CHAPTER 163

An Improved Design Method for the Riprap of Earthfill Dams of Large Reservoirs

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Abstract

Since impounding of the various reservoirs of the La Grande Complex in northern Québec, the riprap of several dams and dykes suffered some damage during the fifteen-year period which followed. A mandate was given to the Société d'énergie de la Baie James (SEBJ) in January 1992 to review the riprap design and evaluate the necessary repairs. The paper focuses on this work. An improved design method, for the riprap of earthfill dams of large reservoirs, is proposed based on four years of intensive studies and fifteen years of field data. Large scale model tests with irregular waves completed the studies.

Introduction

The construction of the various structures on the La Grande Complex (Phase 1), in northern Québec (figure 1), was done over a period of twelve (12) years between May 1973 and December 1985.

The project required the building of 215 embankment dams and dykes along with three powerhouses producing 10 000 megawatts and had a total cost of 13,7 billion dollars (Canadian). Since the filling of the reservoirs, which took place between 1978 and 1983, the upstream protection of some structures underwent damage and had to be repaired. Until 1992, a total of 19 structures required work varying from minor repairs to repeated dumping of rockfill on the upstream slopes.

In January 1992, La Société d'énergie de la Baie James (SEBJ) was mandated by Hydro-Québec to review the overall design of riprap, taking into account the actual condition of the dams and dykes on the Complex and to estimate the work to be done using existing techniques. To fulfill its mandate, SEBJ conducted extensive field measurements, including wind and wave measurements on four reservoirs and large scale model tests of various repair schemes using irregular waves. This paper focuses on riprap design and repair. Revaluation of the design wave with a revised wave hindcast formula is presented by Dupuis et al. (1996), while large scale model testing of the repairs is described by Mansard et al. (1996).

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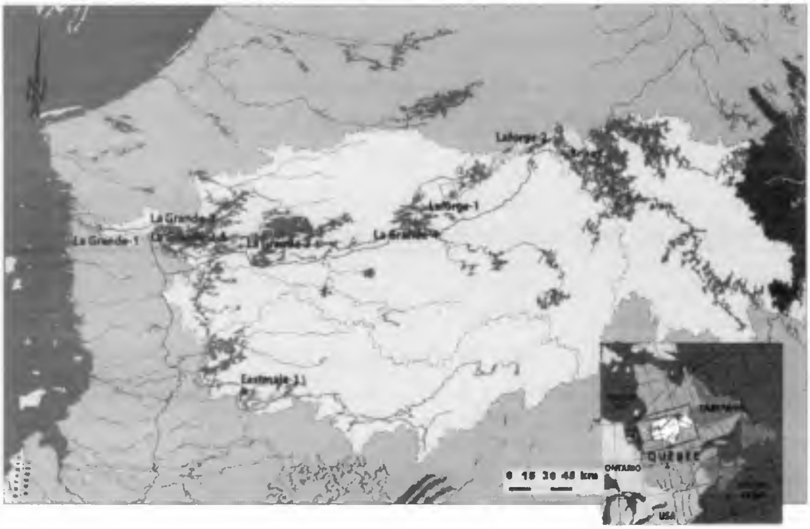


Figure 1. La Grande Hydroelectric Complex

Original riprap performance

The results of extensive studies indicate that the riprap of most of the embankments has performed satisfactory since reservoir filling. In general, the most important damage was caused by the presence of fine material in the riprap. In a few cases, when systematic repairs were required, the riprap was undersized because the wave height was underestimated in the original design or the riprap specifications were sometimes relaxed during construction. Experience has shown that the use of graded riprap evaluated with the median mass M_{50} increases the risk of having local areas of undersized riprap. Of the 215 earth structures, seventeen needed general repairs.

According to the findings, coarser riprap with a narrow gradation was specified for repairs with a strict control on the minimum size to eliminate any contamination by fine material.

