

Review on standards and a proposal for stability safety factors of a breakwater in different load cases for different sliding surfaces

Analyse des normes et établissement des coefficients de sécurité de stabilité d'une digue pour différents cas de charge et surfaces de glissement

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ABSTRACT: Before starting the slope stability analysis of a breakwater, several questions should be answered, like: which load cases at which water levels should be considered, is a hydrostatic water level adequate or should wave forces be considered as well. After answering these questions the factor of safety is calculated for different load cases. To evaluate the slope stability, the calculated safety factors should be compared with an acceptable safety factor for each load case. But what is an acceptable safety factor? An illustrative guideline for the above questions cannot be found in the available standards. Another concern is that the actual more powerful and advanced calculation software allows to find the results with less uncertainty compared to the formerly applied methods. It means that lower safety factors in comparison to the old methods can be applied with the state of art software. In this paper, three guidelines/standards of "Eurocodes", "US Army Corps of Engineers" and "ROM" are reviewed for the above items. Based on the mentioned standards and some considerations a table showing the acceptable slope stability safety factors for different load cases is presented.

RÉSUMÉ : Avant de commencer l'analyse de la stabilité du talus d'une digue, il est nécessaire de répondre à plusieurs questions, notamment les cas de charge à considérer, le niveau d'eau, la prise en compte d'un niveau d'eau hydrostatique ou dynamique du à la houle ... Le coefficient de sécurité est ensuite calculé pour différents cas de charge. Afin d'évaluer la stabilité du talus, les coefficients de sécurité calculés doivent être acceptables pour chaque cas de charge. La question qui se pose donc est : Quels sont les coefficients de sécurité acceptables ? Une ligne directrice pour les questions ci-dessus n'existe pas dans les normes disponibles. Une autre préoccupation est liée aux logiciels de calcul plus avancés qui permettent de réduire l'incertitude par rapport aux méthodes appliquées antérieurement. Cela signifie que des coefficients de sécurité inférieurs pourraient être appliqués par rapport aux anciennes méthodes. Dans cet article, trois normes du "Eurocodes", "US Army Corps of Engineers" et "ROM" sont examinées. D'après les normes mentionnées et certaines considérations, un tableau résumant les coefficients de sécurité acceptables est présenté pour les différents cas de charge.

KEYWORDS: breakwater, safety factors, slope stability, hydrostatic water level, wave forces.

1 INTRODUCTION

The aim of this article is providing a clear and easy guideline for considering different load cases needed for slope stability analysis of a breakwater. Also for each load case a relevant safety factor is introduced based on an overview of different standards. For the slope stability conditions some items are not identically considered in different standards and it is not clear if they should be considered (and even how). These items are wave action, failure surface and calculation under short-term or long term conditions. For the better understanding these items are elaborated in this study. The investigated standards are "US Army Corps of Engineers, USACE", "Eurocodes" and "Recommendations for Maritime Works, ROM".

Breakwaters are built in the sea, where waves always exist. However, most of the time wave conditions are considered only for the hydraulic design of the breakwater (crest height and width, slope of the breakwater, armour layer type, toe structure, etc.). But the wave action is also important for the geotechnical design. The presence of a wave in front of the breakwater results in a decrease of the pore water pressure in the permeable foundation in front of the breakwater. Due to the uprush of waves on the breakwater structure, the pore water pressure increases in the permeable core of the breakwater and in the permeable foundation underneath the breakwater (De Rouck and Van Damme 1996, Mollaert and Tavallali 2016). Applying wave actions results in a lower safety factor compared to applying only a hydrostatic water level at mean Seal Level

(Mollaert and Tavallali 2016, Shafieefar and Fakher 2015). Based on the above explanations wave action should be considered in slope stability analysis.

The second item that should be clarified is the failure surface. The most popular approach for slope stability analysis features a circular slip surface. However the same exercise with considering a non-circular (optimised) slip surface, leads to a lower factor of safety for stability analysis. More powerful calculation means presently allow one to find the results with lower "model uncertainty" compared to the formerly applied methods. It means that lower safety factors in comparison to the old method (with circular failure) should be applied with the recent software that can consider the critical non-circular failure (Van 't Hoff and Van der Kolff 2012). As the uncertainty of sliding surfaces by considering different shapes of failure surfaces is decreased, it is logical to lower the acceptable stability global safety factor.

