Scour assessment in complex marine soils – an evaluation through case examples

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Abstract

Scour in cohesionless soils (i.e. sand or gravel) is relatively well understood. The prediction of scour in cohesive or multi-modal soils (i.e. clay, silt, sand/gravel/clay mixtures) is more complex. Typically the scour process is much slower; as a result the effect of scour is very much dependent on the period of time that the structure will remain at the site. This paper describes the application of the Earth Materials approach to estimating scour depth applied to three different case studies. The approach can be applied using information obtained during site investigations but requires good information on soil properties with depth through the seabed. The method relies on previously calibrated formula for stream power at the seabed, which in the original proposed form theoretically allows scouring to continue even beyond the maximum allowable scour depth in some circumstances.

1. Introduction

Scour in the marine environment is a physical process related to the movement of seabed sediment by the flow of water away from a structure. The soil conditions are described by geotechnical parameters, therefore, scour is of a geotechnical nature as it relates to the reduction in ground level around a structure.

For scour in non-cohesive soils numerous methods have been proposed. In cohesive or multi-modal soils the scour process may be dependent on not only the physical properties of the soil but also chemical, electrostatic and other properties as well as biological activity at the seabed and predictive methods are less well developed in this area.

Annandale (1995) proposed an approach to estimating the erosion potential of complex soils through the use of the stream power parameter, P, and its relationship to the ability of the soil to resist scour, defined through an erodibility index, K. The erodibility index provides a measure of the *in-situ* strength of the material, whilst the stream power provides a measure of the rate of energy dissipation in the near-bed region expressed by the following relationship:

$$P = f(K) \qquad (1)$$

If P exceeds the erosion threshold then scouring will occur. The approach was originally developed for looking at scouring of rock spillways, but the methodology applies equally to marine soils (Chapter 10, Annandale, 2006; Nairn and Anglin, 2002). The erodibility index is defined as:

$$K = M_S K_b K_d J_S \qquad (2)$$

Where M_S is the mass strength number; K_b is the block size number; K_d is the discontinuity bond shear strength number and J_S is the relative ground structure number (see Annandale, 2006, for further details). Equation (2) was originally proposed by Kirsten (1982) to characterize how easily earth material can be excavated.

Whilst other methods have been proposed for scour in cohesive soils, it is the approach of Annandale that will be explored further in this paper through the use of available field data. The method has merit in that, theoretically, it can account for changing soil layers and can be applied using typical information obtained during geotechnical field surveys. Three examples will be presented together with a discussion of the results and recommendations on the application of the method.

2. Scour prediction methodology

To use the approach of Annandale for determining the potential depth of scour around a structure requires the use of several relationships and assumptions. This may limit the application of the approach to more complex situations unless supported by information from additional studies such as physical modelling, and without information on the soil properties including their variation with depth, this method cannot be applied.

The seabed soil profile is discretised into $n = 1, \ldots, N$ horizontal planes, according to the soil characteristics at each level (derived normally from the bore hole log). Each layer is assigned a required stream power for erosion P_R. Starting at the surface layer ($n = 1$) the stream power at the base of each layer, P_n, is calculated by applying a standard form of reduction profile:

$$P_n = ae^{-b(S/S_{\max})} P_a \qquad (3)$$

Where:

a and b are coefficients obtained by fitting to data;

S_{max} is the maximum scour depth independently determined;

S is the depth of the base of each layer ($0 < S \leq S_{max}$);

S/S_{max} is the relative scour depth; and

P_a is the stream power at the surface in the absence of a structure.

At the seabed surface S = 0, so $P_1 = aP_a$ (for an infinitely thin top layer) so the coefficient a represents the increase in stream power caused by the presence of the seabed structure compared to the no-structure case. If scour is to occur, $aP_a > P_R$. Assuming that the stream power is equivalent to the product of bed shear stress and flow velocity, hence on the open seabed $P_a \equiv \tau U$, and to first order based on potential flow theory the speed local to a circular pile is two times the ambient value, then also to first order the local enhancement to stream power acting on the surface layer of the soil adjacent to the pile is $P_1 = 2^2 \tau \times 2U = 8P_a$. The coefficient b denotes the rate of reduction in stream power with depth as layers are removed. Based on fitting of Equation (3) to laboratory data Annandale (2006) gives a = 8.95 and b = 1.92 for circular piles, while for square piles *a* = 8.42 and *b* = 1.88. This implies that the increase in bed stream power caused by the presence of square pier is smaller than that caused by a circular one. The values of the leading coefficient *a* are of similar magnitude to the value of *a* estimated based on potential flow theory, i.e. 8.

