Effect of pile sleeve opening and length below seabed on the bearing capacity of offshore jacket mudmats

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ABSTRACT
Extracting hydrocarbons from beneath the seabed requires offshore platforms to be installed at strategic offshore locations. Depending on the water depth, multi-legged steel tubular framed structures called jackets can be used to support the topsides, risers and caissons. In the temporary condition, before piles are installed, horizontal steel plates located at the bottom of each jacket leg are used to support the jacket. The steel plates are called mudmats, and may be large due to the size of the structures they support and the harsh environmental loading conditions. Depending on the seabed soil condition, mudmats are usually designed with vertical skirts placed around the perimeter. During loading the skirts improve both the vertical and horizontal loading capacity. The piles are installed through openings in the mudmats called pile sleeves, and then driven to target penetration. Following this the piles are grouted to the pile sleeves resulting in the permanent foundation system. Extending the pile sleeves below seabed is used as a mitigation measure to avoid soil masses occupying the space in the sleeve, interfering with pile driving or grouting operations. Additionally local soil failure within the pile sleeve openings may occur. One method of evaluating mudmat foundation stability is to calculate the bearing capacity based on the net area of the mudmat. The net area in this case is the gross mudmat area minus the pile sleeve openings. However, by extending the pile sleeves to a sufficient depth below seabed, it is ensured that the gross mudmat area can be mobilized for bearing capacity evaluation. This paper describes a method to find the optimal pile sleeve length below seabed related to the size of pile sleeve opening and mudmat skirt length. Mobilizing the gross mudmat area in the bearing capacity evaluation reduces the required area of the mudmat. This results in smaller mudmat area and thus cost and weight savings for the jacket structure.

Keywords: mudmat, jacket, offshore, bearing capacity.

1 INTRODUCTION

The term mudmat describes the horizontal steel plate foundations used in the temporary phase of jacket installation before piles are driven and grouted to the pile sleeves. After the piles are installed, the environmental loads and the weight of the structure are carried by the piles. One of the main purposes of the mudmat is thus to support the weight of the jacket and additional load from the environment for a short period of time. Additionally it contributes to the stiffness and structural integrity of the pile cluster for the operational phase.

Figure 1 shows a typical pile cluster with pile sleeve openings. The bearing capacity of a mudmat can be calculated based on the net area of the mudmat. The net area in this case is the gross mudmat area minus the pile sleeve openings. The main reason for this is anticipation of local soil failure within the pile sleeve opening. Depending on the number and size of piles in the pile cluster, the reduction in mudmat effective area may be relatively large. However, the pile sleeves can be extended below seabed. This is of special interest, since the pile sleeve length below seabed is directly related to the soil movement within the pile sleeve opening and with that also to the local soil failure.

This paper seeks to understand the impact on the bearing capacity of the mudmat and soil movement within the pile sleeve opening, when the pile sleeves are extended below seabed. The paper further describes a method to find the optimal pile sleeve length below the seabed using an FE method. PLAXIS 2D software is used in the simulation. In the paper two sleeve opening sizes and three different pile sleeve penetration depths below seabed are investigated.

2 MODEL GEOMETRY AND SOIL CONDITIONS

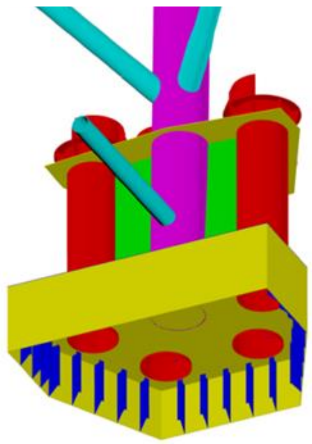


Figure 1: Mudmat with four pile sleeves, skirts and structural stiffeners (Vanberg, 2014).

Skirted mudmats consist of a mudmat plate with thin vertical plates (skirts) connected to the mudmat plate perimeter penetrating the soil. Mudmats for steel jackets are constructed with pile sleeve openings. Piles will be driven through these openings and grouted to the pile sleeve. Figure 1 shows an example of a mudmat with four pile sleeves openings and the mudmat skirt with structural stiffeners. The arrangement and number of pile sleeves and stiffeners varies and are dependent on the specific conditions at the planned location.