Repair work

The decision to do repair work on a given structure is based on the present condition of the structure, the historical performance of the riprap and on the requirement that the in-place riprap meets the dimensions required. Dams and dykes with steep slopes, in general, were treated with special attention due to their importance and the fact that the mode of failure of the riprap was more severe and rapid and could cause sliding or sloughing of the crest. Damage observed on structures with flatter slopes and adequate protection was generally limited and evolved slowly.

Structures which had adequate protection but had minor local damage associate with weak zones needed maintenance or local repairs. The local repairs consisted essentially of repairing the damaged or weak zones by rearranging the existing stones and adding stones of appropriate size. In cases where the structures had generalized damage and the riprap was, in whole or in part, undersized, systematic repairs were done. The design and repair techniques were verified and optimized with large scale model tests at the National Research Council of Canada (NRC) that reproduced the natural conditions found on the reservoirs.

Figure 2. Typical systematic repairs (1)

Figure 3. Typical systematic repairs (2)

The method retained for systematic repairs consisted of dumping the riprap from the crest (figure 2) or on the slope, one meter above the maximum water level (figure 3), depending on the required quantity and the width of the berm.

This berm was then cut back with a backhoe and the rockfill rearranged down to 1 meter below the maximum water level. When required, the freeboard was heightened by adding a layer of rock to form a cap-like protection (figure 4).

Figure 4. Systematic repairs at the Dam KA-03 with heightened freeboard.

At the end of 1997, more than two million tons of riprap will be placed on some fifty embankment dams and dykes, ranging from minor to systematic repairs. The know-how acquired during the execution of this mandate enabled new concepts to be elaborated regarding riprap design. This new approach was also verified in the field and lab, with tests on large scale models.

Design considerations

The following well-known Hudson formula is used to evaluate the mass that should resist a certain wave height for specific conditions such as embankment slope and rockfill characteristics:

$$M = \frac{\rho_r \quad H_S^3}{K(S_r - 1)^3 \cot\alpha} \qquad [1]$$

with M the rockfill mass in kg, ρ_r the rockfill mass density in kg/m^3, S_r the rockfill specific density, cot α the slope, H_s the significant wave height and K the stability coefficient.

Recently, Van der Meer (1988) proposed elaborate equations for irregular wave climates with various types of wave attack (spilling, plunging or surging). However, for the worst wave conditions these equations can be reduced to the same form as the Hudson formula. Along with the required parameters (slope of fill, mass and density of the rockfill), the formula which gives the mass as a function of the wave height contains a stability coefficient K which takes into account all other factors and corresponds to a safety factor. In the literature, this coefficient is known as K_d or K_{rr} according to different conditions. If all the physical and geometrical parameters are fixed, the calculated resisting mass corresponds to a value for the stability coefficient.

For a given test, if the mass is "unique", that is, if all the blocks are identical (as was the case for Hudson's tests) the definition of this coefficient is straightforward and unique (K_d). On the other hand, when mass variation is allowed within the riprap, it is common practice to define this coefficient (K_{rr}) for the average mass M_{50}. However, if all other parameters are constant, each mass can be considered to be associated to a given value of the stability coefficient. Therefore a variation in mass, in effect, translates into a variation in the stability coefficient which is inversely proportional to the mass (figure 5).