To evaluate Equation (3) there is a requirement to calculate the maximum scour depth, S_{max}. Determination of the maximum scour depth is assumed to be given by the HEC18 methodology (Richardson and Davis, 2001). This expression is based on an envelope curve that embraces known data of scour depth around bridge piers. The approach is generally considered to be conservative.

$$S_{\max} = 2.0 K_1 K_2 K_3 K_4 h_0 F_r^{0.43} \left(\frac{D_p}{h_0} \right)^{0.65} \tag{4}$$

Where D_p is the pile diameter (m); h_0 is the flow depth (m); K_1 is a correction factor for pile nose shape; K_2 is a correction factor for angle of attack of flow; K_3 is a correction factor for bed condition; K_4 is a correction factor for size of bed material and F_r is the Froude number.

Having determined S_{max} it is possible to calculate the dimensionless scour depth as a function of the lower depth of each sediment layer. Following Annandale's derivation the relative stream power (P/P_a) as a function of depth can be calculated using Equation (3) with the result from Equation (4) inserted.

At the maximum scour depth (layer *N*) the relative scour $S/S_{max} = 1$ so $P_N = ae^{-b}P_a$ which is by inspection smaller than at the seabed. For a circular pile $P_N/P_a = 8.95\ e^{-1.92} = 1.3$. It follows that if $1.3\ Pa > P_R$ then erosion should occur at a depth of S_{max}. For example, if near a circular pile $P_R = 1.2P_a$, then at the surface $P_1 = 8.95Pa = 7.5P_R$ and at the maximum scour depth $P_N = 1.3P_a = 1.1P_R$. In this case we would expect scour to occur at the maximum scour depth, which is unrealistic. Whilst it appears that Annandale must have calibrated with results *for* $P_R > 1.3P_a$ the method is used as published in the current assessment, although an alternative form of Equation (3) that avoids this problem has been derived but is not reported here (paper in preparation).

3. Case Examples

Several examples will be presented for foundations in the marine environment which use realistic input data for metocean and soil conditions. The calculations have been undertaken for a range of site specific circular monopile foundations varying in diameter from 4 m to 4.75 m.

3.1. Example 1

This example is for a sand site and has been used as a 'control' for the methodology. The site in which the monopile is located comprises fine to medium sand with a median grain size, d_{50}, of around 0.2 mm to 0.4 mm. The mean spring tidal range at the site is 2.1 m and the tidal current velocities range from 1 m/s to 1.25 m/s. The significant wave heights that can be expected here are between 0.5 m and 1 m for 10% of the year and 5 m for 1:1 year waves. Waves with a 50 year return period, however, are known to reach 7 m. A peak wave period of 8.2 s was adopted.

Comparing the predictions using the Annandale approach with two commonly applied methods, namely Breusers *et al.* (1977) and Richardson and Davis (2001) (Table 1), the predictions using Annandale and Richardson and Davis give values which would sit either side of the line of exact fit. The method of Breusers *et al.* with a multiplier of 1.5 gives the largest prediction, with some correction for shallow water reducing the predicted scour. However, there is a time-element to the scouring in that the hydrodynamic conditions from a tidal perspective alone are continually changing and it is uncertain as to what conditions had occurred or were persisting at the time of the scour survey. The methods give a range of predicted depths. The approach of Annandale has been applied to a combined wave and current case as well as a current alone case. For all conditions $S/S_{max} = 1$ is assumed to be the limiting condition and, therefore, in the limit, the results from the Annandale method correspond to the predictions of Richardson and Davis (2001).

Table 1: Comparison of scour predictors against measured data

Methodolgy	Normalised Scour depth	
	$S_{predicted}/D$	$S_{measured}/D$
Richardson and Davis (2001) – typical conditions	0.97	1.20
Richardson and Davis (2001) – extreme conditions	1.30	1.20
Breusers et al. (1977) – 1.5 multiplier	1.46	1.20
Annandale (2006) – typical conditions (currents only)	0.97	1.20
Annandale (2006) – extreme conditions (currents only)	1.30	1.20

3.2. Example 2

The example relates to an area of sandwaves on, and in proximity to, a sandbank with a maximum height of around 5 m. The sandbank and sandwaves consist of fine to medium sands deposited in the Holocene period and are found at a depth of between 0 m to 3 m, approximately. Borehole information indicates that the sediments underlying the sandbank to the east and the sandwave features to the west of the site consist of a soft to firm organic rich clay and these deposits are found at a depth of between 3 m to 5 m. The surficial sediments tend to be fine to medium sands (0.125 mm to 0.500 mm) with low organic carbon content due to the relatively strong current speeds that lead to a winnowing out of the fine grained sedimentary and organic particles. From a benthic study of the site the median sediment characteristics have been indicated to be 0.578 mm with a maximum and minimum grain size of 0.642 mm and 0.470 mm, respectively. This suggests the surficial sediments to be coarse grade rather than fine to medium grade. In the present example median grain sizes of between 0.125 mm and 0.200 mm have been used at BH4 and BH8, respectively, based on the sediment sample analysis.

