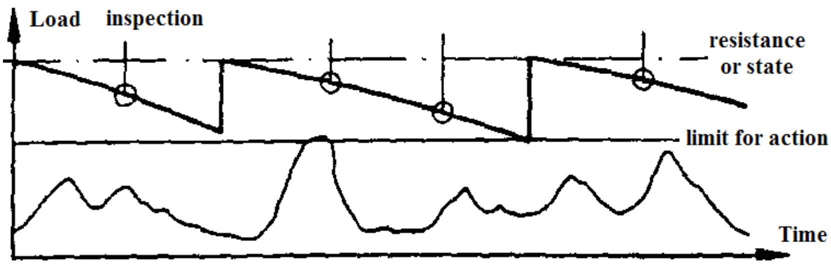

Fig. 5. State based maintenance.

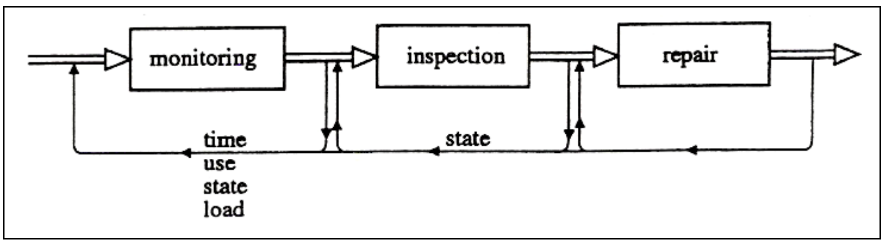

Fig. 6. The sequence of monitoring, inspection and repair strategy.

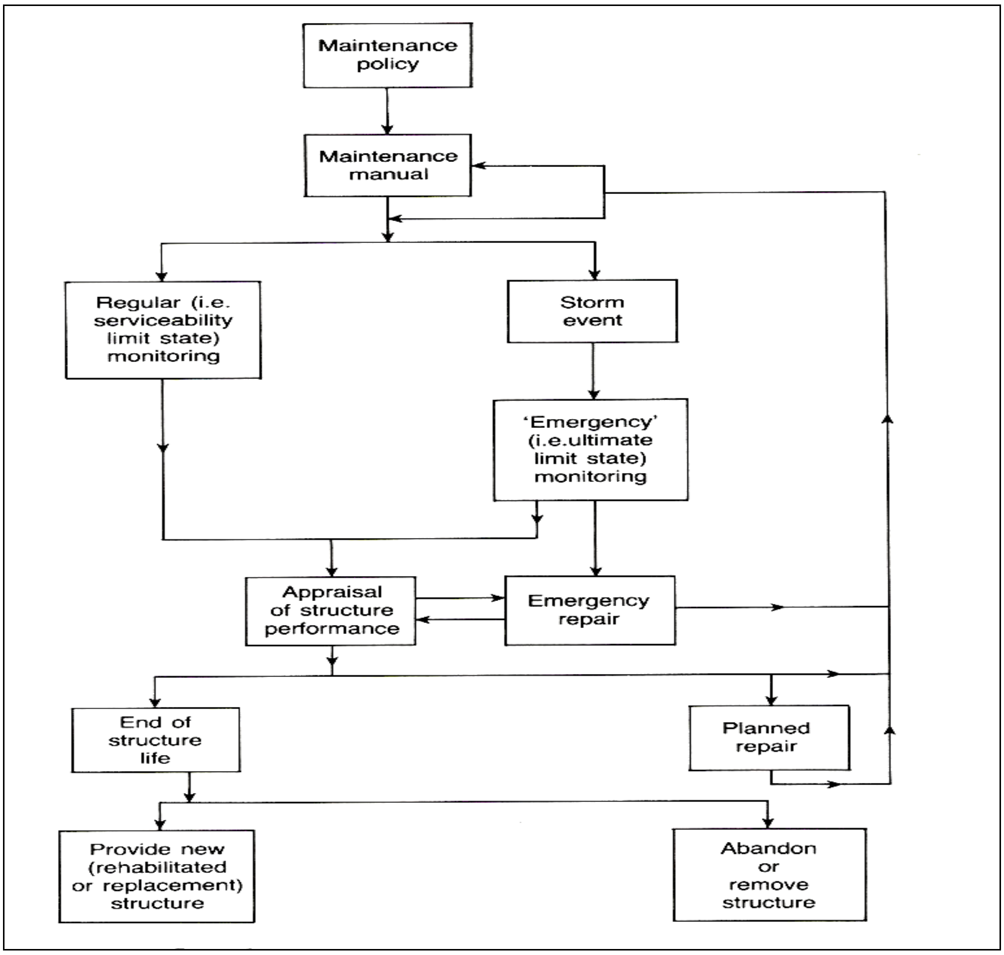

Fig. 7. Maintenance program flowchart.

