CHAPTER 129

THE MAINTENANCE OF HYDRAULIC STRUCTURES

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1.0 INTRODUCTION

With the completion of the Eastern Scheldt storm surge barrier the Delta plan was realized. Herewith a period of the construction of large hydraulic engineering structures ended more or less. Therefore the interest in the optimal maintenance of the existing structures is growing and efforts are made to develop a theoretical basis for the planning of maintenance.

In the field of mechanical engineering considerable progress has been made. Maintenance is defined as consisting of two activities inspection and repair. Inspection implies the observation of the state of the structure and repair the restoration of the structure to it's original state.

Two main classes of maintenance are discerned: corrective and preventive maintenance. In this classification only the last subclass contains inspection besides repair. When a corrective maintenance strategy is applied, the structure will be repaired after failure. In a preventive maintenance scheme the structure will be repaired at specified intervals defined in time or operational hours before failure occurs. In a more refined strategy the state of the structure is inspected at such intervals. On the basis of the inspection result the decision to repair is taken.

The optimal cycle of inspection and repair is found by minimization of the present value of the sum of failure costs, inspection costs and repair costs. In these optimization models simple probability distributions for the time to failure as the exponential distribution are frequently applied. Some times this constant failure rate model is refined by the use of a "bathtub" curve for the failure rate.

Generally in mechanical engineering the failure rate is not related to the environmental conditions or loads. This paper studies if these theories can be applied directly to the maintenance of hydraulic structures like dikes, dunes, breakwaters, bottom protections or that further refinement is required.

2.0 THE MAINTENANCE OF HYDRAULIC STRUCTURES

The design of hydraulic structures is among others based on the analysis of the ultimate and the serviceability limit states (ULS and SLS respectively) that are typical for the structure at hand. Beside one class of ULS two classes of SLS can be discerned.

ULS models the failure of the structure under extreme loads S

SLS describes the deterioration the resistance R of the structure under the ever present loads.

SLS analyses the functional performance of the structure under the ever present loads (e.g. limiting wave transmission for a breakwater.

When maintenance is studied the first mentioned type of SLS needs special attention. As the deterioration due to SLS leads in many cases to an increased likelihood of the occurrence of the ULS over the lifetime [3] and thus to failure. The deterioration may be regularly redressed by systematic repair. The regular heightening of dikes in the Netherlands to neutralize the effects of settlement and sea level rise is an example.

In hydraulic engineering the corrective maintenance strategy is generally not advised in view of the great risks involved when a dike, a breakwater or a bottom protection reaches an unsafe state due to ULS failure. The corrective maintenance strategy can only be applied to relatively unimportant parts of the structure that do not initiate overall failure. The maintenance of dike revetments in Holland gives an example. Every year during major storms minor parts of the dike revetment

are washed away. This poses no threat to the hinterland protected by the dike as a considerable reserve strength is hidden in the clay layers on which the revetments are mostly placed. After the storm the damage will be repaired before the next extreme high water occurs.
In hydraulic engineering only preventive maintenance is advised in view of the high failure costs associated with the breach of a dike, the interruption of harbour activities due to breakwater failure.

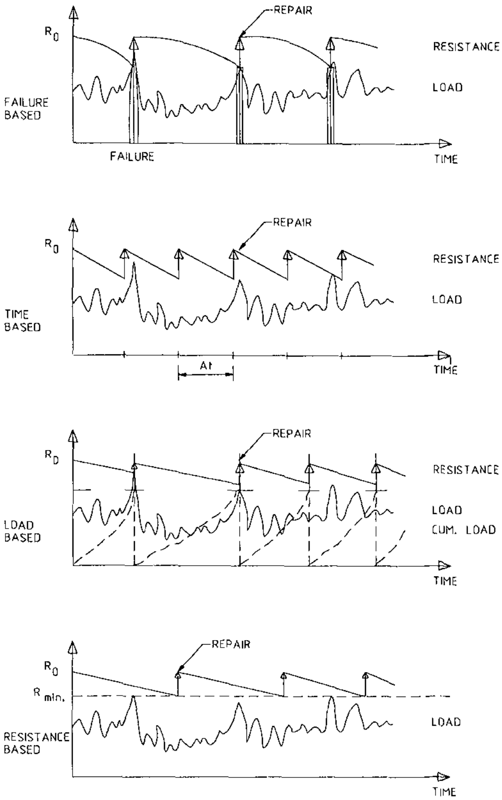

Fig. 1 Corrective maintenance and preventive maintenance governed by various triggers