The tides are semi-diurnal and residual surface tidal currents run approximately parallel to the local coastline. The 50 year design conditions indicate the local depth-averaged current for both tidal and wind-driven currents is 1.3 m/s, whilst the wave conditions are a significant wave height of 7.7 m and a mean wave period of 9.7 s.

Borehole data at two locations, BH4 and BH8 show the soil profiles to a depth of 20 m below the seabed to consist of fine and medium sand with a dense or very dense structure (Figure 1). From analysis of the soil test data a clay layer is interpreted at between 2 m and 2.9 m at BH4, although this does not appear in the borehole record. The undrained shear strength, S_u, within this stratum is calculated to be 20 kPa.

From bathymetric survey measurements the scour depth at the monopile associated to BH4 was 2.9 m deep after 301 days from installation of the foundation. At BH8 the scour hole was 2.1 m deep after 270 days from the installation of the associated monopile. The interpreted clay layer at BH4 inhibits the scour development in the prediction to the start of the clay layer, at 2 m below the existing seabed level (Figure 2). From the bathymetric survey data scouring at this location appears to have eroded through the clay layer.

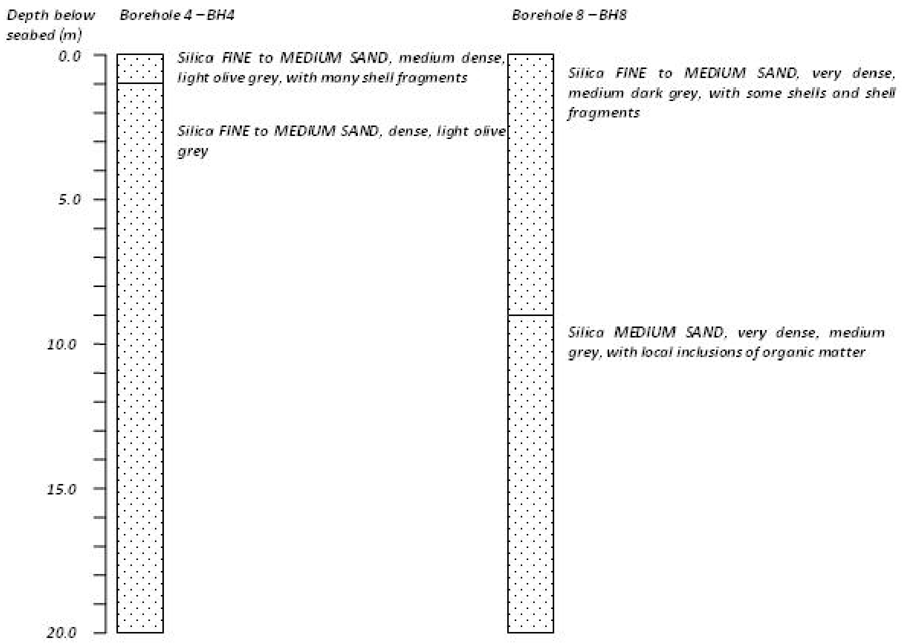

Figure 1: Borehole data for Example 2

An assessment of the scour depth at this location has also been made by applying the SRICOS method (Briaud *et al*., 1999). This approach was developed to predict scour at a cylindrical pier under steady flows, uniform soils and a water depth greater than two times the pier diameter.

$$S_C = 0.00018\,\mathrm{Re}^{0.635} \qquad (5)$$

Where:

$$\mathrm{Re} = \frac{D_p U_c}{\nu} \qquad (6)$$

Re is the Reynolds number, U_c is the depth-averaged current speed, and ν is the kinematic viscosity of water. The formula is independent of soil properties and is considered to represent the maximum possible depth of scour in clay. Therefore, the maximum scour depth is governed by the pile diameter, current speed and kinematic viscosity of the water and it would be expected that as the current velocity increases so the erosive capacity of the flow will also increase.