The geometry of the mudmat with skirts and sleeves investigated in this study is shown in Figure 2. In the figure, s is the depth of the skirt, d is the pile sleeve opening and l is the penetration depth of the pile sleeve below seabed. b is the distance between pile sleeves, and a is the distance between the pile sleeve and mudmat skirt. In the study two pile sleeve openings, d = 2.0 m and d = 3.0 m, are considered. The sleeve opening is determined by the pile diameter and required grout thickness. The pile sleeve is usually designed with an extension below seabed to prevent local soil failure within the pile sleeve opening. A mudmat foundation width w of 20 m is evaluated in this study, which is found as $w = 2(a) + b + 2(d)$. In the two dimensional space, the mudmat is considered as an infinitely long strip foundation. Three different pile sleeve extension depths below seabed are investigated. The sleeve lengths below the mudmat plate studied are 0.5 m, 1.0 m, and 1.5 m.

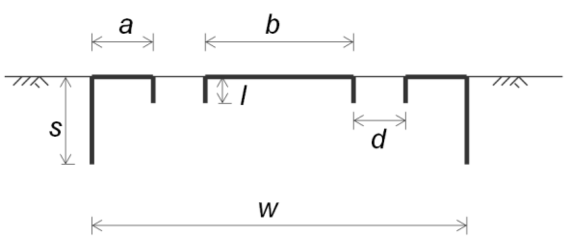


Figure 2: Mudmat model geometry used in the study, with skirt length s = 3 m, pile sleeve distance from the skirt wall a = 2 m, pile sleeve opening d = 2 m and 3 m, pile sleeve length below mudmat l = 0 m, 0.5 m, 1.0 m and 1.5 m.

The soil condition considered in this study is soft clay. Most soft seabed soils show increasing undrained shear strength with depth, and often in a linearly manner.

In this study the undrained shear strength of the soil was assumed to be either constant with depth or to increase linearly with depth according to $s_u = s_{u0} + k \cdot z$, where s_{u0} is the shear strength at the seabed, k is the shear strength gradient with depth as shown in Figure 3 and z is the depth below seabed.

For the mudmat with pile sleeve openings of 2 m and 3 m, the soil deformation within the pile sleeve and the bearing capacity of the mudmat for sleeve extension lengths of 0 m, 0.5 m, 1.0 m, and 1.5 m below the seabed are studied. The base case soil strength below the mudmat is s_{u0} = 5 kPa and k = 2 kPa/m. To investigate the effect of soil strength on the failure mechanism of the soil through the pile sleeve opening, different values of k were used (0, 2 and 5 kPa/m).

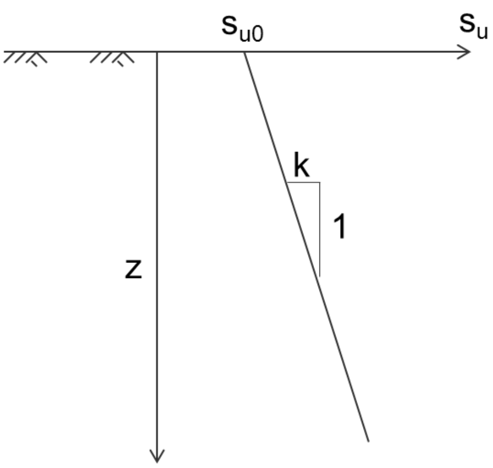


Figure 3: Soil parameters used in the study with linearly increasing undrained shear strength with depth. Base case is s_{u0} = 5 kPa and k = 2 kPa/m.

3 BEARING CAPACITY OF MUDMAT WITH DIFFERENT METHODS

The bearing capacity of a skirted foundation without pile sleeve opening is calculated as a reference case. There is a variety of methods available, and several are based on the proposed equation by Terzaghi (1943), which describes the bearing capacity per unit length, Q, for an infinitely long strip foundation:

$$\frac{Q}{B} = q_f = \frac{1}{2}\bar{\gamma} B N_\gamma + \bar{q} N_q + c N_c \qquad (1)$$

In this formula the parameters are defined as: $\bar{\gamma}$ = effective unit weight of soil, B = width of foundation, N_γ = bearing capacity factor for soil weight. $\bar{q}$ is a unit load acting on the soil surface on the outside of the foundation and N_q is the bearing capacity factor for this unit load. c denotes the cohesion of the soil, and N_c is the factor relating the cohesion to the bearing capacity.