Several types of triggering preventive maintenance can be imagined (Fig. 1). The simplest alternative is time based maintenance which implies that the structure is repaired at fixed intervals. Use based maintenance is a second alternative. Here the structure is repaired after a certain number of uses. A spillway can be repaired after a specified number of spills.

Connected to this type is the load based strategy. Here repair is triggered if e.g. the sum or cumulative effect of the loads exerted on the structure over time exceeds a specified level. In the resistance based strategy the resistance or the state of the structure is inspected and repair is due when this variable falls below a specified minimum level.

Due to the spatial vastness of hydraulic structures, the high cost of inspection and the often poor resolution of the (underwater) observations a strategic approach to inspection is necessary. The decision to start a thorough inspection of the state of the structure is based on the outcome of an observation of variables that provide an indication of the state to be expected in case of a full inspection. The observation of these proxy-variables is called monitoring. Monitoring of the time, the use, the cumulative load or the state will precede an expensive and elaborate inspection of the exact state of the structure. This principle is shown in Fig.2.

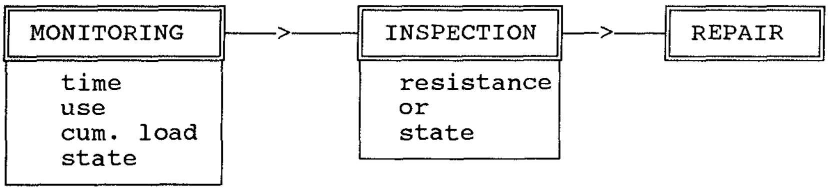

Fig.2 Preventive maintenance with monitoring and inspection

The steel gates of the Eastern Scheldt Storm Surge Barrier provide an example. The cumulative effect of the wave loads is monitored on a continuous basis. When the cumulation exceeds a certain level the nodes of the steel frame, supporting the water retaining surface of the gates, are inspected to measure growth of fatigue cracks.

The way to choose between corrective and preventive maintenance and the various strategies comprised under the latter is depicted in Fig 3. If the consequences of failure are grave preventive maintenance is preferred. The second question is if a description of the deterioration process is known. Without such a deterioration model continuous monitoring and subsequent inspection of the state is the only viable solution. If a good deterioration model is available and if it contains the effect of loading on the process, the monitoring of the cumulative load as a precursor to full inspection of the state seems the right alternative. If there is no clear relation between the loads and the deterioration the monitoring of time forms the only basis for the scheduling of inspections. The use based inspection strategy lies between these extremes. Many specialists assume that deterioration models for various hydraulic structures do not yet exist. Some reflection however shows that with slight adaptation the equations used in the SLS analyses provide excellent deterioration models. The calculation of the settlement of a dike, of the erosion of a bottomprotection, of scour behind a structure, of long shore transport on a berm breakwater, provide examples. The scour behind the bottomprotection of a discharge sluice can be predicted as a function of time via the current velocity, the turbulence and the D50, see [5]. The relatively slow scour process is however only a threat in sofar it may cause an instability of the foundation of the discharge sluice via a slide flow (ULS). The slide flow is initiated by a steep upper slope of the scour hole as is shown in fig.'s 4 and 5. The steep upper slope may be redressed by the dumping of gravel or sand as a maintenance measure.

