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Prediction and back analysis of jack-up barge spud pile installation and extraction

Installation of offshore wind turbines – Noordoostpolder – The Netherlands

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ABSTRACT The stratification of the soil in the Dutch Noordoostpolder varies greatly due to geological processes in the last 150,000 years. Both thickness and strength properties of sand and clay layers show large fluctuations. This poses great challenges when analysing vertical-horizontal stability and pile retrieval for a jack-up barge used for windfarm construction. To insure the stability and retrieval of the jack-up barge spud pile analyses were performed for punch-trough, Vertical-Horizontal (VH) stability and retrieval. The risk of punch-trough was assessed for a variety of soil profiles according to SNAME standard. The VH stability of a spud pile depends on both base resistance and lateral soil resistance. Consequently, a 3D Plaxis model was used to determine the interaction between spud pile and soil. For retrieval of the pile the shaft friction and suction at pile tip needs to be overcome. Unfortunately, the retrieval resistance increases with time. This phenomenon is taken into account using a so called set-up factor based on literature. Due to the large variation in stratification and the uncertainty of soil properties, the spud pile load and penetration was monitored during operation. In this paper, the results of the above analysis will be presented. The predicted pile penetration and installation and retrieval forces are compared with the data obtained from monitoring of the spud pile during preloading and retrieval.

1 WINDFARM WESTERMEERWIND

In the larges Dutch lake IJsselmeer, north east of Amsterdam, a windfarm consisting of 48 nos 3 MW-windturbines is constructed, see figure 1. For the installation of the windfarm a 22 by 80 m jack-up barge with 4 spud piles is used. During installation, operation and relocation different forces are active on the spud pile and for each situation the interaction between soil and pile plays a crucial role.

Due to the different objective in each phase and the different forces active during each phase a typical phenomenon of pile soil interaction has to be identified and analysed.

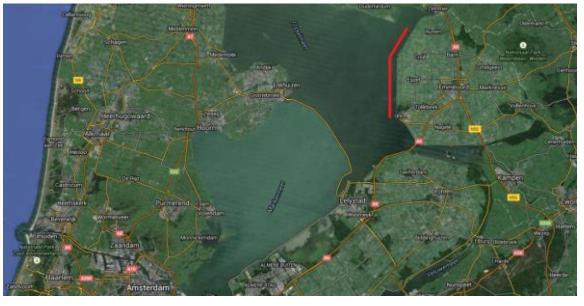


Figure 1. Windfarm Nooroostpolder, The Netherlands.

2 NOORDOOSTPOLDER

During the geological history several processes have been active in the Noordoostpolder. The greatest influence has been the last ice age in the Netherlands, over 150.000 years ago. During the ice age half of the Netherlands was covered with ice, including the Noordoostpolder. The deeper layers are therefore overconsolidated and Keileem (boulder clay) and boulders can be present. Due to the receding of the ice glacier the Keileem layer followed the shape of the glacier tongs. This would explain the presence of a very thick layer of Keileem at one location and the absence of the Keileem layer at another location.

At the start of the Holocene period following the last ice age in Europe (10.000 years ago), the Noordoostpolder was covered with marshes. About 3.500 years ago lakes were formed. During the Middle Ages a connection between the Zuiderzee and North Sea was formed which evolved to a more open connexion at the North-western side of the Zuiderzee. After the construction of the Afsluitdijk in 1932, the Zuiderzee became a lake, disconnected from the North Sea and was called the IJsselmeer. The river systems of the Vecht and the IJssel, East of the Zuiderzee, have also left large deposits in the Noordoostpolder. Due to the many channels of the these rivers gully’s, now filled with silt and clay can be found in the area.

For the foundation engineering of the wind mills Cone Penetration Tests (CPT’s) were performed at each windmill location. The same CPT’s were used in the analyses of the stability of the Jackup barge. From the CPT’s 2 to 3 gully’s can be identified along with several layers of Keileem. In Figure 2 the stratification based on the CPT’s is presented for the approximate 20 km length of the windfarm locations (red line in Figure 1). From the stratification it is clear that subsurface mainly consists of sand. However the CPT’s show that the density of the sand layers can vary greatly.

