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The effect of scour on monopile lateral behaviour

L‘effet d‘affouillage sur la performance laterale des monopieux

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ABSTRACT: A series of centrifuge experiments examining the effect of scour hole formation on the lateral ultimate limit state (ULS) behaviour of monopiles is presented. Model foundation tests were performed at 100 gravities (100*g*) of a prototype pile 5 m in diameter with a pre-scour hole embedment of L/D = 5. The testing schedule saw four separate scour cases - 0.5*D*, 1.0*D* and 1.5*D* local scour (a conical formation around the monopile) and 1.0*D* global scour (a complete loss of embedment). Observations reveal a significant reduction in lateral stiffness and ultimate capacity with an increase in scour depth. In addition design codes are proven to be conservative in their recommendations for dealing with scour. Local $p - y$ curves along the depth of the monopile are presented and exemplify the effects of overburden stresses from soil outside of the scour formation; it would appear that at depth, the effects of scour on soil strength become negligible.

RÉSUMÉ: Une série d'expériences en centrifugeuse examinant l'effet de la formation de trous d'affouillement sur le comportement à l'état limite ultime (ELU) latéral des monopiles est présentée. Les essais de fondation sur modèle ont été effectués à 100 gravités (100*g*) d'un pieu prototype de 5 m de diamètre avec un encastrement avant affouillement de L/D = 5. Le programme d'essais a vu quatre cas d‘affouillage différents - 0.5*D*, 1.0*D* et 1.5*D* affouillement local (une formation conique autour du monopile) et l'affouillement global 1.0*D* (une perte totale d'intégration). Les observations révèlent une réduction significative de la rigidité latérale et de la capacité ultime pour une augmentation de la profondeur d'affouillement. Les recommandations de conception se sont révélées conservatrices dans leurs méthodes de traitement de l'affouillement. Les courbes $p - y$ locales le long de la profondeur du monopile montrent les effets des contraintes supplémentaires provenant du sol en dehors de la formation de l'affouillement; il semblerait qu'en profondeur, les effets de l'affouillement sur la résistance du sol devient négligeables.

Keywords: monopile, offshore, scour, p – y curves, centrifuge

1 INTRODUCTION

The deployment of offshore wind turbines throughout the word is growing at a rapid rate; it is anticipated that the sector will expand from the current 13 GW installed global capacity to around 370 GW by the year 2045 (IRENA, 2016). This presents significant challenges, as well as great opportunities for geotechnical engineers to enhance foundation design and contribute to the drive towards more economical solutions for the offshore wind industry.

To this date, the monopile remains the foundation of choice and this trend is likely to continue provided key logistical challenges (*e.g.* mass-production, transportation and installation) associated with the deployment of larger

diameter monopiles can be overcome. With the enlarged geometries the requirement for design optimisation becomes more apparent, and with this great interest has been placed on the performance under ULS load conditions (*e.g.* Byrne et al., 2015) whereby alternative failure mechanisms for the now more rigid pile behaviour have been identified and introduced into new $p - y$ spring models. The prediction of SLS behaviour associated with long-term cyclic lateral load is also a key theme across literature (LeBlanc et al., 2010; Bayton et al., 2018).

The issue of scour at the mudline, however, has rarely been addressed. DNV GL (2016) guidance indeed states that the "*effects of scour shall be accounted for*", however this has not encouraged significant work in this field despite the apparent gaps in knowledge. An opportunity for design improvements therefore presents itself; one which may eventually lead to foundation cost reduction. This paper presents a series of centrifuge model experiments examining the performance of model monopiles subject to varying scour conditions. The behaviour, both in terms of global moment capacity and local soil stiffness change, is documented.

2 SCOUR AROUND MONOPILES

2.1 Scour assessment

The installation of a large diameter monopile in an offshore environment presents a physical obstacle to the natural flow of water in which it is placed – be it against the prevailing current or waves, or a combination of both – and ultimately leads to a change in the flow pattern in its immediate locality. Phenomena such as flow contraction, horseshoe and lee-wake vortex formation and pressure differentials (DECC, 2008) all lead to the generation of turbulence close to a monopile, thus increasing the likelihood of local sediment transport and the tendency for a local scour formation (see Fig. 1).