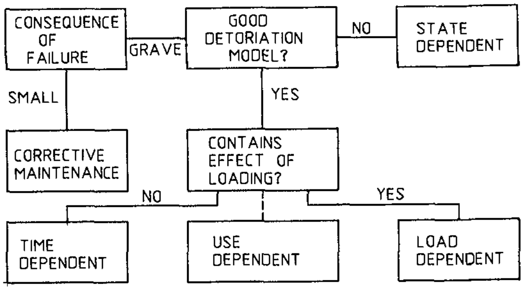

Fig. 3 Choice between maintenance strategies

The value of inspection was analyzed for two types of SLS behaviour common in hydraulic engineering (Fig.6). The first type is characterized by a deterioration of the resistance R linear with time, as is the case with settlement and sea level rise. The derivative with respect to time is constant but uncertain. If an inspection is performed the derivative can be accurately estimated and a precise prediction of the resistance R(t) at some moment in the future can be provided. The value of the inspection is that the wide p.d.f. of R(t) existing before changes into a very narrow one after.

The behaviour of a dune under the continuous action of waves and wind, that is conveniently described by a random walk model [3], constitutes the second type. Now the inspection provides the position of the dunefoot at t_i. Due to the random walk character of the process the position of the dune foot at some future moment can only be predicted in terms of a fairly wide p.d.f. Quite narrower however than before inspection. So generally speaking inspection reduces the standard deviation of the prediction of the state of the structure in the future, for instance the planned moment of repair.

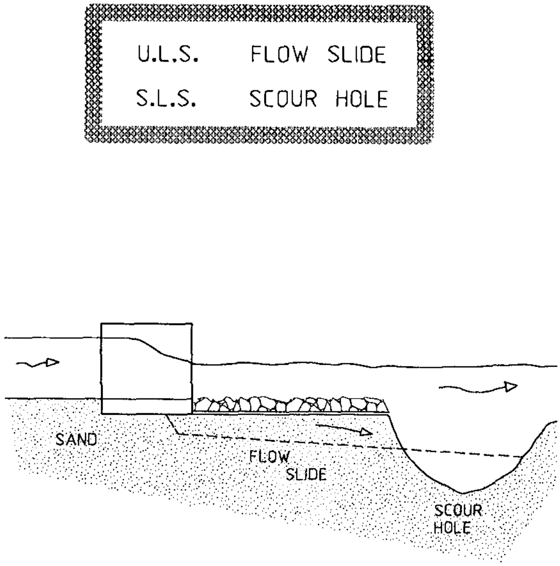

Fig. 4 Scour hole (SLS) leading to a flow slide (ULS) threathening the foundation

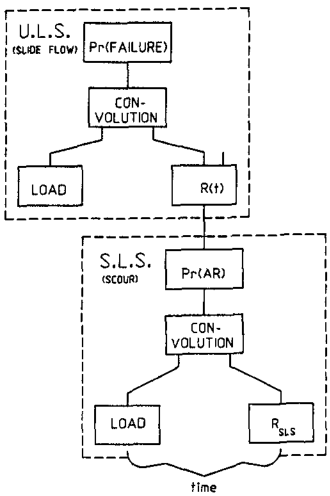

Fig. 5 Relation SLS-ULS

The optimal intervals of inspection and repair can be evaluated by minimizing the expected value of the present value of the total cost. The total cost comprises the cost of inspection, the cost of repair and the risk defined as the product of the probability of failure and the consequential damage D. Moreover the expected value of the present value of the total cost has to be taken as the various costs are stochastic variables. In the literature decisions are based on expected values neglecting the variance of the total cost. Most decisionmakers are however risk averse. Therefore the study of the variance might be of interest for future studies.