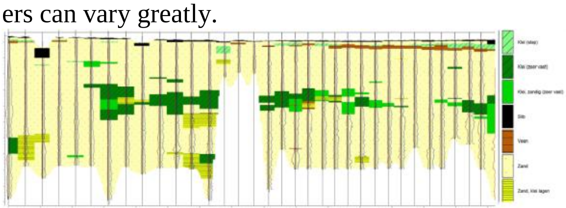


Figure 2. Stratification windfarm Noordoostpolder, The Netherlands.

3 JACK-UP BARGE

For the installation of the windmills a jack-up barge with spud piles will be used. The 22 by 80 meter platform (Figure 3) of the barge is stabilized during operation by four spud piles, one at each corner.

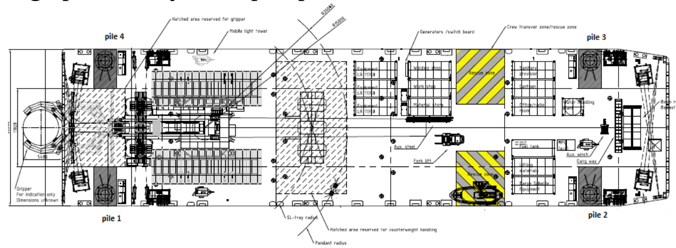


Figure 3. Top view Jack-up barge.

Unlike spud cans, spud piles do not have an enlarged foot and can therefore be compared to a closed ended pile. Per windmill location 3 phases can be identified for the operation of the barge namely; (i) installation phase during which the piles are preloaded, (ii) operational phase during which both vertical and horizontal loads need to be accommodated, (iii) retrieval phase during which the spud pile are lifted out of the ground. Figure 4 illustrates the forces during these three phases at spud level.

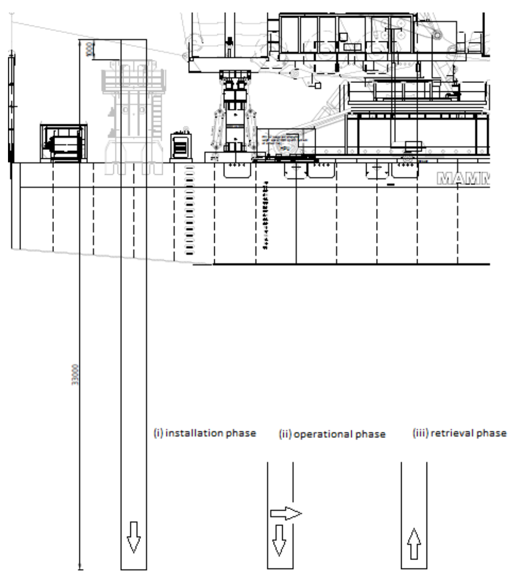


Figure 4. load cases (i) installation phase,(ii) operational phase and (iii) retrieval phase.

4 PREDICTION AND BACK ANALYSIS

4.1 Soil profiles

For the prediction of the stability during installation, operation and relocation 5 soil profiles were selected.

Table 1. .Soil profile

Ground model	Soil profile of the top 12 to 15 m[1)]
GM1	Dense sand 14 m thick
GM2	Medium dense sand, 12 m thick, top 3 m loose sand and clay
GM3	Soft clay underlain by a 4 m thick dense sand layer
GM4	Loose to Medium dense sand with thin clay layers
GM5	Clay 2m thick, then loose sand 4.5 m thickness followed by medium dense sand 2.4 m thickness.

[1)] Below 12 m over consolidated clay and sand are present

Note that GM1 and GM2 are the most common profiles and GM3 to GM5 are based on most unfavorable CPT's.

4.2 Installation phase: Leg penetration

The installation of the legs occurs by applying a preload of 3 MN on each leg. Due to this load the leg penetrates into the soil until it has sufficient resistance. The tip soil resistance was calculated according to the SNAME 2008 standard. However, the SNAME 2008 standard is designed for spudcans (where the footing is larger than the pile diameter) and does therefore not take into account any soil friction along the shaft of the pile. This soil friction causes an additional resistance and can be considered when pile foot is equal to the pile diameter.

