Modeling of concrete mattress for shore protection by Plaxis 2D

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ABSTRACT

Traditionally, shore protection revetments are designed by limit equilibrium method developed by Pilarczyk (Pilarczyk, et.al, 1998; Breteler, et.al, 1998; Pilarczyk, 2003). The method is also applicable for determining thickness of concrete mattress required to withstand a certain height of waves. However, the method cannot predict deformation of concrete mattress subjected to repetitive wave loads. This paper elaborates the modeling of concrete mattress against the dynamic loading of waves by means of Finite Element Method (Plaxis 2D). It is found that the conventional method is adequate in determining thickness of concrete mattress required against wave height with a factor of safety against lift off in the order of 3.5. The movement of the concrete mattress can be assessed by simulating the wave loads as a concentrated sinusoidal dynamic load at the point of wave impact.

Keywords: shore protection, concrete mattress, concentrated sinusoidal dynamic load, Plaxis 2D.

1. INTRODUCTION

Traditionally, an assemblage of fine and coarse broken stones or rocks materials are commonly installed and arranged along a shoreline to prevent abrasion of shorelines. This structure is known as ripraps (Figure 1). The size and mass of the ripraps material absorbs the impact energy of waves, while the gaps between the rocks trap and slow the flow of water, lessening its ability to erode soil along the coastal lines.

As geosynthetics technology advances, geotextiles in combination with assemblage of rocks has become a norm for shore or coastal protection. At site where rock is difficult to obtain, two layers of geotextiles connected with high strength spacing elements of equal length in a square grid pattern is fabricated to form a formwork. The formwork is then filled with concrete to form a so called concrete mattress (Figure 2). By altering the length of the spacing elements, the thickness of the mattress can be varied from 10, 15, 20, 25, and up to 100 cm; which when filled with concrete can have an area weights of 220 to 2200kg/m².

The fundamental purpose of concrete mattress is to replace the traditional ripraps system where rock is difficult to find or too expensive to transport. The fabrication of the geosynthetics can be made in such a way that it provides two-dimensional flexibility. This allows large deformations and causes the mattresses to crack at predetermined breaking points or

Fig. 1. Ripraps Construction

Fig. 2. Concrete Mattress
lines, while the concrete mattresses are still tied together with their spacing elements which also act as reinforcing elements.

The weight, the all-over coverage of the shore surfaces and the two dimensional flexibility of the concrete mattress provide resistance against hydrodynamic wave loads.

2. TYPE OF CONCRETE MATTRESS

Broadly categorized, there are two types of concrete mattresses, i.e. the first type is the **impermeable mattress** with a relatively rigid and uniform cross section and the second type is the **permeable mattress** with non-uniform cross section, and predetermined breaking points/lines, therefore it is also known as flexible mattress (Figure 3).

![Impermeable Mattress](image1)

![Permeable Mattress](image2)

Fig. 3. Impermeable and Permeable Mattress

The impermeable rigid mattress is especially useful for lining the river beds, sluiceways, pumping stations and other structures where the beds have to be protected against erosion.

The permeable flexible mattress is primarily used to provide resistance against extreme hydrodynamic forces, such as: wave loads. The self-weight of the mattress withstands the wave impacts. The induced water pressures of the saturated soils below the mattress is filtered out by the built-in drainage points placed at certain grid distance. To ensure that the soil grains are not washed out, a non-woven fabric with high filtering capability is fitted below the mat over the entire surface of the soils it protects. This flexible mat can also accommodate large deformations. The flexibility is guaranteed by providing thinner layer at a certain square spacing, so that if there is differential deformation the mats will crack at this predetermined weaker lines. The internal spacing elements (see the inset in Figures 2 and 3b), made of high strength threads of polyester, guarantee that the mats are still tied together when the mats cracks and even if the upper fabric layer damages.

The shapes of the concrete mattress can be varied further to give a crib, a slab, or a tubular appearance (Figure 4). Herein after, the paper shall present the analysis of the permeable mattress for shore / coastal protection.