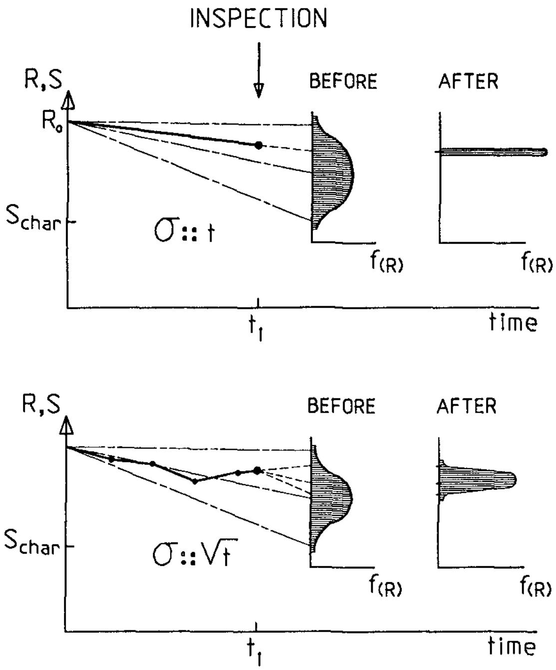

Fig. 6 The value of inspection for two types of degradation processes

3.0 EXAMPLES

Some examples that were solved succesfully elsewhere where already mentioned. The linear degradation of the dikeheight by sea level rise and the regular heightening was studied in [2]. For the settlement of the dike, a logarithmic function of time, an analysis is given in [6]. The optimal interval of beach nourishment to combat the erosion of a dune, that can be modelled as a random walk process was studied in [3] and [7].

A fourth type describes the gradual deterioration of a bed protection or a berm breakwater that looses once in every year an uncertain amount of material due to the extreme load. Given the threshold character of the transport relation the transported amount is in many years zero and has some years a positive value causing erosion. The p.d.f. of the significant wave height and the consequent p.d.f. of longshore transport is given in Fig. 7.

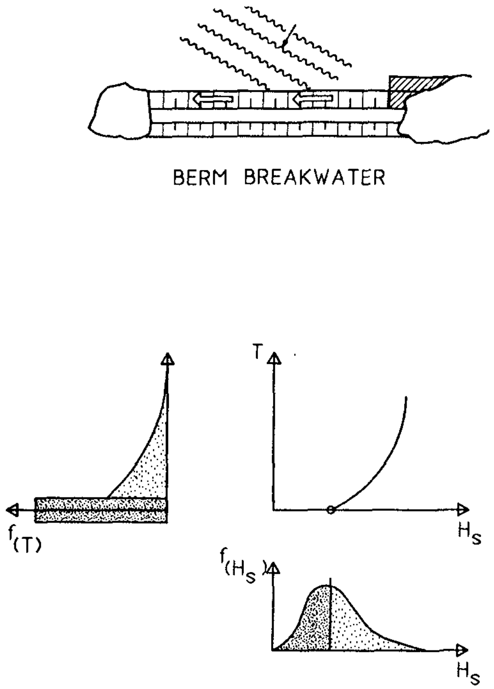

Fig. 7 Longshore transport T

In this paper a similar process leading to the degradation of the bottom protection (BP) behind a discharge sluice will be studied. The BP consists of a sand tight cloth ballasted by a layer of rock. The layer of rock is gradually eroded over time by extreme discharges. This leads in due time to one of two failure modes (Fig.8): either the cloth is exposed to the current and fails or the weight of the rock layer becomes insufficient to withstand the uplift pressure, that is a fraction of the head difference, when the sluice is closed.

The uplift pressure follows a Gumbel-distribution with parameters of 1.55 and 0.78 kN/m2 for mode and width.

The maximal current velocity U is normally distributed with a mean of 2 m/s and a standard deviation (s.d.) of 0.4 m/s.