The bearing capacity factors N_q and N_c can be found by the theoretical formulas by Prandtl (1921):

$$N_q = e^{\pi \tan\varphi} tan^2(45° + \frac{\varphi}{2}) \qquad (2)$$

$$N_c = (N_q - 1)\cot\varphi \qquad (3)$$

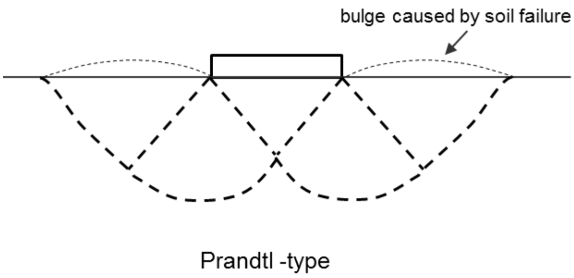
Where φ = the friction angle of the soil. For the case of pure clay conditions as are evaluated in this paper, the value of the friction angle is zero and the bearing capacity factors above will be N_q = 1 and N_γ = 0.

The above equations are valid for the simple case of a centrically loaded infinitely long strip foundation on a vertical surface with no horizontal load or moments. Meyerhof (1963) and Brinch Hansen (1968) used extended versions of the formula where several factors were included to account for the shape and embedment depth of the foundation, and inclination of the load, base and the ground. Additionally other authors have further developed the above bearing capacity formulations, or developed other formulae, like for example Janbu et. al. (1964).

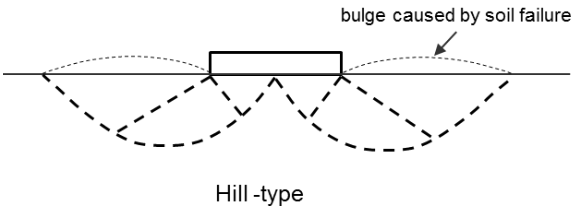
Equation 1 does not account for any increase in shear strength with depth, and a correction has to be made if the soil is non-homogenous. Davis and Booker (1973) proposed a method for surface strip and circular footings on soil to take into account a linear increase in shear strength with depth. However, the solution by Davis and Booker does not take into account effect of skirt or effect of foundation shape.

4 FAILURE MECHANISM OF SKIRTED FOUNDATION

The failure mechanism of shallow foundations has been widely studied by different researchers. Several parameters influence the failure mechanism of a skirted mudmat with pile sleeve openings. Among others the size and location of pile sleeve openings, the skirt length, the pile sleeve extension below seabed and the soil type under the mudmat. Figure 4 shows a typical general shear failure mechanism of Hill type and Prandtl type (Chen, 1975) for a solid foundation with no pile sleeve openings and skirt. The clear distinction between the Hill and the Prandtl type of failure mechanism is that the downward movement of soil volume just under the foundation is different. Analytical solutions for bearing capacity of rough-based circular surface and shallowly embedded foundations indicate that a Prandtl type mechanism is appropriate for uniform soft soil (Kusakabe et al., 1986; Martin and Randolph, 2001), while a Hill type mechanism is optimal for a soil with increasing profile of undrained shear strength with depth. The width and depth of the plastic failure zone decreases with increasing soil strength with depth.



(a)



(b)

Figure 4: Soil failure mechanisms of shallow foundation (modified from Mana et al., 2012).

5 FEM SIMULATION

2D plane strain FE simulations were carried out using PLAXIS. The main focus of the FE simulation was to study the effect of pile sleeve length below seabed on the failure mechanism of the soil within the pile sleeve opening and the bearing capacity of the mudmat. Figure 5 shows the FE model used in the simulation of the mudmat model shown in Figure 2.