The dimensions of a scour hole depend on a number of factors, including sea current velocity, wave height and sea bed material, to name a few (Whitehouse, 1998). A number of methods are available for the prediction of scour hole dimensions in sand, and a comprehensive review of these can be found in Matutano et al. (2013). Conclusions from these have subsequently been adopted in the latest DNV GL design code where an average scour depth (S_d) relative to pile diameter (D) of 1.3, with a standard deviation of 0.7, is recommended when site specific monitoring data is unavailable.

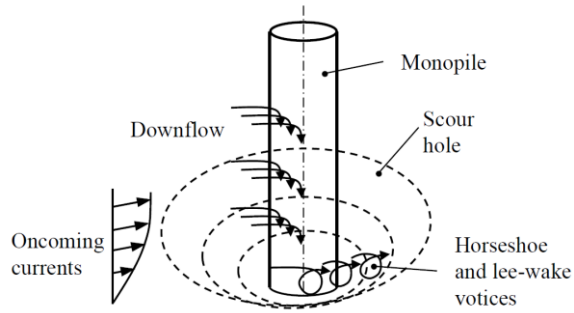

Figure 1. Local scour hole formation

By means of a comparison, Table 1 presents a summary of available scour monitoring data from a selection of existing large diameter monopiles across Europe. Observed magnitudes appear to coincide well with previous predicitive tools, thus providing confidence of their translation across different offshore site locations. The surface layers here consist of medium to very dense, fine to medium-fine grained sands.

Table 1. Summary of full-scale scour monitoring

Wind farm / structure	**Period (mo.)**	***D* (m)**	**S_d/D (-) Mean**	**Max**
Scroby Sands	4	4.2	1.20	1.66
Robin Rigg	10	4.3	1.46	1.79
Pr. Amalia	11	4.0	0.58	1.15
Kentish Flats	36	4.3	0.40	0.48
N7 Sector	60	6.0	0.80	1.05
Otzumer Balje	6	1.5	1.47	-

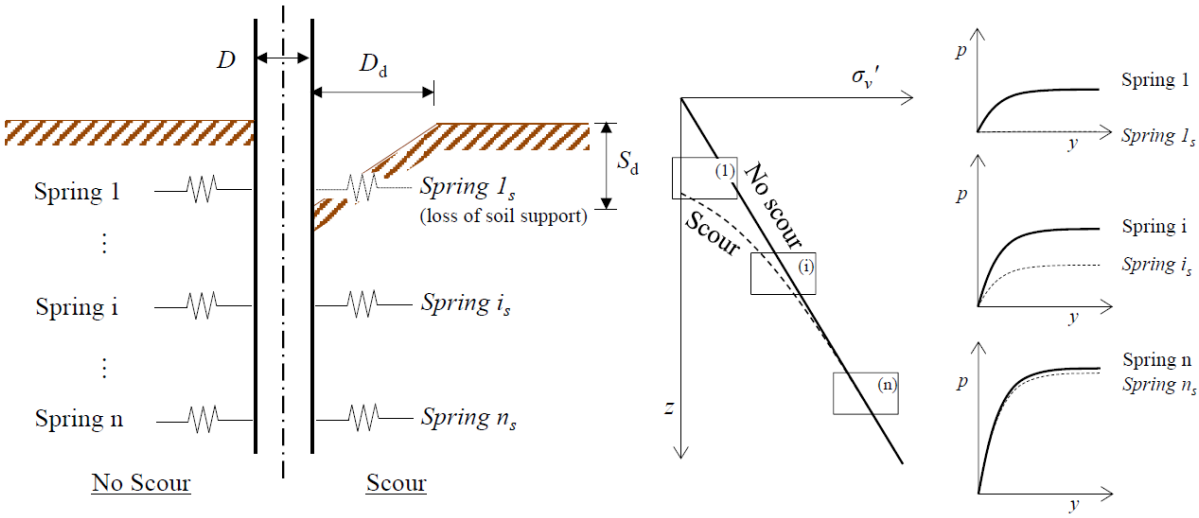

Figure 2. Schematic illustration of variation in effective stress with depth of a scoured monopile

As previously mentioned, recommendations in current DNV GL design are to account for the effects of scour, and two possible solutions present themselves. Firstly by means of mitigation through the provision of scour protection to reduce sediment transport in the immediate locality. Concrete aprons and mattresses are difficult and expensive to install offshore, and therefore rock amour is often dumped around the base of the pile as soon as possible after driving (Herbich et al., 1984). This process in itself is expensive, with typically up to €330,000 worth of rock required at each turbine (Van Oord, 2003). That said there are associated ecological advantages with rock armour solutions, since they can act as artificial reefs for seabed life (Wilson, 2007).