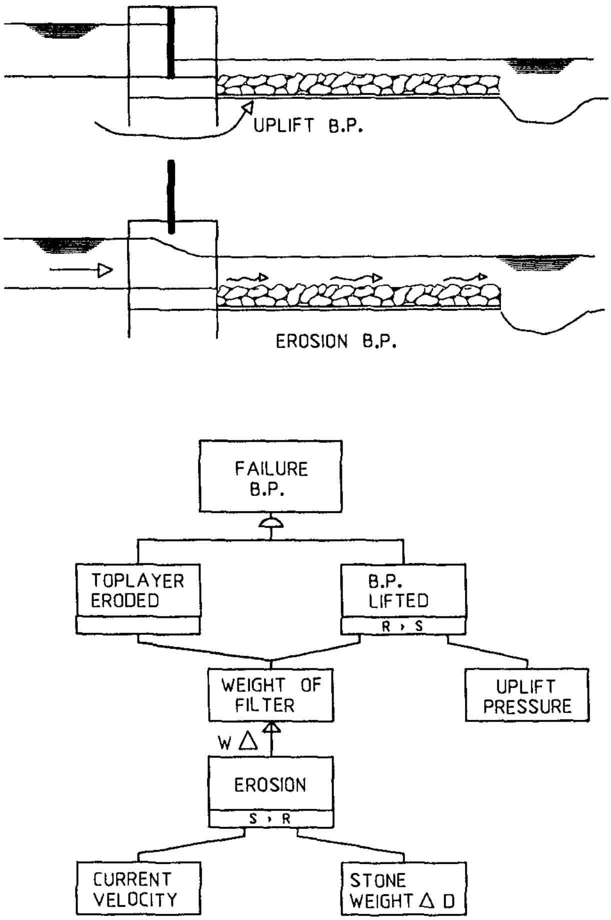

Fig. 8 The two failure modes of the bottom protection

The transport relation has the following form T = 1260 $(U - 2)^2$ kg/m2 per year for U>2 m/s and T=0 elsewhere.

The conditional p.d.f. of the transport per year if transport occurs is derived as:

$$f_T(X|X>0) = \frac{1}{\sqrt{5040*X}} * e^{\frac{-X}{403.2}}$$

The probability of transport is 0.5 and equal to the probability of no transport. Numerically the mean and the s.d. of the transport per year are calculated at 101 and 226 kg/m2.The degradation as a function of time is the sum of the yearly erosion. The p.d.f. of the degradation after 5,10,20 and 40 year is given in Fig. 9.

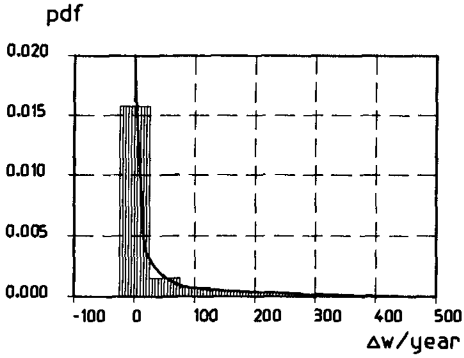

Fig. 9 The p.d.f. of degradation of the B.P. after 5, 10 20 40 years

Next the probability of uplift is calculated for every year and the probability of total erosion leading to the exposure of the filter cloth. In the area (I) near the sluice the latter is the deciding mechanism and in the areas further away (II & III) erosion forms the main failure cause. The p_f is given as a function of time in Fig.10.

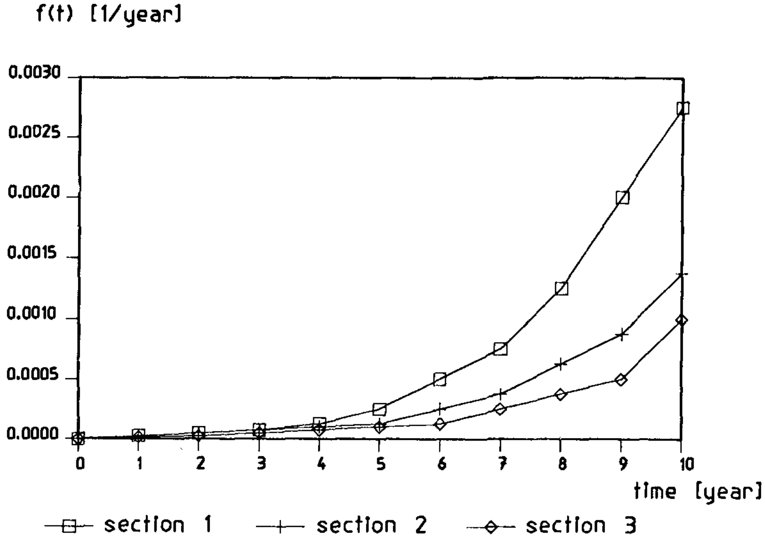

Fig. 10 The failure rate p_f as a function of time

The present value of the risk is written as follows:

$$\sum (D*f(t)*\frac{\Delta T}{(1+r)^{t}})$$

The cost of repair is based on the expected value of the erosion, which equals 101.t kg/m2 after t year for area I. The present value of the total cost of repair at t is given by:

$$\frac{C+c*(101*t)}{(1+r)^{t}}$$

Now the present value of the cost of repairs and the risk between repairs has to be added over the life time of the structure. This defines the objective function that has to be minimised with respect to t_i the repair interval.
For the numerical evaluation the following values have been assumed:

D = 40 Mfl
C = 10 kfl
c = 100 fl.m2/kg (equal to 50 fl/ton)
r = 0.04

The present value of the total cost as a function of the repair interval is given in Fig. 11. The optimal interval is 4 year if the three areas of the B.P. are repaired at the same time. The calculation was also performed for separate intervals for each of the three areas of the B.P. Withe the reasonable assumption that the mobilization cost C has to be paid only once when the repairs for the areas coincide and three times when not, the minimum cost is reached at 4 yearly interval for all areas. If inspection of the state of the B.P. is introduced the p.d.f. of the resistance R(t) will be replaced by the result of the inspection the deterministic value R_I. Ex ante the value of R_I is uncertain and follows the p.d.f. of R(t). To find the value of the inspection under the assumption of instantaneous repair, we have to integrate over all possible results of the inspection with their respective probabilities given by the p.d.f. of R(t).

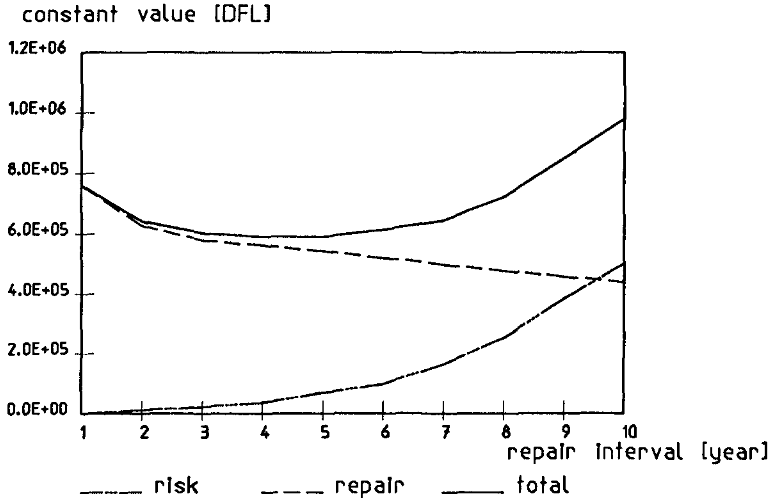

Fig. 11 Total expected cost as a function of the repair interval

4.0 CONCLUSIONS

The maintenance theory developed in mechanical engineering has to be adapted and refined to account for the typical problems of hydraulic engineering. A probabilistic approach proves to be highly effective and necessary in the approach of the problem. Moreover the serviceability limit state (SLS) equations used in the design of hydraulic structures may be easily adapted to serve as degradation models.

The advantage of the use of rigorous maintenance models is that the risk of deferred repair and the value of inspection can be objectively assessed. Therefore the theory can assist managers of coastal structures in the definition of optimal maintenance strategies.

However all decisions in the described model are based on expected values of the costs. The limitations imposed by the omission of the variance of the cost has to be further explored.

REFERENCES

[1] Hahn, G.J.,Shapiro, S.S., Statistical models in Engineering, Wiley & Sons, New York , 1967.

[2] Vrijling, J.K., Beurden, J. van, Sea level rise; a probabilistic design problem, Proc. 22d ICCE, Delft, 1990.

[3] Bakker, W.T. and Vrijling, J.K., 1980. Probabilistic Design of Sea Defenses, Proc. 17th ICCE Sydney, 1980.

[4] Vrijling, J.K., 1991, Berm breakwater design; the longshore transport case, a probabilistic approach, Coastal structures and breakwaters '91, London.

[5] Jorissen R.E. and Vrijling,J.K., Local scour downstream hydraulic constructions, IAHR XXII congress, 1989, Ottawa

[6] Kuiper,H., Onderhoud in de waterbouwkunde, Delft University of Technology, 1992. [In Dutch]

[7] Verhagen, H.J., Method for artificial beach nourishment, Proc. 23rd ICCE Venice,1992