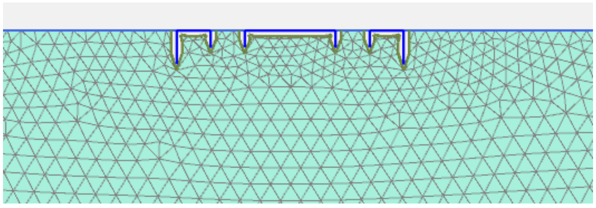
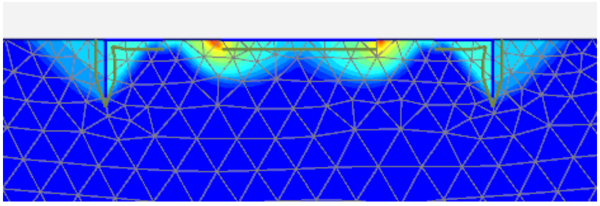


Figure 5: PLAXIS 2D FE model of the soil, mudmat with skirts and pile sleeves extended below seabed, and interface element used in the simulation.

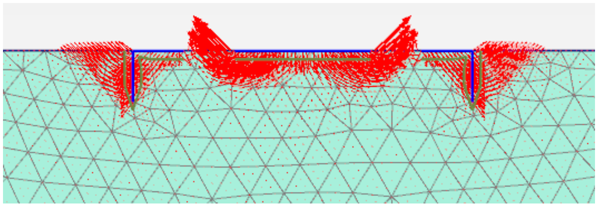
The soil in the model consisted of very soft clay and was modelled as an isotropic elastic perfectly-plastic continuum, with failure described by the Mohr-Coulomb yield criterion. The undrained shear strength increased linearly with depth $s_u = 5 + 2z$ kPa, where z (m) is the depth below seabed. The stiffness modulus at seabed was $E_0 = 3400$ kN/m^2, increasing linearly with depth $E_{inc} = 400$ kN/m^2/m, and the undrained Poisson’s ratio $\nu = 0.33$, according to undrained type B model in PLAXIS (2015). The interface roughness of mudmat base, the sides of the skirt and sleeves were taken to be $R = 0.8$.

The mesh was composed of triangular elements with a mesh similar to that shown in Figure 5. As finite element analyses are sensitive to number of elements used, the number of elements were increased until the failure loads converged towards the same result.

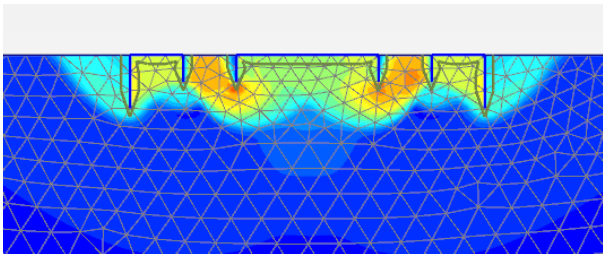
The failure mechanisms of the soil beneath the mudmat with skirts and pile sleeves were studied by two different approaches, and yet both approaches resulted in similar effect on the soil below the mudmat. The first approach is by applying distributed vertical load on the mudmat. The second approach is by applying prescribed vertical displacement of the mudmat. Figure 6 shows the soil deformation pattern under the mudmat and through the pile sleeve openings for both no pile sleeve extension and 1.5 m pile sleeve extension below seabed. The soil deformation pattern based on the above two approaches are similar. Results from both approaches are discussed in the paper.



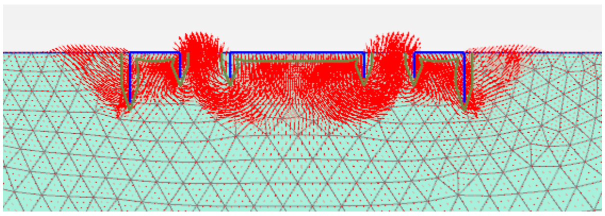
a) No pile sleeve extension



b) No pile sleeve extension



c) *1.5 m pile sleeve extension*



d) 1.5 m pile sleeve extension

Figure 6: Failure mechanism and soil deformation pattern under the mudmat and through the pile sleeve openings, for the case with no pile sleeve extension and 1.5 m pile sleeve extension below seabed for 0.5 m prescribed vertical movement of mudmat.