3. Monitoring and inspection

Rock structures respond to the destructive effect of wave and current by changes in their profile, and changes in the size and shape of their components. The changes in shape can also be due to loss or changes in foundation or core material. Armor rock may be displaced, abraded, fractured or dissolved. Any quantitative description of the state of the structure must identify these different responses, which may either take place gradually SLS, or suddenly ULS during a major storm. The description must be able to link the environmental forces to the responses. Failure based maintenance does not require a monitoring program.

The SLS is most appropriate for monitoring as they show slowly developing phenomena like settlement. Sometimes these SLS are extremely important because they influence the resistance in a connected ULS, which may lead to failure of the structure.

A regular monitoring program for both structure and environment allows one to plan repair and replacement activities with a good understanding of slowly acting mechanisms and damage trends. Without the aid of a monitoring, deterioration of the armor layers or foundations may be unnoticed and may result in the failure of the armor layers or large settlements.

4. Types of monitoring

There are three principal areas of monitoring:

1. Measurement of structural state.

2. Measurement of environmental loading conditions.
3. Measurement of deformation, erosion or damage.

Structural state monitoring concerns the resistance or strength of the structure and its foundation against loading. The variable defining the resistance should be measured directly, for example, the mean grain size, D_{n50}, of the armor layer. When this is difficult to do, the average stone size, crest level of the structure or overall geometry should be measured.

The simplest structural state monitoring consists of walkover surveys carried out to record, with the aid of photographs, the overall condition of the structure including any obvious rock movements, changes in geometry or volume. This type of survey remains very subjective. An experienced engineer may pick up minor signs of impending failure.

A simple survey, to take a few profiles of the structure above and under water, forms the second class of state monitoring. The results of these surveys may provide an experienced engineer with sufficient data for a detailed quantitative assessment of the actual behavior of the structure.

A conventional survey supplemented with special measurements and soundings of details of the structure is the third class. Besides normal profiles, special soundings in the area where scour holes are predicted, photography of armor layers and sonar surveys of toe structures should be carried out. An overview is given in table 1.

The monitoring program may include:

The environmental conditions: water level, current velocity, wave and wind climate, live loads. The external loading on the structure: differential head, wave load, wave pressure wave run-up, wave overtopping. The structure effect on the environment: bathymetry, topography. The internal responses of the structure: soil stresses, pore pressures, deformations, accelerations.

Table 2 gives details of environmental conditions which may be monitored and the appropriate monitoring techniques. For a detailed discussion of environmental data collection, the reader is referred to [1].

Table1
Measures of the state of hydraulic structures

Aspect measured	Output from the comparison of subsequent measurements.
Walkover	Settlement of foundation-change in alignment.
Geometry, profiles	Settlement of foundation-consolidation of foundation Incipient slope failure Scour, erosion.
Profiles and details	Losses of armor rock, failure of armor our due to toe failure, loss of material via voids, damage to pitched rock protection.
Profiles, details and special variables	Displacement of armor rock abrasion and rounding of rock damage pattern movement of rock under wave action.

Table 2
Measures of environmental conditions, loading or loading effects

Environmental condition of loading	Monitoring technique
Water level	Tide board read regularly, recording nearest tide gauge - installing local tide gauge
Wave climate	Pressure cell at sea-bed wave rider buoy- local wave gauge hind-cast using wind records
Wind climate	Local recording anemometer nearest recording anemometer
Wave run-up	Step gauge on slope filming wave run-up
Wave transmission	Local wave gauge at rear wave rider in harbor
Pore pressures	Recording piezometers in core
Grain and water pressure in foundation	Recording piezometers and pressure cells
Bathymetry	Echo-sounding below high tide aerial photography above low tide

5. Frequency of monitoring and inspection

It is important to commence the monitoring of new structures by establishing a "base-line" set of data regarding the structure and its environment at the time of construction and during the construction guarantee period. The recording of details about the structure during the construction stage is also required as a check against the assumptions and details established at the design stage. The recorded data should include basic geometric survey data of profiles and failures of the rock elements during the construction period.

The method and the frequency of monitoring and inspection are governed primarily by the minimum cost requirement stated above. A balance should be established between investment in the structure, cost of inspection and monitoring, cost of repair and the consequences of failure (risk), all in the light of the predictability of the deterioration process of the structure. This may differ considerably from one structure to another and even for mechanisms within the same structure. So a practical approach is advised, favoring, for example, monitoring as a simple cheap continuous type of measuring and inspection instead of more elaborate, in-depth measurement of variables, fig. 2.