![Slab Shapes](image3)

![Crib Shapes](image4)

![Tubular Shapes](image5)

Fig. 4. Shapes of Concrete Mattress

3. CONVENTIONAL DESIGN METHOD

Studies have shown that uneven settlement of the subsoil underlying the concrete mattress will cause cavities to be formed under the mattress. In this case, the mattress shall span over the cavities. Wave impacts may then cause the concrete to crack, and the span to collapse. Hydrodynamic load of high waves can
induce pressure difference over the mattress, and may create pumping action that can lead to the collapses of the concrete mattress.

Based on the method developed by Pilarczyk (Pilarczyk, et al., 1998; Pilarczyk, 2003) for the design of conventional riprap system, Breteler et al., 1998, suggested the following formula for determining the thickness of concrete mattress.

\[
\frac{H_s}{D} = \frac{F}{\tan^2 \alpha} \quad \text{with:} \quad \frac{H_s}{D}_{\max} = 4 \\
\Delta = \frac{\gamma_m - \gamma_w}{\gamma_w} = \text{relative unit weight} \\
\xi = \frac{\tan \alpha}{\sqrt{\gamma_{w}/(1.56\gamma_{w})}} = \text{breaker parameter}
\]

\(H_s\) = significant (max) wave height (m), as presented in Figure 5.

\(D\) = thickness of the concrete mattress (m)

\(F\) = revetment stability factor, which can be taken as follows:
- \(F = 2.5\) or \(\leq 3\) for low permeable mattresses on fine granular filter.
- \(F = 3.5\) or \(\leq 4\) for low permeable mattresses on compacted sand.
- \(F = 4.0\) or \(\leq 5\) for permeable mattresses on sand or fine filter \((D_{15} < 2\text{mm})\).
- Higher values can be applied for temporary applications or on clay and the mattresses are properly anchored.

\(\gamma_m\) = unit weight of concrete mattress = 22 kN/m\(^3\)

\(\gamma_w\) = unit weight of sea water = 10.1 kN/m\(^3\)

Hence \(\Delta = 1.18\)

\(\alpha\) = slope of shore lines

\(T\) = wave period at the peak of spectrum (s)

Example: For a slope of 1 horizontal to 2 vertical \((1\text{V}:2\text{H})\) or \(\tan \alpha = 0.5\), \(H_s = 1.0\text{m}, T = 2\text{seconds}, F = 4\) (permeable mattress on sand), the thickness required for the concrete mattress is in the order of 25 cm.

4. FINITE ELEMENT MODEL

The above Breteler et al method gives the thickness of the concrete mattress required to sustain a certain wave height. However, the method does not give any indication on the deformation of the concrete mattress subjected to the hydrodynamics wave loads. In order to find out such deformation a finite element analysis is necessary. Plaxis 2D geotechnical software (Brinkgreve, 2011) is subsequently used to model the concrete mattress and the dynamic loading of the waves.

The permeable mattress, used as example in section 3, was modeled as a drained linear elastic material. The underlying soil is sandy material as shown in Figure 6. Figure 6a shows the whole model. The wave load is modeled as a concentrated dynamic load system. The sea water level is located 6.0m from the base. The boundary of the model is set as dynamic load absorbent boundary. Figure 6b shows the input parameters of the model.

The wave load shall be simulated as dynamic loading. In Plaxis, this is done by applying a concentrated load of 10.1kPa, i.e. sea water of 1m height, perpendicular to the concrete mattress (select Point Load A in the input program), and in the ‘Loads’ menu activates the ‘Load system A’ as dynamic load system (Figure 7).

![Fig. 6. Finite Element Model](image1)

![Fig. 7. Setting the Dynamic Load System](image2)
The calculation step of the finite element model is presented in Table 1. It is important to note that many Plaxis users are not aware that for an initial condition where either the ground surface, the subsoil layer, or the ground water level is not horizontal, the \( k_o \) procedure will lead to inaccurate initial stresses within the soil body because the \( k_o \) procedure only calculates the vertical stresses and horizontal stresses with no shear stress developed within the soil body. This means \( k_o \) procedure is only valid for horizontal ground. If the ground surface, the subsoil layer, or the ground water level is not horizontal, to maintain equilibrium, there will be shear stresses developed within the soil body. Therefore, the \( k_o \) procedure should not be used, instead a gravity loading procedure should be chosen. The option of gravity loading and \( k_o \) procedure in the initial phase is only available in Plaxis 2D version 2011 and above. For Plaxis 2D version 9 and below, the gravity loading stage needs to be done by skipping the \( k_o \) procedure. This is done by setting \( \Sigma Mweight=0 \) in the \( k_o \) procedure i.e. in the initial stage. This way no initial stresses within the soil body is developed. The initial stresses of the soil body is then calculated in the calculation module of the program by selecting the first phase as plastic ‘Calculation type’, and if any of the soil layer is modeled as undrained, the ‘Ignore undrained behavior’ option in the ‘Parameter’ tab has to be selected (this is due to the fact that initially, when no external load and no geometry changes is made, the soil is in a drained condition). In the ‘Loading input’ section, the ‘Total multiplier’ option is selected, and in the ‘Multiplier’ tab, key in \( Mweight=1 \). Then the next actual construction stages, in this case the construction of concrete mattress and the application of the wave loads, are modeled.