The soil resistance with depth curves for each soil profile are presented in Figure 5. From the curves the pile penetration for a preload of 3MN can be derived. For GM1 the penetration is very shallow, and can be considered a lower boundary for the site, whereas for GM 3 a punch through to a depth of 23 m is foreseen. However it should be noted that this soil profile is based on 1 CPT approximately 400 m from the windmill locations.

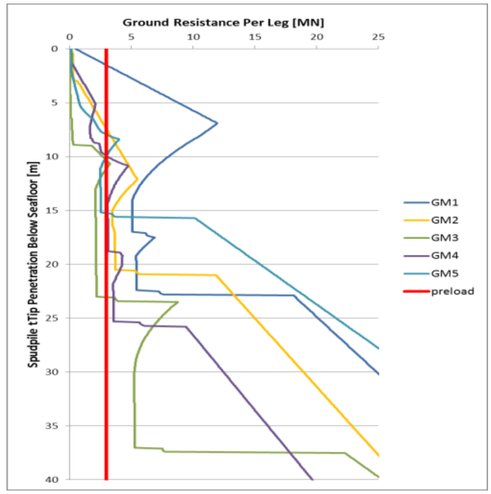


Figure 5. Spud pile penetration curve

4.2.1 Back analysis

The actual penetration in the field was registered for each pile during preload. In Figure 6 the actual pile penetrations have been added to the prediction curves.

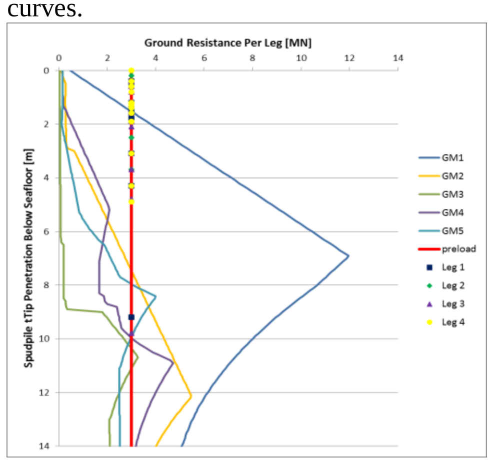


Figure 6. Spud pile penetration curve and registered pile penetration

The registered penetration of the piles are predominately in agreement with the predicted penetration of GM1. This soil profile with dense sand ($\varphi=40^o$) for the top 12 m below sea level can also be found for a large number of the CPT's. Penetration slightly deeper than GM1 is probably due to the difference in density of the sand, less dense, more in line with soil profile GM2. At a large number of locations the penetration is less than the predicted lower boundary of GM1 indicating that the soil is denser than considered in the analyses (φ>40°). At one location 2 legs penetrating deeper than 9 m and are in line with the prediction of soil profile GM4.

4.3 Operational phase: Horizontal stability

During the operational phase the larges horizontal forces will be active. This is mainly due to the crane operations while installing the monopiles for the windmill foundation.

The soil resistance under a combination of vertical and horizontal load is derived from the theory of shallow foundations. (ISO 19901-4, 2003). Here are both the bearing capacity and sliding resistance analysed. However, since the spud pile footing is equal to the pile diameter the calculation of the horizontal soil resistance based on the tip bearing capacity (modelled as a shallow foundation) only, would be a significant underestimation of the horizontal bearing capacity as the resistance along the pile shaft would be neglected.

In order to include the soil resistance along the shaft of the pile an assessment employing the p-y curves according to API RP 2 GEO (2011) was performed to determine the lateral resistance. Combining the results of both analyses (shallow foundation analyses for horizontal tip bearing capacity and p-y curves for lateral resistance) a Vertical-Horizontal (V-H) diagram was compiled for profile GM1, see Figure 7. For horizontal loading profile GM1 was most unfavourable due to the smallest penetration of the piles for this soil profile.