An alternative measure is to allow scour to form and subsequently manage this in pile design, by means of increasing pile embedment (L) to account for the lowering of the mudline in the immediate vicinity. Indeed DNV GL considers this, whereby a new horizontal mudline level is assumed at the base of the local scour and thus a "*complete loss of lateral and axial resistance down to the depth of the scour below the original seabed*" is taken into consideration in design. This inherently presents a highly conservative philosophy, since the effect of overburden stress from surrounding soil outside the scour hole is neglected.

2.2 Implications on monopile design

Given the high cost associated with scour mitigation, in some cases it may be cost effective to allow the scour formation and adjust the monopile design accordingly. In order to be confident of the performance subject to this scour, greater insight of the pile-soil interaction is required to inform accurate and safe design. It is to be noted that this paper will solely concentrate on the implications of scour on ULS performance. Indeed, there are additional challenges associated with pile-soil interaction stiffness changes with scour and the implications on structural natural frequency (Prendegast et al., 2015), however this is beyond the current scope.

As stipulated, in current DNV GL design practice a new horizontal mudline level is assumed at the base of the local scour hole with effects from surrounding soil outside the conical scour neglected, *i.e.* a monopile with 5D embedment experiencing 1D local scour subsequently becomes a monopile with 4D

embedment in design coupled with an increase in load eccentricity. Analyical and empirical models, which provide simple modifications to the original Reese et al. (1974) wedge $p - y$ method, have since proven the conservatisms associated with this (Lin et al., 2014; Qi et al., 2016). These models recognise the additional overburden stresses felt at depth from the soil beyond the scour formation, and the subsequent increases to the effective stress and soil strength that accompany this. Figure 2 provides a schematic illustration of this variation in soil effective stress with depth, and the implications on $p - y$ curve performance.

Proposed predictive models have been derived and validated, both numerically using FEM simulations and experimentally in a geotechnical centrifuge, for flexible pile cases with the magnitude of L/D ranging from 12.5 to 35 and effective pile-soil stiffnesses, K_r, greater than 10^3 ($K_r = E_s L^4/EI$, where E_s is soil stiffness and EI is pile flexural stiffness; Poulos and Hull, 1989). In these cases, failure is governed by excessive pile bending and the majority of lateral soil resistance is developed within the upper surface wedge. Any soil removal here due to scour will therefore have a very pronounced impact on lateral behaviour. However with the recommended design scour depth of 1.3D being only a small length of the total pile embedment, a large proportion of embedded pile remains.

In contrast, for the large diameter monopiles deployed today which have L/D ratios as low as 4-5, a reduction of 1.3D embedment presents a significantly greater percentage of the pile depth and therefore will have a very different impact on performance. That being said, mechanisms of failure for these rigid monopiles are completely different and a greater proportion of lateral resistance is generated from the deep seated rotation and "toe-kick", and it is here where the soil strength remains relatively unaffected.

With this in mind, a series of tailored centrifuge experimental model monopile foundation tests have been performed at the University of Sheffield to explore these uncertainties and to provide insight into large diameter monopile design subject to scour.

3 CENTRIFUGE MODELLING

Experiments were performed at the University of Sheffield's 4m diameter 50g-tonne beam geotechnical centrifuge (Black et al., 2014). The tests were carried out at an acceleration of 100 times Earth's gravity (100g), with stress similitude taken at a depth of 2/3rd embedment of the pile (pre-scour). This was achieved by having a radius to the sand surface of 1.615 m and an angular velocity rotational frequency of 23.5 rad/s. The cylindrical strong box had internal diameter and height of both 500 mm and provided a rigid boundary.

3.1 Sand preparation and model monopile

A fine grained sand, commercially known as HST95 was dry pluviated by hand through a series of meshes at a constant drop height of 750 mm relative to the soil surface to an average relative density (R_d) of 80.7% (standard deviation across test matrix of 0.6 %). After an initial 100 mm thick base layer of sand was pluviated, the model pile was centrally positioned by means of a guide and wire restraint arrangement and then "wished-in place" (WIP) to an embedment L/D = 5 (L = 250 mm). It is recognised that the procedure of WIP installation does not fully reflect the local *in situ* stress changes that may arise during installation in practice.