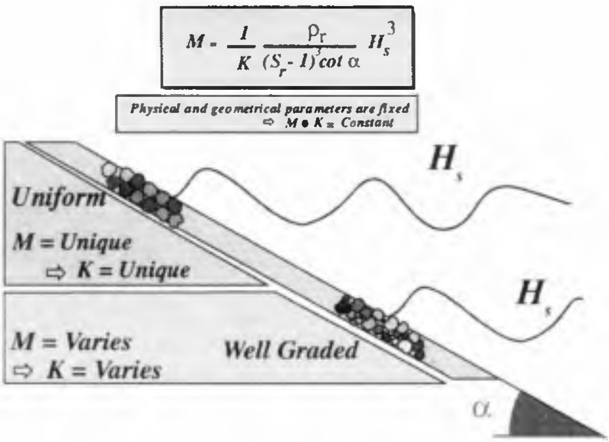


Figure 5. Schematic representation of the relation between *M* and *K*

By using this approach, the variations in the mass according to the different methods can be represented in terms of the variations in the stability coefficient equivalent (figure 6). It can be noted that a wide range in the variation of the mass, as in the case for well graded riprap, implies that a large portion of the rockfill has a stability coefficient above 5,0, and can reach 9, 10 or even 17,6 depending on the case and corresponds to the fine part of the riprap. This confirms the results of our studies that the damage was due mainly to the presence of fines and to our approach of using graded or uniform riprap.

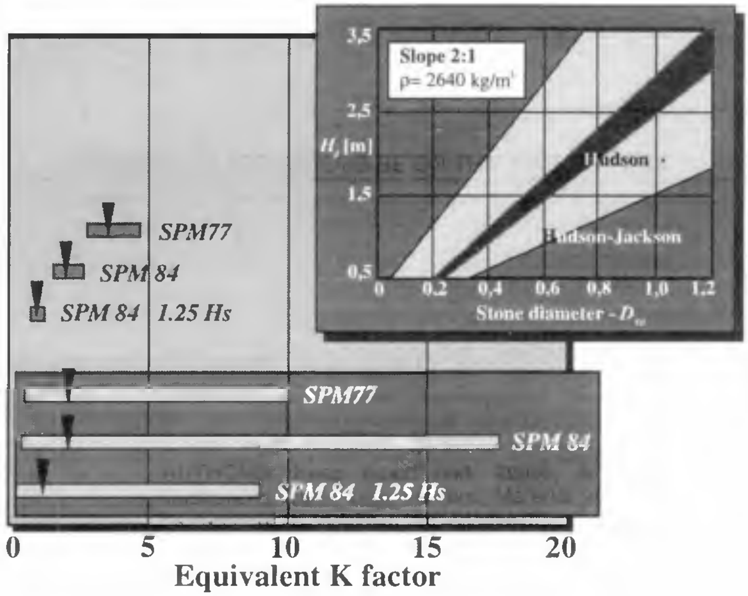


Figure 6. Effect of gradation on the equivalent K coefficient

Therefore, for the design, we should determine an acceptable lower limit of the mass, that is an upper limit to the stability coefficient which will resists a given wave height with an acceptable damage index value. In common practice, the damage index S is defined as follows:

$$S = \frac{A}{D_{n,50}^2} \qquad M_{50} = \rho_r D_{n,50}^3 \qquad [2]$$

where A is the eroded cross-section area and D_n the nominal stone diameter.

For the evaluation of this upper value of the stability coefficient, a new damage index is proposed, based on the minimum mass:

$$\hat{S} = \frac{A}{D_{n,\min}^2} \qquad M_{\min} = \rho_r D_{n,\min}^3 \qquad [3]$$

The ratio of damage between the two indexes, for a given area of damage, is:

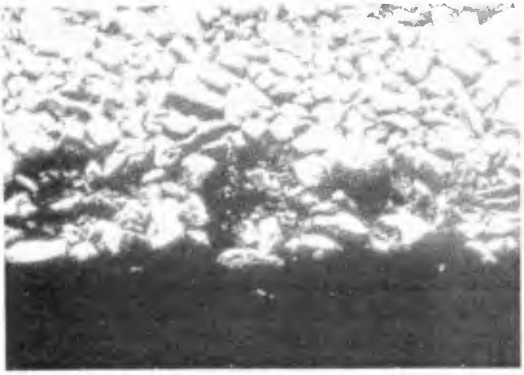
$$\frac{\hat{S}}{S} = \sqrt[3]{\left(\frac{M_{50}}{M_{\min}}\right)^2} \qquad [4]$$

Practically, a value of $\hat{S}$ equal to 2,5 is considered as the beginning of damage while a value of 5 is defined as tolerable damage. The results indicate that beyond values of 7 or 8, the damage rate tends to accelerate and can lead to major damage. It should be noted that the condition $\hat{S}=$ 2,5 or 5,0 is more severe than the condition S=2,0 or 4,0 generally used.