6 RESULTS AND DISCUSSION

The failure mechanism of skirted foundation with pile sleeve openings is a 3D situation. There are therefore obviously some modelling limitations to simulating the skirted mudmat with pile sleeve openings with a 2D model. However, a simplified 2D model can be used to assess the failure mechanism and to study the effect of pile sleeve length below seabed on the bearing capacity. The simulation results clearly show the effect of pile sleeve length below seabed on both the bearing capacity of the mudmat and the movement of soil mass within pile sleeve opening. Hill-type failure mechanism is observed from the FE simulation for a mudmat with no pile sleeve extension below seabed, Figure 6 (a) and (b). For a mudmat with 1.5 m pile sleeve extension Prandtl-type failure mechanism is observed, Figure 6 (c) and (d).

It can be seen from figure 6 (a) and 6 (c) that the failure mechanism is pushed deeper down in the soil when the pile sleeves are extended to a length of 1.5 m below mudmat. This will have an effect on the bearing capacity, since the undrained shear strength increases with depth, and soil with a higher strength is mobilized. Figure 7 and Figure 8 show the bearing capacity for a mudmat with 2 m and 3 m pile sleeve openings with the three different pile sleeve lengths studied. In the figures base case soil condition are used, and the undrained shear strength is hence increasing with a rate of k = 2 kPa/m.

The curves in Figure 7 and Figure 8 show that as the pile sleeve length below seabed increases the bearing capacity of the mudmat also increases. It can be seen that the capacity is approximately 40 kN/m/m when no pile sleeve extension is included, and 60 kN/m/m when 1.0 m pile sleeve extension is used. Hence, the capacity is increased by about 50 %.

In this case no significant difference in bearing capacity is observed for pile sleeve lengths of 1.0 m and 1.5 m. Pile sleeves longer than 1.0 m may therefore not result in much gain in the bearing capacity, and 1.0 m pile sleeve length may therefore be considered optimal in this case.

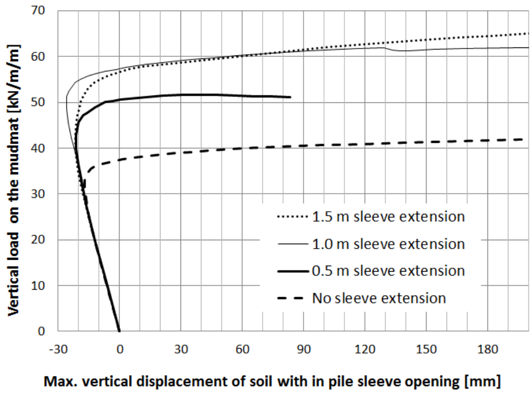


Figure 7: Failure curves for the most critical point within the pile sleeve opening of 2 m diameter.

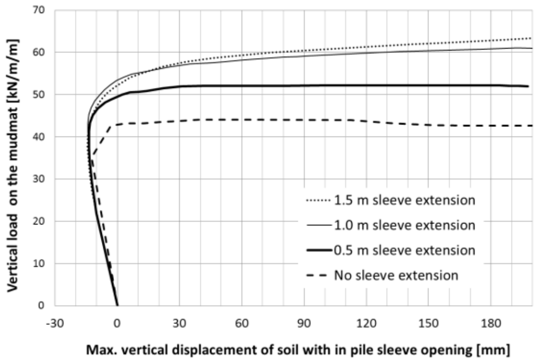


Figure 8: Failure curves for the most critical point within the pile sleeve opening of 3 m diameter.