The ratio of model pile diameter (D = 50 mm) to sand d_{50} (= 0.17 mm) value was equal to 290, well above the limit of 88 for stiff piles outlined in Klinkvort et al. (2013), illustrating no expected grain size effects on pile response.

The model aluminium pile had an outer diameter of 50 mm and wall thickness of 2.8 mm and was the same configuration as used in Bayton and Black (2016), where information of strain gauge preparation and arrangement can be found. The model pile geometry replicated a prototype monopile of outer diameter 5 m with wall

thickness 84 mm. The magnitude of pile-soil relative stiffness, K_r, was 54 which is in line with a typical prototype monopile, and therefore failure mechanisms are expected to replicate those experienced in the field.

3.2 Scour hole formation

The aim of this study was to model the effect of scour on monopile geotechnical performance, not to model its hydrodynamic formation process, and therefore only the accurate and repeatable formation of the final scour shape was desired. A plastic 3D printed outline of the scour hole suitable for each test setup was designed and positioned on supporting legs adjacent to the pile. The support prevented the mould from making contact with the sand surface and thus providing any unneccesary disturbance. Suction was applied to a plastic pipe guided by strategically positioned holes through the mould to lift sand particles from the desired depth and width to generate the scour hole (see Fig. 3). It is noted that the removal of the sand at 1*g* did not allow for the complete capture of its field initial state, since the rebound that occurs after the additional overburden stress of the pre-scour formation removed during the natural scour process is not fully replicated. This, therefore, provided a conservative stress condition in terms of reduced soil strength in relation to prototype condition.

3.3 Experimental setup

The model pile was loaded statically using an 80 mm diameter bore compact double action pneumatic cylinder actuator, capable of providing a maximum load of 5.0 kN. A load cell calibrated over this range was attached between the end of the actuator piston and load arm which interfaced with the pile. Load eccentricity, in relation to the original pre-scour surface, was kept constant at $e = 5D$.

Pile deflection was measured using two Baumer (OADM 12 type) laser displacement sensors directed perpendicular to the pile at two locations (approximately 40 and 140 mm from the sand surface). A GoPro™ camera was mounted to the underside of the loading plate to record image data of soil surface displacement.

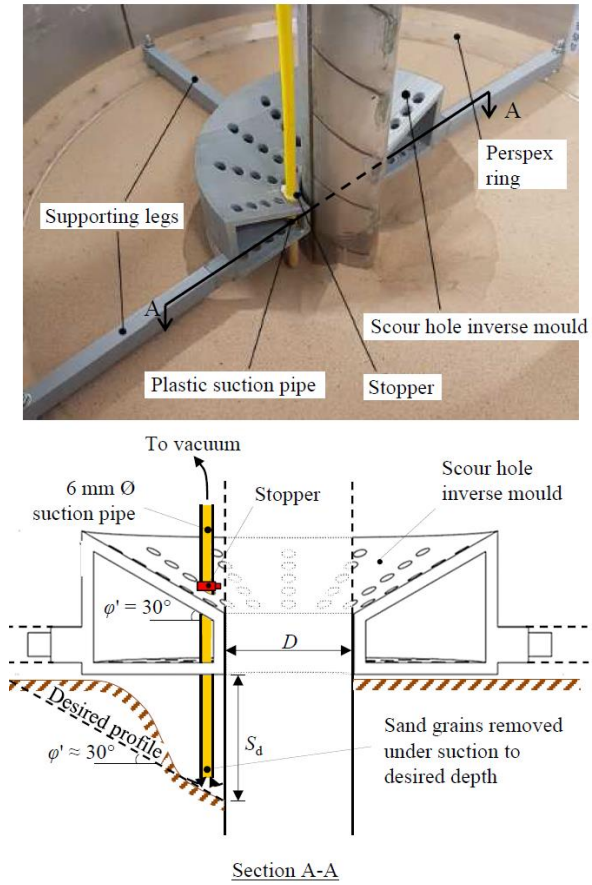

Figure 3. Scour hole formation arrangement

The tesing schedule saw six centrifuge tests conducted at a centrifugal acceleration of 100*g* (see Table 2).