Tests conditions

SEBJ designed test cases for riprap that could withstand events with a significant wave height of 2,5 m with an accepted degree of damage $(\hat{S}=5)$. Large scale tests (15:1) were performed by the NRC for two different slopes with irregular waves. In the first phase, irregular wave trains were generated with spectral characteristics similar to those measured in the reservoirs and tests were conducted to check if observed damage could be reproduced. As can be seen on figure 7, similar damage zones indicate that the tests were conclusive.

Preliminary large scale model tests allowed a stability coefficient value of 3,5 to be used by SEBJ. Typical wave trains were generated following analysis of wave records gathered at the site. For both steep (1,8:1) and flat (2,25:1) slopes the minimum rock mass was calculated using formula [1]. The rock mass gradation was specified with a ratio, between maximum and minimum mass equal to 2,5.



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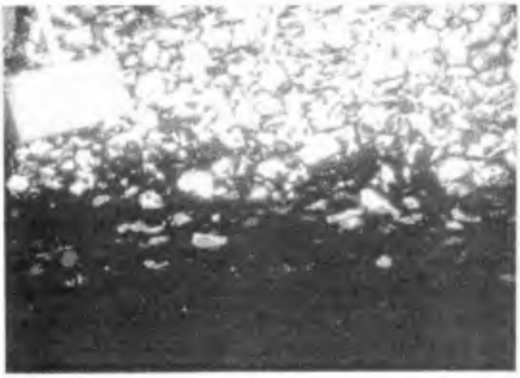

Scale Model

Figure 7. Comparison of damage

The riprap layer thickness is given by:

$$d_c = 2D_{50} \qquad D_{50} = \sqrt[3]{\frac{M_{50}}{C_f \rho_r}} \qquad [5]$$

with d_c the depth of cover and C_f a form factor taken to be 0,6. Gradations of 2,4 and 2,9 were realized respectively for steep (CTR) and flat (CTD) slope tests. There were three different levels of attack. The riprap thickness (d_c) was taken as the average thickness of the riprap within the zone of influence, that is 5 meters above and below the level of attack which was 2 times the target design wave height. Other tests (CTRU, CTDU) were performed with uniform blocks (M_{max}/M_{min} < *1,2*) to confirm that the minimum mass was a key parameter for graded riprap design. Finally, some tests were conducted to verify the influence of a greater ratio between M_{max} and M_{min} (up to about 9 which could occasionally occur in the field) on the performance of riprap designed according to this new approach.

Results

As a first step, SEBJ designed tests with a stability coefficient K=3,5 applied to the minimum mass for an accepted degree of damage ($\hat{S}$ = 5). A graded material (M_{max}/M_{min} around 2,5 to 3,0) was specified for the riprap and two different slopes were tested. The data, obtained from the tests, was as follows:

Test	Slope [H:V]	M_{min} [kg]	M_{50} [kg]	M_{max} [kg]	M_{max}/M_{min}	$d_c/D_{n,min}$ (*)	$d_c/D_{n,50}$ (*)
CTR	1,80	1515	2585	3686	2,43	2,6	2,2
CTD	2,25	1023	2052	3007	2,94	3,1	2,5

(*) Mean value at intermediate level.

The rockfill mass density is 2710 kg/m³ and the theoretical values of H_s, according to equation [1] are respectively 2,60 and 2,46 for steep and flat slopes . The results, as shown on figure 8, represent the variations in the equivalent coefficient K obtained as a function of the damage index after 4 cycles of waves for a given H_s applied to the intermediate level for steep and flat slopes. After 4 cycles, or about 5000 waves, the level of equilibrium was obtained, at least, up to a damage index S=4 or $\hat{S}$ = 6. For these conditions, a linear variation in the equivalent coefficient K can be noted for the same reference mass (minimum, median or maximum) as a function of the damage index. Similar results are obtained for different attack levels.