The monitoring of the environmental loading conditions should be performed on a continuous basis. In some cases the detailed measurements may be limited to severe conditions to reduce the amount of data to manageable proportions, but a complete log should be kept under all circumstances. Such logs of the weather, tidal levels, river discharges are already kept on a routine basis by Meteorological Offices and we may rely on them. Sometimes, hind-casts have to be made on the basis of these data to arrive at the local environmental loads.

Time based inspection concerns the simplest approach, [3]. The rational minimum interval based on the changing of the seasons is 6 or 12 months. Longer intervals, up to several years, may be chosen if the deterioration process is mainly a function of time and is well known. If the inspection confirms deterioration, repair will be planned. If the deterioration depends mainly on the usage or the loading the cumulative use or the cumulative loading forms the basis for inspection. In this case, inspection is due after a specified number of uses (spillways) or storms (revetments).

State based inspection might be of an incremental nature. Walkover surveys carried out by experienced engineer may form the basis of a decision to perform a suitable in-depth inspection involving more resources. After the first few years of life of a structure with satisfactory performance, adequate monitoring will still be achieved if the detailed surveys are reduced in frequency from say 12 to 24 months or even longer.

Two basic frequencies of monitoring will be involved, one related to normal conditions or SLS and the other related to extreme conditions or ULS. Monitoring related to the serviceability state should take place on a planned basis at frequencies identified at the design stage. Ultimate state monitoring will only take place during and following severe storm events. The minimum wave conditions for which should be stated at the design stage.

The frequency of monitoring should be determined according to the risk of the different failure mechanisms; structural elements, foundation conditions, exposure conditions and design criteria. This frequency differs with different types of monitoring. It could increase during the life of the structure due to the reduction of the structure's resistance with time.

6. Evaluation of structure performance

After performing the monitoring and inspection program, it is required to document all the collected data and carry out an analysis to form the basis for decisions regarding the need for and extent of maintenance works. Each structure state monitoring report should contain the environmental conditions recorded during the interval. For ULS mechanisms the appraisal is relatively simple as damage is only expected when the design conditions are exceeded. If damage is caused by lower conditions a thorough analysis of the design calculations and the as-built structure is advised.

It is essential after each monitoring survey to make an estimation of the remaining life of the structure assessed in relation to each potential damage pattern SLS or ULS in order to monitor the overall safety. The remaining life can be estimated by an extrapolation of the graphical representation of the state variable as a function of time, fig. 5.

The decline effect can be presented by constructing a kind of "measuring watch", fig. 8. On this watch, both the actual damage level and the damage limits (warning limit, action limit and failure limit) can be presented on a time scale [2].

To provide a good presentation, the "measuring watches" of all relevant damage patterns for the structure can be collected together into one control panel, to provide a complete overview of the structure's overall actual and near-future safety condition. After completing the assessment, one may decide to opt for one or more of the maintenance actions indicated in the flow chart, fig. 7. The options may be one of the following:

1. Do not repair/replace and await next planned monitoring report.
2. Do not repair/replace but plan for additional future monitoring of the structure state and/or environmental conditions.
3. Carry out further detailed inspection before making a decision.
4. Undertake temporary or "emergency" repair/ replacement works.
5. Undertake permanent repair/replacement works.
6. Develop a new (rehabilitated or replacement) structure.
7. Abandon or remove the structure.

The decisions made based on an inspection report should be set against performance and failure criteria stated at the design stage. It should be noted that performance and failure criteria can change due to technical understanding development and as the requirements for the function of a structure change because the changes in use, safety or environmental standards.

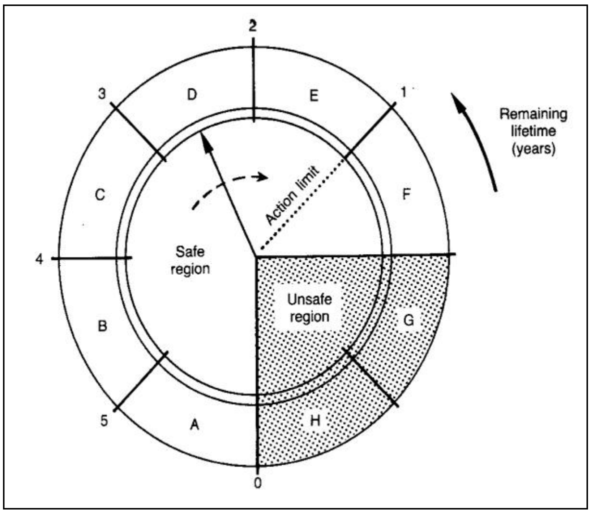

Fig. 8. Measuring watch for a selected damage pattern.

