# STABILITY ANALYSIS OF A CAISSON UNDER BREAKING WAVE BY MEANS OF A GRADUAL APPROACH

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## INTRODUCTION

The design stages of breakwater projects include the stability analysis of the structures. In the project of the present article, two alternatives were studied: a rubble-mound and vertical caisson breakwaters. The challenges faced for the stability analysis of the caissons are presented and discussed here. Initially, analytical approaches were performed and allowed to achieve a preliminary design of the caissons. Then, a reduced scale model (1/59) equipped with pressure sensors was built in laboratory. The measured pressures were much higher than the usual analytical estimations (Goda, 2010). The shape of the measured pressures is described as impact load on the Proverbs (Kortenhaus, 2001). According to the same reference, under such conditions, the Froude's similarity laws cannot be applied since both air and water compressibility should be scaled. A treatment was then applied based on the work of Cuomo (Cuomo, 2010). However, this resulted in still too high real-scale final time-series. Hence, the caisson stability could not be validated with analytical rigid-block approach considering that:

- The wave impact force is the maximum from the time-series,
- The reaction of the backfill behind the caisson is that of soils at rest.

Consequently, a series of numerical pseudo-static and dynamic analyses were performed in order to better capture the behavior of the caisson. Similar advanced calculations were performed in recent works (Burcharth, 2009) (Andersen, 2010) (Wang, 2015) but for caissons without backfill reaction force. The used approach demonstrates that this reaction force increases with the wave impact force. This increase in reaction force cannot be modelled with simple limit equilibrium approach. On the other hand, the mobilization of a backfill reaction pressure higher than at rest pressure requires any residual displacements to be quantified.

## OBJECTIVES

The signal treatment to obtain real-scale time series from the laboratory data is not discussed in detail in this article which rather focuses on the used approach for the stability analyses from given loads. The main questions to be answered are:

- What is the intensity of backfill reaction force under a specific breaking wave load? What is the safety factor against failure for a given layout of geometry and loads?
- Does the reaction force evolve during a storm (sequence of several waves)?
- What is the required displacement to mobilize this reaction? Does this displacement evolve during a storm?
- Is there any residual displacement?

## METHODS

The stability analyses (sliding, overturning, bearing capacity) at early stage use an analytical approach. The pseudo-static horizontal and vertical forces (uplift) are selected from the measured and treated time-series. Since the calculated safety factors for sliding and overturning do not reach the criteria, a 3D non-linear stress-strain numerical model is carried out with FLAC3D developed by Itasca. Excepting the caisson concrete which uses linear elastic constitutive law, the model materials follow non-linear constitutive laws:

- Hardening Soil Model (Brick algorithm) for the surface alluviums, the ballast and the backfill,
- Mohr Coulomb for the remaining materials.

Moreover, the caisson-ballast and caisson-backfill interfaces follow Coulomb's friction rule without any tensile strength. This comprehensive numerical model is used to update the results of the stability analysis by means of a pseudo-static approach.

Then, a dynamic analysis involving time-series wave loads is performed to check if the cyclic and final residual (if any) displacements are acceptable.

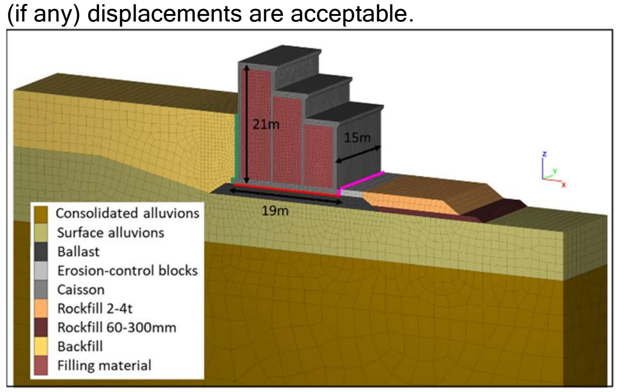


Figure 1 –3D stress-strain model for stability analysis.

## RESULTS

With the analytical approach, most of the safety factors do not respect the project requirements. The use of the numerical model allows a backfill reaction with a lateral coefficient of earth pressure K=1.7 to be justified. This is to be compared to the at-rest $K_0$=0.4 and passive coefficients $K_p$=3.7. With the caisson moving toward the backfill, passive earth state is gradually triggered mostly at higher elevation due to its motion which denotes rotation around its base. This behavior cannot be captured by a simple limit equilibrium approach.

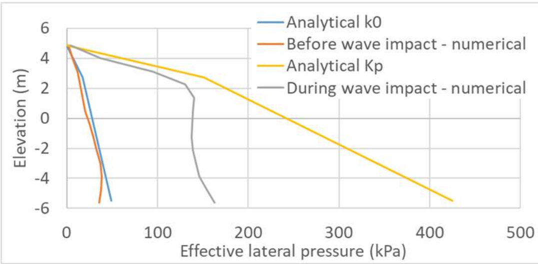


Figure 2 - Reaction of the backfill at-rest and under wave breaking load.