Table 2. Summary of full-scale scour monitoring

Test no.	Description	S_d/D (-)	D_d^*/D (-)
1	No scour	-	-
2	No scour (repeat)	-	-
3	1.0D 'global' scour	1.0	∞
4	0.5D 'local' scour	0.5	0.86
5	1.0D 'local' scour	1.0	1.73
6	1.5D 'local' scour	1.5	2.60

* D_d – Radius of scour hole

4 RESULTS

4.1 Global monopile behaviour

In the following section when examining the global pile behaviour subject to varying scour, the reference point for overturning bending moment and monopile rotation for each experiment is at the same location, this being the original mudline position prior to any scour.

Figure 4 presents the dimensionless moment-rotation ($\widetilde{M} - \theta$) relationships across all the tests. As to be expected, an increase in scour depth results in both a reduction in monopile stiffness and ultimate lateral capacity. As an illustration, at $\widetilde{M}$ = 25.0 (equivalent of a prototype magnitude 258 MNm), the rotation at the original mudline increases by 17, 37 and 117 % for local S_d/D = 0.5, 1.0 and 1.5 respectively. This is in close agreement with numerical estimations of Achmus et al. (2010). Furthermore, it can be seen that at S_d/D = 1.0, the local scour case significantly outperforms the global scour by approximately 50 % in capacity (at $\widetilde{M}$ = 25.0), proving the significant conservatisms present in the current design recommendations.

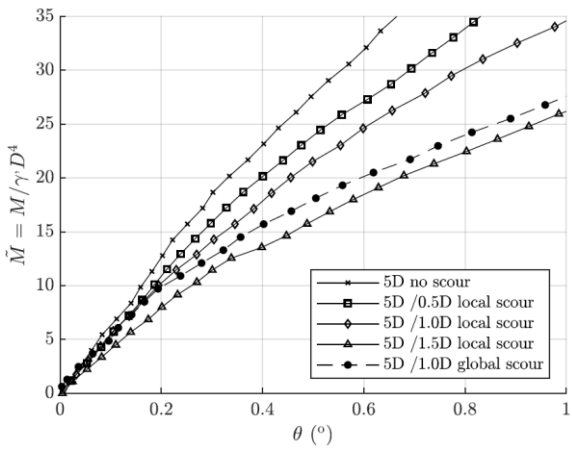

Figure 4. Normalised moment-rotation response

Furthermore, variations in bending and shear profiles are illustrated in Figures 5(a) and 5(b) respectively. For the same normalised applied bending moment taken at the level of the original pre-scour mudline (z = 0), it can be seen that the magnitude of maximum bending as well as the depth to this maxima increases with the increase in scour depth. This is the direct result of the lack of lateral soil restraint where the soil has been removed, effectively increasing the load eccentricity. The increased bending is then maintained across the full depth of the pile until the toe. Direct comparison of the bending moment profiles at both S_d/D = 1.0 scour scenarios reveals much reduced bending for the local case, therefore proving that the soil beneath the base of local scour provides much greater resistance than that for the global case.

Observations of shear force show greater resistance derived at depth for increased scour, and this is particuarly noticeable at the pile toe. With the reduction in effective embedment associated to increased scour, the failure mechanism tends further towards pure rotation which increases the 'toe-kick' phenomenon.

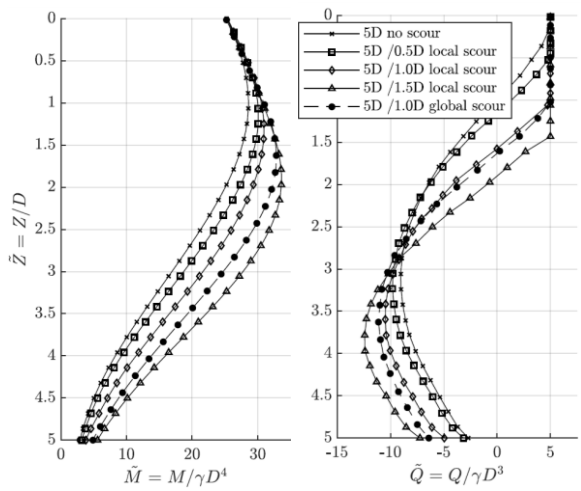

Figure 5. Normalised (a) moment; and (b) shear profiles with depth

4.2 Local p – y curve behaviour

The following section examines the individual p – y curves with depth across the test matrix. These inform of local soil strength and stiffness changes across the test matrix. In previous literature analytical models, it has been shown that the soil strength in close proximity below the

base of the scour hole is most affected whereas deeper soils exemplify similar behaviour to a non-scour scenario. With this is mind, $p - y$ curves are presented in Figure 6 for a selection of absolute depths (*i.e.* taken from original pre-scour surface). It can be seen that for shallow depths, $p - y$ initial stiffness is greatly compromised, however as the absolute depth increases, the individual $p - y$ curves for increasing scour cases begin to exhibit a very similar response. This is exemplified for $z > 2.25D$ where the $p - y$ trends appear to be almost superimposed suggesting no loss of soil strength.