7. Repair and replacement methods

The repair methods adopted for any particular rock structure is strongly influenced by the decisions taken during the design and project appraisal stage.

Financial considerations are important items. The maintenance budget has a strong influence. Generally, it will be uneconomic to under design the structure so that when damage occurs it reaches the under layers or core. Repair, in this situation, is expensive. Economic maintenance procedures will therefore generally be confined to repairs to the armor layer. Economic considerations suggest different approach to parts that can be reached afterwards (armor) and parts of the structure that cannot (filter layers). Since armor stone is a re-usable commodity, in many cases of shoreline protection structures, repair works will only require dislodged stone to be retrieved and placed back. For environmental reasons this re-use may be preferred even under adverse cost conditions.

In some cases new armor stone is required for repair. In this case, if provision for suitable access has been made at design stage and there are no financial constraints, the stone can be imported as required. Importing small quantities of armor stone is very expensive, especially, if the quarry is remote. In addition, access for trucks after construction may be difficult or impossible. In this case, stockpiling of spare material at the site as part of the main initial construction operation should be considered.

8. Case study

Let us consider the gradual deterioration of the bed protection due to losing the covering material by extreme current. Given the threshold of the transport relation, the transported amount may be zero in some years and positive in other years. The last circumstance causes erosion. Figure (9) shows a sluice where the bed protection in the downstream consists of geotextiles covered by rock. The rock is gradually eroded over time by extreme discharges. This leads to failure because either due to exposing the geotextiles to the current or the weight of the rock layer becomes insufficient to withstand the uplift pressure, which is caused by the head difference, when the gate is closed.

The current velocity U is normally distributed with a mean of 2 m/s and a standard deviation 0.4 m/s. The amount of the rock eroded, T, is given by [5]:

$$T = 1260\,(U-2)^2 \;\; kg/m^2 \;\; per\ year \quad (U > 2 \quad m/\sec.)$$

The mean and the standard deviation of the eroded rock per year are 101 and 226 kg/m^2, respectively. The degradation as a function of time is the sum of the yearly erosion. The probability of failure increase with increasing the time between maintenance works. Fig. 10 gives the failure rate versus time.

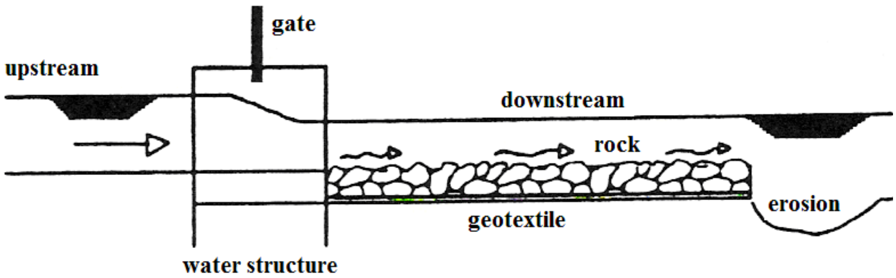

Fig. 9. The eroded bed of the sluice.

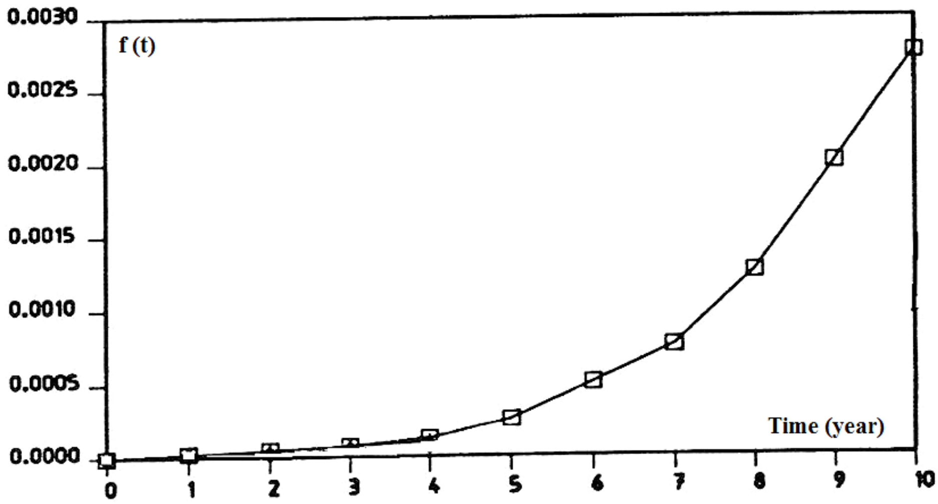

Fig. 10. The failure rate as a function of time.