### Table 1. Calculation Steps in Plaxis 2D Model

| Identification | Phase no. | Start from | Calculation   |
|---------------|-----------|------------|---------------|
| Initial phase | 0         | N/A        | Gravity loading |
| Concrete Matt | 1         | 0          | Plastic       |
| Wave 1.0m    | 2         | 1          | Dynamic       |
| Wave 2.0m    | 3         | 1          | Dynamic       |
| Wave 3.0m    | 4         | 1          | Dynamic       |
| Wave 4.0m    | 5         | 1          | Dynamic       |

The construction of the concrete mattress is done in phase no. 1 of the calculation procedure by selecting ‘Plastic’ in the ‘Calculation type’. Selects ‘Stage construction’ in the ‘Multiplier’ tab. Activates the geometry of the concrete mattress. At the same time also activates the dynamic point load for the application of the dynamic wave load in the next calculation phase.

In the next phase, the wave load is then applied, by selecting ‘Dynamic’ in the ‘Calculation type’, and key in 20 seconds in the dynamic ‘Time interval’ to model 10 cycles of wave loads with a wave period of 2 seconds (a rather severe waves). Select the ‘Multiplier’ tab, click the wave icon adjacent to the \( \Sigma MloadA=1 \), and key in the value as shown in Figure 8 to model the 1.0m height wave load presented in Figure 9. As shown in Table 1, wave loads of 1.0m, 2.0m, 3.0m, and 4.0m height were analyzed.

![Fig. 8. The Input of 1.0 m Height Wave Load](image)

![Fig. 9. The 1.0 m Height Wave Load](image)

### 5. THE FINITE ELEMENT RESULTS

![Fig. 10. Maximum Deformation of the Concrete Mattress vs. Wave Height at 1.0 m](image)
Figure 10, 11, 12, and 13 shows the maximum lift up of the concrete mattress against wave height.

Figure 14, 15, and 16 shows the impact of wave cycles against the movement of the concrete mattress for 1.0m, 2.0m, and 3.0 m height of waves.

Figure 17 shows the displacement of the concrete mattress with 4.0m height of wave.
6. DISCUSSIONS

The Plaxis 2D results show that with a wave height of 1.0m, the maximum movement of the concrete mattress is less than 2 mm (Figure 10 and Figure 14). For wave height of up to 2.0m the maximum cyclic movement or displacement of the concrete mattress is tapering off at around 17mm (Figure 15) and this maximum movement takes place at the point of the wave’s impact. For 3.0m height of waves, even after 20 cycles of the waves impact the movement is still increasing, the movement at the last cycles varies within 75mm to 125mm (Figure 12 and 15), and concrete mattress started to lift off the ground along the slope (Fig.12). The concrete mattress is completely lifted off the ground and fails when the wave goes higher as shown in Figure 13.

It is to be noted here that the finite element simulations have been performed with varying slope angles and soil properties. The results of the analysis shows similar trends as presented above.

7. CONCLUDING REMARKS

The numerical analysis shows that the conventional design method developed by Breteler et al in 1998 to determine the thickness of the concrete mattress is adequate. The safety against lift off of the concrete mattress determined by the finite element method is in the order of 3.5 (three point five), where the stability factor determined by Breteler et al method is in the order of 4.0. Judging from the fact the finite element simulation can predicts the movement of the concrete mattress, as well as the stability of the slopes of the original ground, it is advised that the conventional method developed by Breteler et al is combined with finite element analysis in designing and evaluating the performance of concrete mattress.

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