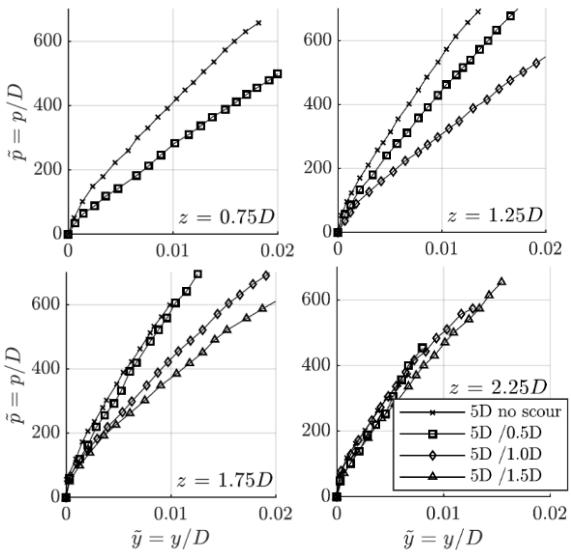

Figure 6. Local p – y curves with absolute depth, z, from original pre-scour mudline

Switching focus from absolute depth along the monopile to relative depth from the base of each individual scour hole ($z_e = z - S_d$), the consequence of surrounding overburden soil stress presents itself more clearly. Figure 7 illustrates the $p - y$ behaviour now in terms of relative position beneath individual scour cases. It can clearly be seen that at the same relative depth, for deeper scour cases, the $p - y$ initial stiffness is significantly greater. This can be attributed to the greater overburden stress from soil surrounding the deeper scour formations. As an example, at a relative depth of $z_e = 0.5D$, the monopile with scour $S_d/D = 1.5$ presents over twice the stiffness of that of a non-scour case. This increase in strength is more pronounced at lower relative depths, however the trend appears to be maintained across the full pile.

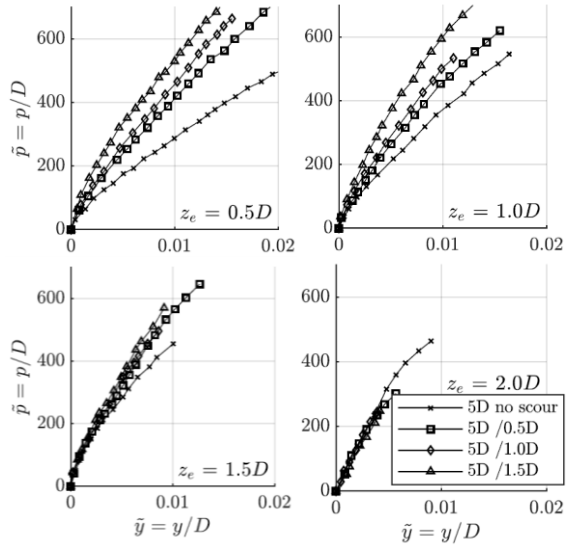

Figure 7. Local p – y curves with relative depth, z_e, from base of individual scour hole formations

5 CONCLUSION

A series of centrifuge model experiments have been performed to examine the effects of scour hole formation on the lateral performance of monopile foundations.

Global moment-rotation observations show a clear reduction in both lateral stiffness and ultimate capacity with increasing scour hole depth. The current design recommendation of a complete loss of overburden stress from the soil surrounding the scour formation (*i.e.* to treat local conical shaped scour in the same manner as a complete global loss of embedment) is found to be very conservative, such that the local scour case with dimension $S_d/D = 1.0$ significantly outperforms the global scour case by 50 %.

Examination of individual $p - y$ curves indeed reveal a reduction in soil strength in the

immediate depths below the base of the scour hole in relation to a non-scour case. However the effects of the overburden stresses associated with the soil surrounding the scour profile become apparent as an increase in strength of the soil with depth is clear, to the point where the effects of scour can be considered negligible at the base of the pile.

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