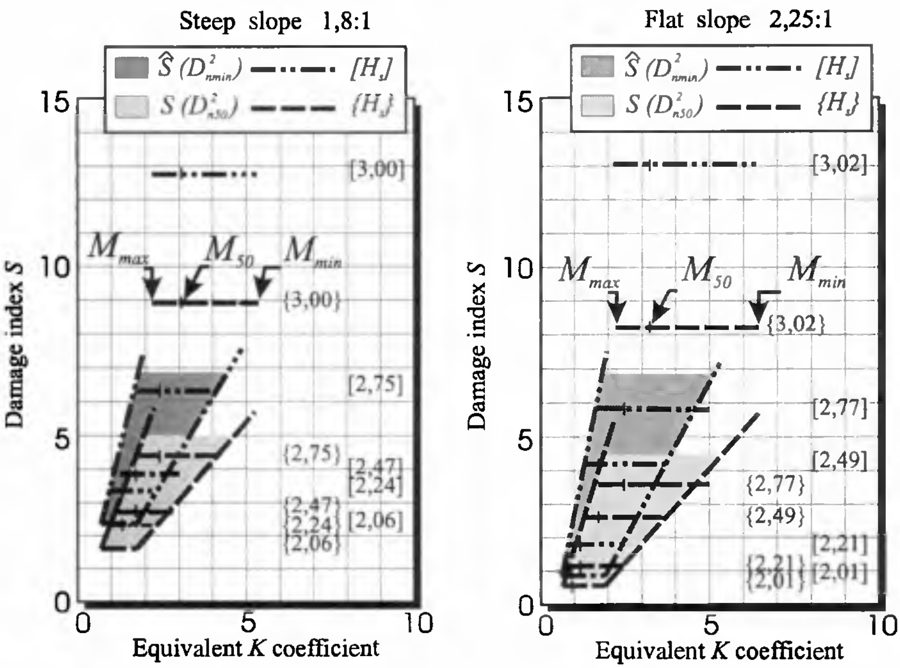

Figure 8. Relation between K and S

These results were obtained using a graded riprap with a tolerance for the rockfill of M_{max}/M_{min} = 2,4 and 2,9. In order to verify if this tolerance had an influence on the upper limit obtained for the coefficient K, similar tests with uniform rock equal to the minimum mass were performed. The data, obtained for the tests, was as follows:

Test	Slope [H:V]	M_{min} [kg]	M_{50} [kg]	M_{max} [kg]	M_{max}/M_{min}	$d_c/D_{n,min}$ (*)	$d_c/D_{n,50}$ (*)
CTRU	1,80	1499	1596	1681	1,12	2,6	2,6
CTRUM	1,80	1499	1596	1681	1,12	2,1	2,0
CTRU5	1,80	2342	2552	2913	1,24	2,2	2,1
CTDU	2,25	1154	1252	1340	1,16	3,0	2,9
CTDUM	2,25	1154	1252	1340	1,16	2,1	2,0

(*) Mean value at intermediate level.

Figure 9 shows the variation in the equivalent coefficient K obtained as a function of the damage index after 4 wave cycles for tests with uniform material and the equivalent test with graded material.