All the safety factors are satisfied by means of the stress-strain approach except for the overturning (1.2 for a criterion of 1.5). However, the overturning of the caisson requires the backfill to fail first. On the other hand, the higher the wave pressure, the higher also the backfill reaction until the backfill fails i.e., Coulomb's wedge is triggered. Therefore, the calculated safety factor based on force equilibrium is not representative of the real safety factor of the system including the caisson and the backfill. Hence, two methods are used to verify this hypothesis and assess a more realistic safety factor: strength reduction and pushover approaches. The strength reduction method results in a safety factor of 2.7 while the ultimate load factor given by the pushover approach is 2.8. This confirms that the more realistic safety factor is much higher than the required 1.5.

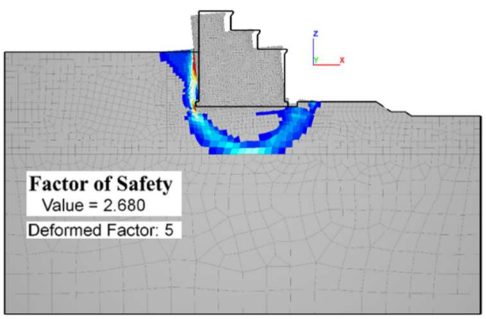


Figure 3 - Result of the strength reduction method showing an overturning tendency.

The dynamic analysis highlights a reversible caisson crest maximum displacement of 7mm toward the land side and 1mm toward the seas side due to the wave load cycles. The mobilized reaction of the backfill also does not present any evolution. The final residual displacement after 10 cycles of waves is negligible.

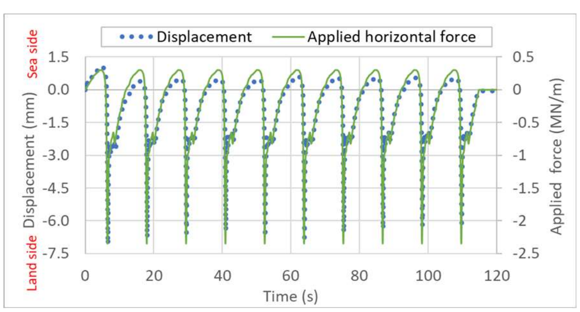


Figure 4 - Evolution of crest displacements for 10 cycles of breaking waves.

## CONCLUSION AND DISCUSSIONS

The conclusion of the analysis is that the required safety factors are respected provided that non-linear stress-strain analysis is used. Moreover, the expected displacements are expected to allow the operation of the breakwater with very minor repairment if any after the breaking wave even if that load case is to occur yearly.

Several points of the presented work can be discussed further since it is an innovative approach for this type of structure and load. Some of the main points are:

- Analytical rigid block or numerical stress-strain model: when the safety factors are all respected with the analytical approach, it could be enough to rely on the analytical estimations. The numerical model may be recommended if the stability is not justified with the simpler approaches.
- 2D or 3D: a 2D model could be enough for the stability analyses if equivalence in density and/or stiffness is considered for the caisson unless the breakwater does not have a straight layout.
- Pseudo-static or dynamic approach: dynamic analyses may be more interesting for high return period load cases for which the stability state may be acceptable with safety factors slightly lower than 1 i.e., some irreversible displacements can be accepted. This could also be the case when there is suspicion that the duration of the peak loads is very short compared to the natural frequency of the caisson system.

This new approach paves the way to the necessity of definition of acceptable displacements (reversible or irreversible) as a basis of design of breakwater projects. An enhanced monitoring of existing structures and the creation of an extensive database of their behavior and the relating acceptance is a first stage that may be considered to move forward.

## REFERENCES


Andersen, Burchart, Andersen (2010): Validity of simplified analysis of stability of caisson breakwaters on rubble foundation exposed to impulsive loads, Coastal Engineering Proceedings, 1(32), structures.46.

Burcharth, Andersen, Lykke (2009): Analyses of stability of caisson breakwaters on rubble foundation exposed to impulsive loads, Proceedings of the 31st International Conference on Coastal Engineering, World Scientific, 3606-3618.

Cuomo, Allsop, Takahashi (2010): Scaling wave impact pressures on vertical walls, Coastal Engineering, ELSEVIER, vol. 57, pp. 604-609.

Goda (2010): Random Seas and Design of Maritime Structures, Advanced Series on Ocean Engineering: Volume 33, 732 pages.

Kortenhaus, Vrijling et al (2001): Proverbs: Probabilistic design tools for vertical breakwaters, CRC Press, 392p.

Wang, Wang, Hong (2015): IOP Conference Series: Earth and Environmental Science, 153 052016.