The third item that should be discussed is performing the calculations in short-term and long-term conditions. During the breakwater construction, the height of the breakwater gradually increases, and consequently the load on the foundation increases. Load increase on the foundation in a short period of time induces excess pore water pressure. As generally there is not enough time for the excess pore water pressure to be dissipated, the effective strength of the foundation does not increase (without stage construction or vertical drain installation). Therefore, the factor of safety of the breakwater decreases. It can also be concluded that the maximum load

applied on the foundation at the end of construction, represents the critical short-term loading condition. In the case that the breakwater is built in stages, the end of any stage may represent the most critical short-term condition (U.S. Army Corps of Engineers 2003). In the short-term condition for the foundation soil material (with low permeability), the undrained mechanical properties should be considered for the stability computations.

With time following completion of the breakwater, construction induced excess pore water pressures dissipate within the foundation material. The shear strength of the soil material (foundation) increases due to the consolidation. In other words the factor of safety against failure will increase (U.S. Army Corps of Engineers 2003). Therefore, for long-term conditions the drained mechanical properties should be considered for the foundation soil material (with the sufficient length of time for dissipation of the excess pore water pressure). It means that the stability computations should be performed using shear strength expressed in terms of effective stresses.

Although the mechanical properties of the foundation soil material improve with time following breakwater construction, the risk of having a more severe condition also increases. Wave heights with a higher return period are more probable. Consequently, for both subjects, material strength and the applicable load, the short-term and long-term conditions should be considered for the stability computations. However, as most of the breakwater lifetime generally is in the long-term condition, risk of having more severe conditions is higher and consequently the slope stability safety factor should be considered higher as well.

Based on the presented explanations, it is clear that the three items: wave action, failure surface and short-term/long term conditions, should be considered in slope stability calculation of the breakwater.

2 STANDARDS FOR STABILITY ANALYSIS

In this part very briefly the three standards “Eurocode”, “US Army Corps of Engineers, USACE”, and “Recommendations for Maritime Works, ROM” concerning slope stability analysis are discussed. The focus is on the three items as discussed; wave action, failure surface and short-term/long-term analysis. These items are not identically considered in those standards and it is not clear how and if they should be considered for slope stability analysis.

2.1 Eurocode

The Eurocode 7 (2014) (EC7) standard is part of the Structural European programme. The standard sets-out the principles and requirements for the geotechnical aspects of the design of buildings and civil engineering works. In the EC7 five limit states are defined. For the geotechnical design it should be verified that the relevant limit states of the project specific situation are not exceeded. For slope stability analysis, which is discussed in this paper, the limit state covering failure or excessive deformation of the ground (GEO) is relevant and should be verified (Eurocode 7 2014).

The limit states should be verified by considering one of the three defined design approaches. The design approaches differ in the way the partial safety factors are considered for actions, effects of actions, material properties, and resistances (Eurocode 7 2014). Furthermore, the partial safety factors also differ for different limit states. As the design approach which should be considered, can be defined per country in their National Annexes of the Eurocode 7, the way these partial safety factors are considered can differ from country to country.

The partial safety factors as provided in the EC7 should be considered for persistent and transient situations (Eurocode 7 2014). This means that the EC7 does not make a difference

between the short-term and long-term design situation. On the other hand, the EC7 also indicates that less severe values of the partial safety factors may be considered for temporary structures or transient design situations. No clear indication is given about the value of these less severe partial safety factors.

For overall slope stability analysis, the EC7 indicates that for slopes in relatively homogeneous and isotropic ground or embankment material, it is sufficient to assume circular failure surfaces. In case of layered soils with considerable variations of shear strength, non-circular failure surfaces may be required (Eurocode 7 2014). No difference is made in the considered partial safety factors for circular or non-circular failure surfaces.

Eurocode 7 clearly indicates that wave actions should be considered as actions in the geotechnical design. As wave actions results in variation of the ground-water pressure, the rules to define the design value of these actions can be considered. In that case the EC7 defines the design value as the representative most unfavourable value that could occur during the design lifetime of the structure for the case of ground-water pressures for limit states with severe consequences. In terms of wave conditions, this will correspond with the design wave characteristics considered for the hydraulic design. In general, for hydraulic structures with a design lifetime of 50 years, the design wave characteristics are defined for a return period of 100 years. For limit states with less severe consequences, the design value of the ground pressure can be considered as the most unfavourable value which could occur in normal circumstances (Eurocode 7 2014). In terms of wave conditions, this would correspond with a normal wave climate with a return period of for example 1 year. Next to that the EC7 also indicates that extreme water pressures may be treated as accidental actions. In that case one could say that a wave climate with a return period of for example 100 year is an extreme condition and can be considered as an accidental load. This conflicts with the first approach of considering this wave action as a design value in case of limit states with severe consequences. So the EC7 gives no clear indication on how the wave actions should be implemented in the geotechnical design. The EC7 does indicate how the partial safety factors should be considered for the ground-water pressures: either by applying partial factors to characteristic water pressures or by applying a safety margin to the characteristic water level.