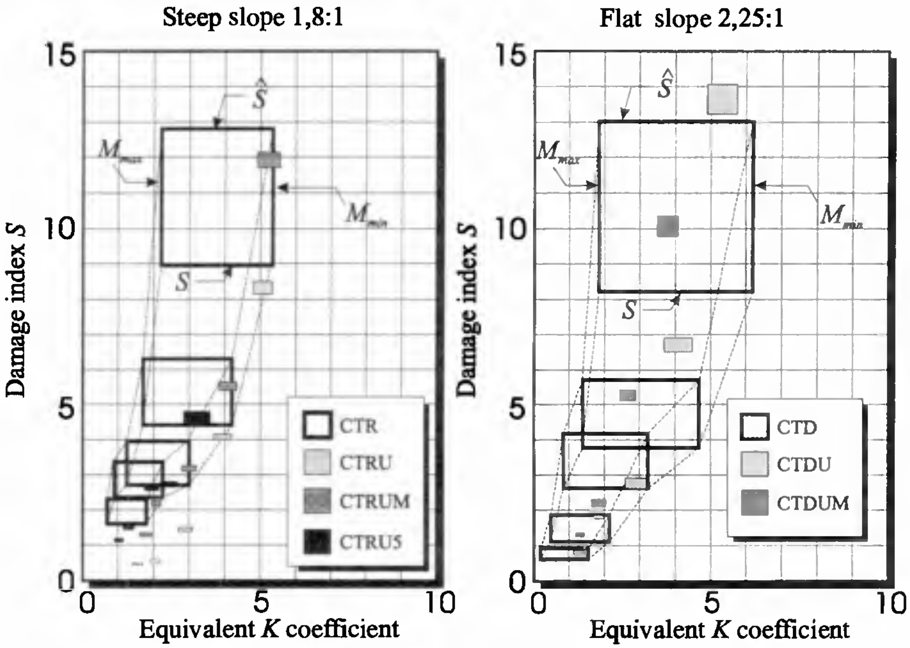

Figure 9. Comparison between graded and uniform material

The values obtained for K with tests on material with a uniform mass are comparable to the corresponding values for the minimum mass for tests with graded material or slightly superior for low values of the damage index and a steep slope. These results indicate that the minimum mass controls the resistance of the riprap for these gradations. It can be noted that a uniform material test (CTRU5), on a steep slope, with a larger minimum mass (2342 kg in comparison to 1499 or 1515 kg) shows the same trend. In the same way, the apparent discrepancy of test CTDUM on a flat slope is explained by the influence of the riprap thickness ($d_c / D_{n,min}$ = 2,1 in comparison to 3,0 or 3,1). The results confirm that a thicker riprap is more resistant.

Finally, in the field, it is difficult to keep a ratio M_{max}/M_{min} lower or equal to 3,0 as specified. Experience has shown that a ratio between 4 to 6 can be readily obtained. So tests on steep slopes were conducted to verify the influence of such a ratio on the performance of riprap.

The data, as obtained for these tests, was as follow:

Test	Slope [H:V]	M_{min} [kg]	M_{50} [kg]	M_{max} [kg]	M_{max}/M_{min}	$d_c/D_{n,min}$ (*)	$d_c/D_{n,50}$ (*)
CTR3	1,80	854	2498	4323	5,06	3,1	2,2
CTR4	1,80	543	2606	4725	8,70	3,6	2,1

(*) Mean value at intermediate level.

The results of these tests (CTR3 and CTR4) are shown on figure 10, along with the results of the other tests on steep slopes, as a function of equivalent coefficient K obtained with minimum mass to damage index $\hat{S}$ also according to a minimum nominal diameter. The K values obtained from tests with a ratio M_{max}/M_{min} up to 5,1 are almost identical, and superior for CTR4 test with a ratio equal to 8,7. The higher value is due partly to a relative larger thickness ($d_c/D_{n,min}$ = 3,6 in comparison with a mean value of 2,6) and also due to the more severe conditions imposed on a well graded material using minimum mass. In fact, back calculations indicate that the performance of CTR4 corresponds approximately to the resistance of M_{10}. So the use of a minimum mass approach is a conservative approach and finer material of at least 10% can be tolerated without much effect on the required resistance.