Figure 7 illustrates the factored and un-factored maximum allowable load combinations where safety factors of 1.1 for general shear resistance and 1.25 for sliding resistance are taken into account.

From the diagram presented in Figure 7 it becomes clear that the lateral resistance of the pile is approximately 50% of the total horizontal pile bearing capacity. Therefore a shallow penetration would result in the lowest bearing capacity.

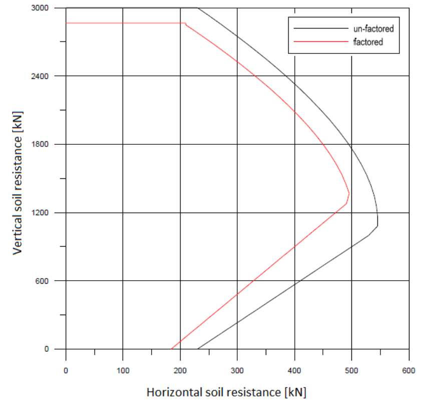


Figure 7. V-H interaction diagram, safety factor 1.1 on the foundation capacity and 1.25 in the sliding resistance.

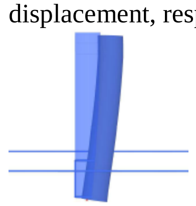
Since the diagram is based on combining two separate analytical models, a conceptual 3D Plaxis (finite element) model was made to analyse the fully coupled behaviour.

In this 3D Plaxis model the following starting points were adopted:

1) The soil was model as medium dense to dense (φ=35°).
2) Pile penetration of 1.7 m.
3) Pile head (almost) rotational fixed.

In the first calculation phase a vertical load of 3 MN was modelled. In the following phase a downward vertical load of 2.3 MN and an increasing horizontal load of 0.25 to 0.6 MN. Note: this is the maximum V-H combination that could be active during operation.

From the analysis the governing failure mechanism can be determined. Figure 8.a and 8.b illustrate the spud pile deformation and direction of the soil displacement, respectively.



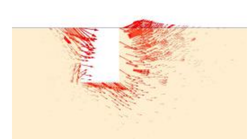


Figure 8.a **Figure 8.b**

Figure 8.a. Deformation spud pile under V-H loading.

Figure 8.b. Direction of displacement of the surrounding soil under V-H loading.

From the illustrations in Figure 8.a and 8.b the failure mechanism calculated using the finite elements can be described as follows: The pile rotates at tip level, pushing more into the soil at one edge of the tip and leaning against the soil alongside the shaft resulting in the development of a shear plane (fig 8.b). When the shear stress becomes too high the shear plane will show failure and large deformations will occur.

This failure mechanism is different from the failure mechanisms calculated with other analytical models used for the V-H diagram. It should however be noted that the development of shear stress under the pile is not large (it take quite extensive deformations to develop shear stress in the finite element model).

However, the Plaxis model shows that there is significant passive soil resistance next to the pile. Therefore an additional horizontal resistance due to the soil next to the pile should not be neglected. Adding the analytically calculated lateral soil resistance to the base resistance seems justified.

4.3.1 Back analysis

During operations only the vertical loads were recorded. To be able to utilize the maximum horizontal soil resistance the vertical load was lowered to 1500 kN, which results in the highest allowable horizontal resistance in the V-H diagram, Figure 7.

Even though the penetrations were shallower in reality than predicted, no problems occurred.

4.4 Relocating phase: Leg retrieval

When the windmill is installed the jack-up barge can move to the next location. The legs are lifted out of the soil and secured for transport. In order to pull the leg out of the soil the shaft friction along the shaft needs to be overcome. In case the pile tip is located in a clay layer an additional downward suction force needs to be overcome. Suction underneath the pile tip in clay occurs because of the lifting of the pile which creates an under pressure underneath the pile tip. This water under pressure will dissipate slowly, depending on the permeability of the soil.

From the penetration predictions it follows that the spud piles will be founded in sand layers. Consequently suction will not occur and only shaft friction needs to be overcome for leg retrieval.