2.2 US Army Corps of Engineers

In the slope stability manual of U.S. Army Corps of Engineers (2003), the main focus is for rock-fill dams. Then it is mentioned that the described analysis procedures are applicable to other types of embankments such as breakwaters. The analysis conditions relevant for the slope stability analysis of the breakwater are the end of construction (for upstream and downstream slopes) and long-term condition (for downstream slope). It is clear that for the rock-fill dams in the long-term condition only the downstream slope is critical (due to reservoir load) and should be verified. For the breakwater the condition is different as the hydraulic forces generally exist from both sides. Therefore, in slope stability computations always both slopes should be verified.

In the manual different methods of slope stability analysis that can apply different slip surfaces are mentioned. However, it is not linked to the acceptable slope stability safety factor.

Considering the wave forces is addressed in another manual of USACE (1993). However, it is mainly focused on the design of required armour units of the breakwater exposed to selected design wave and water level conditions.

2.3 ROM, Recommendations for Maritime Works

ROM standards are elaborated and published by the Spanish Ministry of Public Works. The Spanish Ministry has

implemented in these standards its extensive experience with design and construction of marine works, with the purpose of achieving “standardization in the area of planning, design, execution and exploitation of ports, in order to guarantee higher quality and safety in Spanish marine infrastructure”.

The ROM standards cover the subject of design of rubble mound breakwaters. The Limit States Method is used for the design of rubble mound breakwaters in these standards. Calculations for Level I, II and III methods are described in ROM 0.5-05 and it is recommended to always perform Level I calculations and use them as a base for more detailed calculations. In particular, for geotechnical stability, ROM 0.5-05 defines the Design Situations or States to be taken into account, including geometrical parameters, ground properties and definition of actions and combination of actions for Level I calculations. Nevertheless, ROM 0.5-05 recommends for works with high or very high ERI (Economical Repercussion Index) that an additional check applying Level II and III methods is performed. In order to assess the convenience of performing further reliability analyses ROM 0.5-05 provides a simplified method that enables engineers to rate the uncertainty of the safety factor obtained for Level I procedures (basically a sensitivity analysis). It has to be noted that detailed criteria for applicability of the verification methods (Level I, II or III) are also given in ROM 1.0-09.

In case the Level I method is applied in order to calculate geotechnical stability, ROM 0.5-05 provides the combinations of actions to be considered:

- Quasi-permanent combinations
- Fundamental or characteristic combinations
- Accidental combinations
- Seismic combinations.

These combinations are defined by using compatibility and partial weighing coefficients that are applied to characteristic values of loads. Waves are especially relevant for definition of load combinations. In this respect it has to be noted that waves are part of the Environmental Loads group defined in ROM 0.2-90. In this standard compatibility coefficients are provided for Environmental Loads in order to be taken into account in different load combinations.

Once the actions are defined, ROM 0.5-05 proposes to formulate the equation for safety for a geotechnical failure mode in terms of the safety factor, considering increased load and non-reduced resistances:

$$F=R/E_d > F_m \quad (1)$$

Indications about calculation of minimum safety factors F_m are provided depending on the design situation (Persistent, Transient including Short Term situations, and Exceptional) and the load combination considered.

Specifically for Rubble Mound Breakwaters, values for minimum safety factors are given depending on load combination considered and for each Geotechnical ULS (Ultimate Limit State), including sliding. These values are given for occurrence probability of failure modes in the order of 0.01. In any case, the occurrence probability of every failure mode has to be defined by the designer (maximum recommended values for joint probability of failure are given in ROM 0.0-01). In this respect, it is stated in ROM 0.5-05 that relevant diagrams of failure for each type of breakwater and recommendations for assigning failure probabilities to failure modes will be included in the future publication of ROM 1.1.

Regarding overall stability checks, ROM account for different types of sliding surfaces. Specifically, the analysis of non-circular sliding is developed in ROM 0.5-05, where methods for slices with non-circular lines and a wedge method are presented. In ROM 0.5-05 sliding of the protection layers is also considered as one of the Geotechnical Ultimate Limit states.

2.4 Short overview of standards

Based on the explanations mentioned in paragraphs 2.1 to 2.3, a short overview is presented in Table 1. For the slope stability analysis, it is mentioned how the different standards deal with circular and non-circular sliding surfaces, short-term/long-term conditions and including wave actions.