Figure 6 (b) and 6 (d) shows the pattern of soil movement when the mudmat is pressed downwards with a prescribed displacement of 0.5 m in the simulation. A more detailed study of the soil movement showed that at the beginning of loading, the soil within the pile sleeve follows the vertical elastic downward deformation of the soil. This can also be seen in Figure 7 and Figure 8, since the vertical displacement of the soil is negative relative to the original seabed. As the loading increases, the soil movement within the pile sleeve opening starts to move vertically upward towards failure following the failure mechanism of the soil, as shown in Figure 6 (b) and (d). This point of turn depends on the pile sleeve length below seabed and the size of pile sleeve opening. The magnitude of the movement within the pile sleeve opening is also depending on the pile sleeve extension below seabed. This can be more clearly seen in Figure 9 and Figure 10 for a prescribed vertical displacement of the mudmat. The figure shows the soil displacement pattern for a point selected at the most critical location (maximum soil movement) within the pile sleeve opening of 2 m and 3 m. In this case the mudmat is given a vertical displacement (vertical axis) and the displacement of the soil (horizontal axis) is relative to the original seabed. Hence, 0 mm vertical displacement of soil means that the selected node in the mesh is at the original seabed.

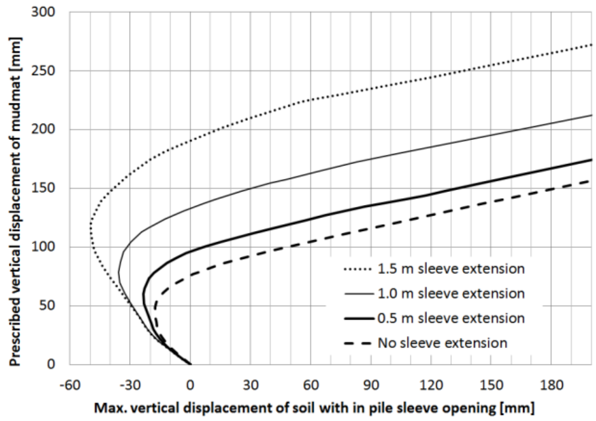


Figure 9: Soil vertical displacement for the most critical point within the pile sleeve opening of 2 m, when the mudmat is pressed vertically.

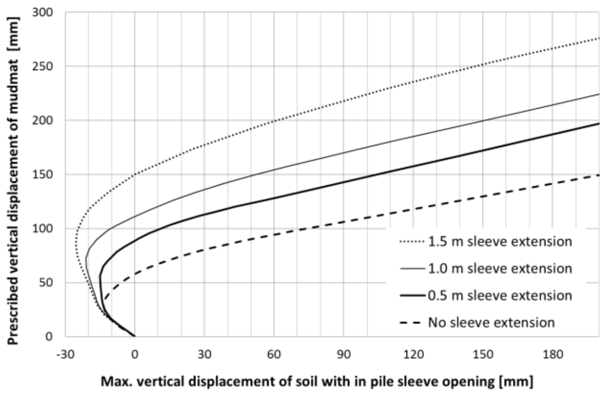


Figure 10: Soil vertical displacement for the most critical point within the pile sleeve opening of 3 m, when the mudmat is pressed vertically.

The vertical upward soil movement within the pile sleeve opening decreases as the pile sleeve extension increases. From Figure 10 at 15 cm prescribed vertical displacement of mudmat, the soil within the pile sleeve opening moves 0 mm, 50 mm, 105 mm, and

200 mm relative to the original seabed for pile sleeve lengths of 1.5 m, 1.0 m, 0.5 m and 0 m respectively.

To investigate further the sensitivity of the results, various analyses were carried out. The increase in soil strength with depth has pronounced effect on the bearing capacity and the deformation pattern of the soil under the mudmat and through the pile sleeve opening. Figure 11 shows the failure curves for a mudmat with 1.0 m long pile sleeve below seabed, when the increase in undrained shear strength with depth is changed.

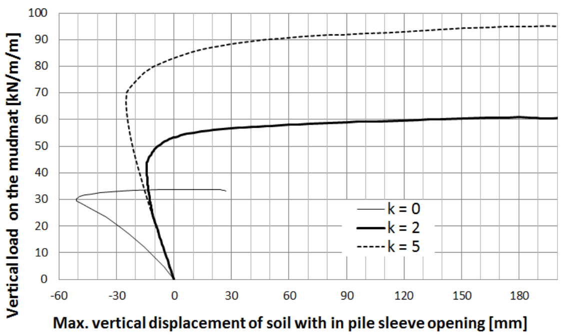


Figure 11: Failure curves for the most critical point within the pile sleeve opening of 3 m, when the pile sleeve length below seabed is 1 m, with different ratios of increasing undrained shear strengths with depth.