The present value of the risk, V_R, is given by [5]:

$$V_R = D \sum \left(f(t)\, \Delta t \,/\, (1+r)^t \right)$$

Where:

D is the repair cost and loss due to total failure,
$f(t)$ is the failure rate function,
r is the rate of interest,
t is the time interval between repairs, and
Δt is the time step for the failure rate function sampling.

The cost of repair, R_c, depends on the volume of the eroded rock, C_r, and the cost of equipment mobilization, M_c, and is given by [5]:

$$R_c = \frac{M_c + D.C_r.T}{(1+r)^t}$$

The present value of the cost of repairs and the risk between repairs has to be added over the lifetime of the structure. This defines the objective function that should be minimized with respect to the repair interval. The numerical values of D, M_c, C_r and r are; D =40E[6] Dutch gui1ders, M_c = 10000 Dutch gui1ders, C_r = 100 m^3, and r = 0.04, T = 101 kg/m^2. The present value of the total cost as a function of the repair interval is given in fig. 11. The optimal interval is 4 years.

9. Conclusions

Maintenance should form a part of the design considerations. The ease and cost of the maintenance of parts of a rock structure will influence the design and the level of safety against failure. The empirical failure rate is represented by probabilistic calculations based on the engineering models of the serviceability limit states SLS. Depending on the exact situation a choice should be made from various approaches for maintenance, such as failure dependent, time based, load based and state based. Variables influencing the choice are given.

Due to the vastness of coastal structures, the cost of frequent and detailed inspection may be prohibitive. Therefore a hierarchy of frequent light monitoring, strategic, in-depth inspection and repair should be proposed. Inspection strategies may be classified in the same way as maintenance.

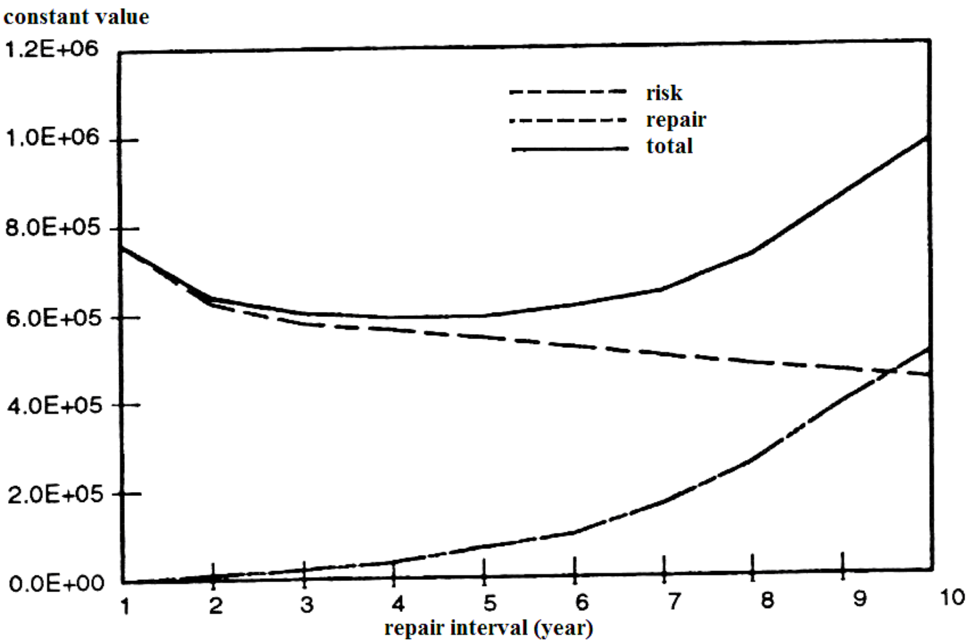

Fig. 11. The total expected cost versus repair intervals.

10. Notations

r is the rate of interest,
t is the time interval between repairs,
f_1 is the present value operator,
p_t is the probability of failure per year,
D is the repair cost and loss due to total failure,
I is the investment in the structure,
M is thecost of monitoring,
T is the amount of the rock eroded,
U is the velocity,
C_r is the volume of the eroded rock,
C_t is the cost of failure,
D_{n50} is the mean grain size of the armor layer,
M_c is the cost of equipment mobilization,
V_R is the value of the risk,
R_c is the cost of repair,
$f(t)$ is the failure rate function, and
Δt is the time step for the failure rate function sampling.

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Received January 30, 2007
Accepted May 14, 2007