Table 1. Overview on how the different standards for slope stability analysis deal with (1) different partial/global safety factors for circular and non-circular sliding surfaces, (2) different partial/global safety factors for short-term/long-term conditions and (3) including wave actions.

Standard	Circular / non-circular sliding surfaces (1)	Short-term/long-term (2)	Wave action (3)
Eurocode 7	No	No	Yes
ROM	Yes	Yes	Yes
USACE	No	Yes	No

3 REQUIRED SAFETY FACTORS

Based on the mentioned standards and some considerations, the required (acceptable) slope stability safety factors for different load cases of a breakwater are proposed. In the first step, due to the variation of soil characteristics in the field and also the inaccuracies of the laboratory tests the determined characteristic values are reduced by the factor of 1.3 for the cohesion and by the factor of 1.1 for the tangent of friction angle (EAU 1985). Although in the later versions of EAU mentioned factors are not mentioned, they are considered to be on the safe side.

Sometimes the calculations are performed using characteristic values for soil parameters and the overall safety approach is considered (Van 't Hoff and Van der Kolff 2012).

For the proposed required slope stability safety factors for different load cases the following items are considered and summarised in Table 2:

- Three normal hydrostatic water levels as (1) lowest astronomical tide (LAT), (2) Mean sea level (MSL) and (3) highest astronomical tide (HAT)
- Two extreme hydrostatic water levels (W_{LE}) with the return period of for example 100 years: highest (HW_{LE}) and lowest (LW_{LE})
- Normal (daily) waves, waves with an exceeding probability of 1% (W_1)
- Extreme waves with the return period of (for example) 100 years (W_{100})
- Pseudo-static seismic condition (S)

For the short-term slope stability analysis the undrained shear resistance of the foundation soil material is considered. Without wave action consideration, the slope stability needs to be verified only for LAT as it gives the lowest slope stability safety factor. However, when the normal (daily) wave action is considered, different hydrostatic water levels (LAT, MSL, HAT) should be considered. It should be mentioned that at the port side and the sea side of the breakwater the wave climate can be different. For the determination of the wave profile for the geotechnical calculations it is referred to a method that is described and given by De Rouck (1991), De Rouck and Van Damme (1996), De Rouck et al. (2010) and Mollaert and Tava llali (2016). For the short term slope stability, also the different extreme (highest and lowest) hydrostatic water levels with a 100 year return period are combined with the wave heights with a return period of 100 year. However, as it can be imagined that the last condition is an extreme condition, a high safety factor

cannot be expected. To verify the slope stability in case of the pseudo-static seismic condition, the hydrostatic water level of MSL is considered without any wave condition.

For the long-term slope stability analysis the drained shear resistance of the foundation soil material is considered. For the long-term condition, the load cases are similar to the short-term condition. Only the extreme lowest hydrostatic water level with the return period of 100 years, (LWL_E) is considered for the design case without wave action as it gives the lowest slope stability safety factor.

Table 2. Required factor of safety for slope stability analysis

Soil condition	Design case	Stability factor of safety	
		Circular failure	Non-circular failure
Short-term	LAT	1.3	1.2
	LAT, MSL, HAT + W ₁	1.3	1.2
	WL _E + W ₁₀₀	1.05	> 1
	MSL + S	1.05	> 1
Long-term	LWL _E	1.5	1.4
	LAT, MSL, HAT + W ₁	1.5	1.4
	WL _E + W ₁₀₀	1.1	1.1
	MSL + S	1.1	> 1

For each of the short-term and long-term conditions 12 design cases (in total 24 cases) are considered by combination of different water levels and wave conditions which are presented in Table 3. It should be mentioned that the slope stability analysis of the breakwater for each design case should be computed for both sides of the breakwater.

Table 3. Design cases for each of the short-term and long-term conditions.

Condition	Design cases
Hydrostatic water level	1
Hydrostatic water level combined with waves with an exceeding probability of 1 %	6
Extreme hydrostatic water level with combination of extreme wave climate	4
Pseudo-static seismic condition in hydrostatic water level MSL	1
Total	12

4 DISCUSSION

For the slope stability analysis of the breakwater below proposed items should be performed:

- The mechanical properties of the foundation material achieved from laboratory tests should be reduced.
- The overall safety approach and the characteristic values for soil parameters are considered.
- Long-term and short-term conditions should be considered for foundation material properties and also for load condition.

- Wave actions should be implemented in slope stability computation.
- Different failure surfaces (circular and non-circular) can be considered, but should be verified with the relevant slope stability safety factors.
- In total 24 load cases should be considered for the slope stability analysis of the breakwater (by combination of different water levels and wave conditions).
- In all the load cases, the slope of both sides of the breakwater should be verified.

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