The curves show that the increase in undrained shear strength has a significant effect on the bearing capacity. For a soil with constant strength with depth, $k = 0$ kPa/m, the soil within the pile sleeve actually follows the downward movement of the mudmat, and does not turn to reach its original point at seabed before failure. This can be more clearly seen in Figure 12 where the movement within the pile sleeve opening is plotted against prescribed vertical displacement. The selected critical node in the mesh does not go back to its original point at seabed before the mudmat has moved 45 cm vertically downward. Another consequence of constant strength with depth is that the failure mechanism is pushed deeper down in the soil. However, the undrained shear strength is constant with depth there is not much gain in the bearing capacity.

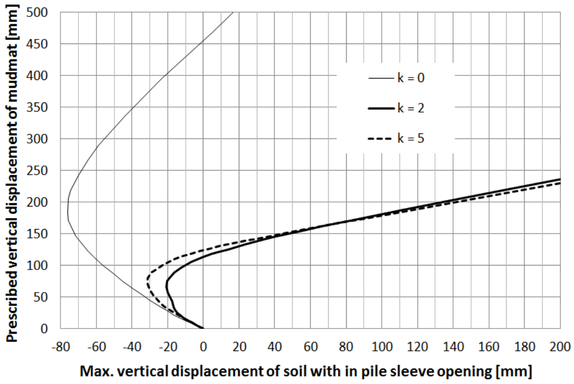


Figure 12: Soil displacements for the most critical point within the pile sleeve opening of 3 m, when the pile sleeve length below seabed is 1 m, with different ratios of increasing undrained shear strengths with depth.

The bearing capacity of the mudmat with pile sleeve extensions are compared with a mudmat with no pile sleeve openings, denoted solid. In the comparison soil displacement outside the mudmat is used as a reference point, i.e. the global failure mechanism determines the bearing capacity. Figure 13 shows the effect of the pile sleeve extension using the base case soil data. The result shows that piles with a sleeve extension of 1.5 m give similar bearing capacity as a solid mudmat.

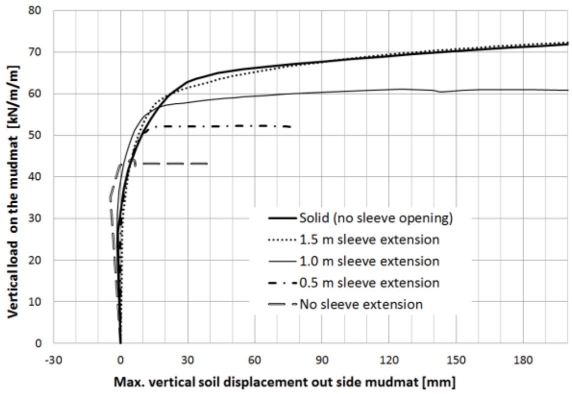


Figure 13: Bearing capacity of the mudmat with different pile sleeve extension below seabed for the pile sleeve opening of 3 m and solid mudmat with no pile sleeve opening.

7 CONCLUSION

In this paper the failure mechanism and the soil movement through the pile sleeve opening of skirted mudmat has been studied. In the study two sleeve opening sizes and three different pile sleeve penetration depths below the seabed were investigated. Simplified 2D FE method using PLAXIS software was used in the simulation. The results show that the pile sleeve length below seabed has substantial effect on the failure mechanism of the soil and the bearing capacity of the mudmat. For a specific mudmat geometry, pile sleeve opening and soil condition, the analyses show that it is possible to find an optimal pile sleeve length below seabed to control the soil movement within the pile sleeve opening and maximise the bearing capacity. Pile sleeve lengths longer than this optimal length may not result in much gain in the bearing capacity or reduction in soil movement within the pile sleeve opening. By using the optimal pile sleeve extension below the seabed there could be a reduction in gross mudmat area and thus cost and weight savings for the jacket structure.

8 ACKNOWLEDGEMENTS

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