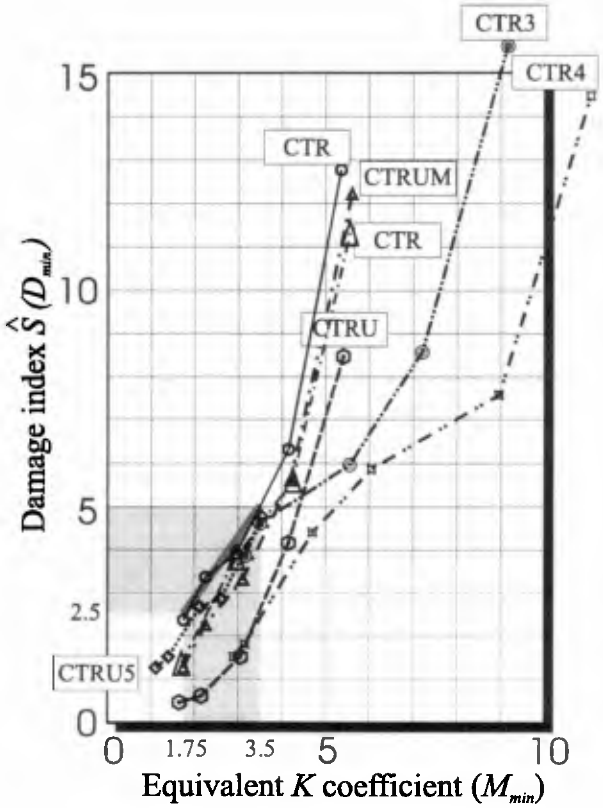

Figure 10. Relation of K versus $\hat{S}$ for all tests (steep slope)

It is generally accepted that a damage index, based on the median mass, of 2 or 3 is considered as no damage and that a value of 4 or 5 is a level of acceptable damage. Using the minimum mass approach, a damage index value of 2,5 and 5 respectively is recommended to define the limits of no damage and acceptable damage, which, in terms of median mass, translates into values less than to 2 and 4.

Figure 10 represents the variation of the stability coefficient as a function of the damage index using the minimum mass approach for all the tests done on a steep slope with a minimum acceptable riprap thickness of two layers. The upper limit obtained for the coefficient K, which allows for the calculation of the minimum mass, is 3,50 (as predicted) for tolerable damage and 1,75 for no damage. The test results on flat slopes are quite similar and confirm the values for the coefficient K.

To sum up, the riprap design for the tests was based on the coefficient $K = 3{,}5$ for the minimum mass with a tolerance in the variation of mass M_{max}/M_{min} = 2,4 to 2,9 and an acceptable damage $\left(\hat{S} = 5\right)$. The results are:

Tests	H_S	
	Design	Observed
Steep slope (1,80:1)	2,60	2,61
Flat slope (2,25:1)	2,46	2,59

and confirm that these parameters are justified.

In terms of design, the choice of the damage index should be related to the selected period of occurrence of the maximum wave attack. We recommend the tolerable damage for a return period of 1000 years and no damage for a period of 100 years.

Conclusion

Tests results show good behaviour of the riprap layer designed according to the approach based on the minimum mass and even some reserve for flat slopes. Tests have indicated that protection should extend to 2 times the design wave height below the attack level.

Uniform riprap is at least as resistant as graded riprap and for these gradations, stability is controlled by the minimum mass.

Results of tests and performance of riprap are more easily explained in terms of the minimum mass concept. Using this concept, values of 2,5 and 5 are proposed for the damage index respectively for the start of damage and acceptable damage. Within these boundaries, evolution of the damage index is linear with respect to the stability coefficient.

In accordance with Hudson's original work, the studies showed that a relatively uniform riprap performs best, so a ratio of 3,0 between the maximum and minimum mass is used for design purposes. In the field, however, it is difficult to preserve such a ratio. Experience has shown that a ratio between 4 and 6 can be readily obtained and is acceptable. The Hudson formula is used to obtain the minimum mass of the rock. For the design, the significant wave height is used with a return period of 1:1000 years and a stability coefficient equal to 3,5. These values correspond approximately to the no damage condition with a 100 year return period and a stability coefficient of 1,75.

Resistance to wave action is a combination of both rock mass and permeability of the riprap. Sufficient void volume within the riprap allows for efficient wave energy dissipation. Rocks uniformly sized and uniformly graded with sufficient thickness achieve this objective.

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