Various literature studies have shown that shaft friction increases in time, see Table 1. This increase in resistance is taken into account with a setup factor, which in literature is shown to be linearly increasing in log time.

Table 1. .Setup factor, literature

Source	Setup factor
Kirsch (2012)	1.5 after 30 days
Jardine et al. (2006)	1.5 to 2.0 after 10 days
Visser et al. (1985)	2.6 for 24 hours

Table 1 shows a wide bandwidth in setup factor. However the situation between the studied cases concerns driven open ended steel piles which are permanently installed, whereas the spud piles and pushed closed ended temporary piles.

For the retrieval analyses the following approach was adopted:

1) Recalculation of penetration depth using a soil-pile interaction coefficient α of 0.0075, which is 1.5 times the value for the penetration analysis (α=0.005).
2) Calculation of the retrieval resistance for two cases, using an α–factor of 0.0075 (setup factor = 1) and an α–factor of 0.015 (setup factor = 2).

This results in a retrieval resistance upper and lower boundary as shown in Figure 9 for soil profile GM2. This is including a pile weight of 40 Tons.

Excluding any mechanical complications or weather delays the barge will be approximately 1 day at each location.

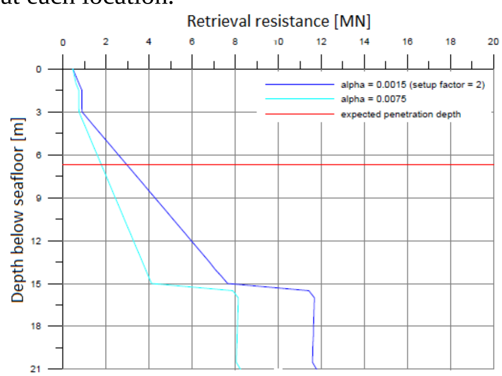


Figure 9. retrieval resistance for GM2, setup factor 1 (lower boundary) and setup factor 2 (upper boundary), including weight of the pile.

4.4.1 *Back analysis*

For leg retrieval a force of generally 0,8 MN (including pile weight) would be necessary, which would be in agreement with shallow penetrations.

At a few locations the retrieval force was 1,2 MN, this would be consistent with a deeper penetration and a setup factor of 1.

5 CONCLUSION

For the stability of the spud piles of the jack-up barge used for the construction of the windfarm in the IJsselmeer close to the Noordoostpolder three load situations have been analysed; (i) installation phase, (ii) operational phase and (iii) retrieval phase.

The predicted pile penetration ranges between 1.7 m and 23 m below sea floor. However, soil profiles GM1 and 2 are based on the majority of the CPT’s and it is expected that the penetrations will fall within the range of 1.7 m penetration for GM1 and 7.5 m for GM2. This is confirmed by the registered pile penetration. There are 2 leg penetrations that show a large penetration greater than 9 m correlating with soil profile GM4. Some leg penetrations are shallower than the lowest predicted penetration of 1.7 m indicating the soil could locally be denser than expected.

For spud piles the soil alongside the pile shaft also provides lateral resistance. Therefore an V-H stability resistance diagram was configured by adding the lateral resistance derived from p-y curves to the tip resistance. This is verified by the fully coupled finite element 3D Plaxis analyses.

For retrieval of the piles the shaft resistance alongside the pile needs to be overcome. Predictions show that the pile tip of the spud piles will likely be in a sand layer. The shaft friction in sand layers increases linearly with log time. However, the bandwidth found in literature is very large. Therefore an upper and a lower bound for the expected retrieval force have been calculated. Monitoring data onsite indicates that the retrieval force falls within the predicted bounds.

In general it can be concluded that in cases where a spud pile is used in areas with large variations in soil conditions such as the Noordoostpolder an upper and a lower boundary should be determined for both leg penetration and retrieval.

In case of the V-H stability of spud piles, the lateral resistance of the spud pile should be taken into account. When only the base stability is considered, the horizontal stability is largely underestimated. This is supported by 3D finite element analyses.

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