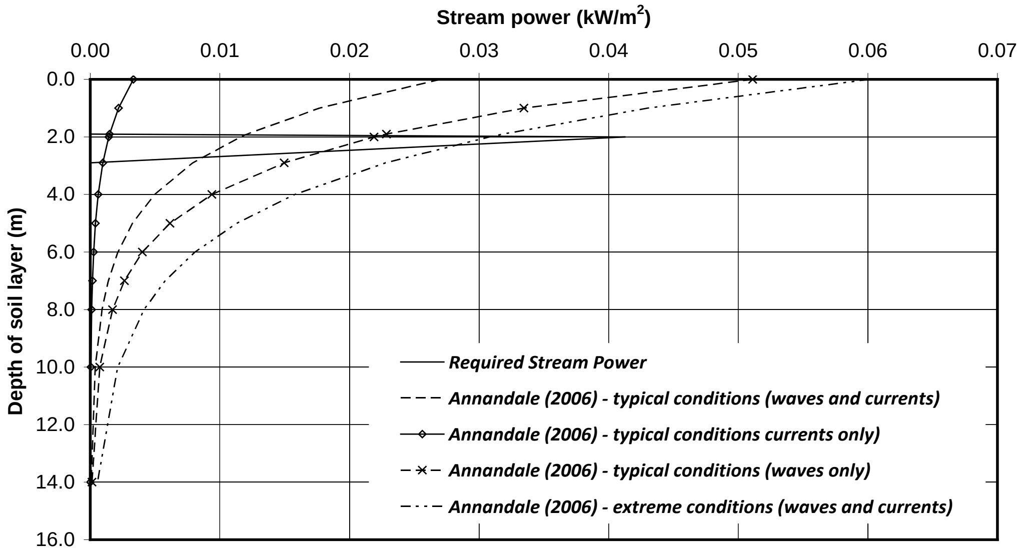

Figure 2: Plot showing the extent of scour for typical and extreme hydrodynamic conditions at BH4

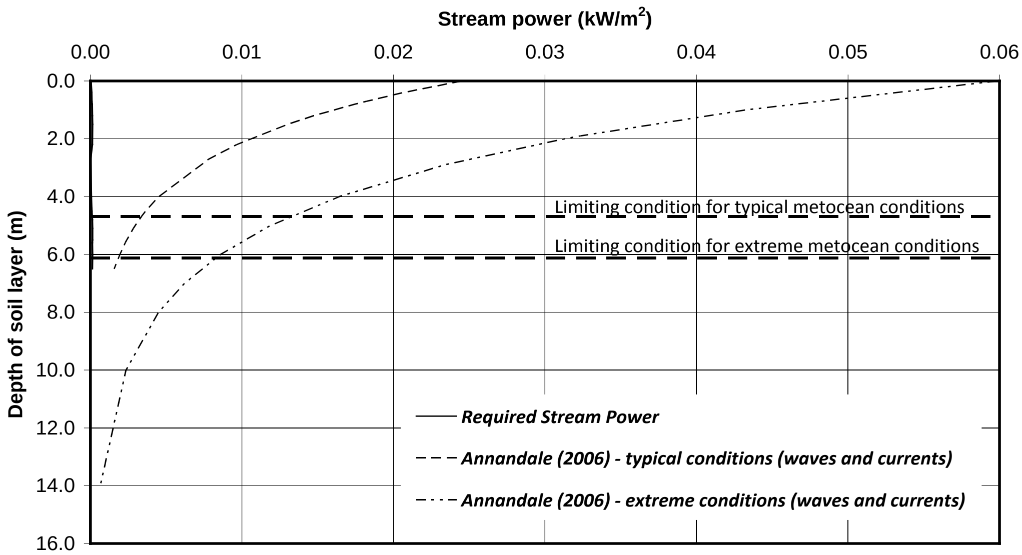

Figure 3: Plot showing the extent of scour for typical and extreme hydrodynamic conditions at BH8 (Example 2)

If we assume that the clay layer at BH4 exists from the seabed level downwards, the maximum predicted scour depth using this approach is between around 2 m to 3 m depending on the hydrodynamic conditions, whereas the using the Earth Materials approach, the stream power is not of sufficient magnitude to get through the clay layer limiting the scour to 2 m or less.

The prediction for scour development at BH8 using the method of Annandale corresponds to the limiting condition of S/S_{max} = 1 (Figure 3). From measurements at the site the scour depth after 270 days is around

2.1 m suggesting either infilling has occurred or that the scour depth is being limited by the geotechnical conditions. However, without knowledge of the metocean conditions existing at the time of the survey, as well as the time history of the metocean conditions that have occurred since installation of the foundation, it is unclear as to whether the scour hole as measured can be associated with typical hydrodynamic conditions at the site.

3.3. Example 3

This example site comprises mainly sand with concretions overlying tillite and clays, and an area where exposures of tillite and clays dominate and the surface sand becomes patchy. The depth of surface sediment reaches 10 m in some parts but this depth includes bedded muddy sands as well as the surface layer of sand.

Geophysical surveys including borehole sampling revealed the bed material at the western side of the site consists of medium dense becoming very dense brown silty fine sand with occasional shell fragments. This layer extends to 10.8 m beneath the surface, with patches of very dense sand and occasional other material, such as coal fragments and quartz granite fine to coarse gravel. The sand at this location is very fine at 1.75 m below the surface, with a significant fraction smaller than 0.06 mm (the boundary between sand and silt). The sand increases in size on going down through the layer. Beneath the sandy layer is a thick layer of stiff, becoming very stiff, slightly gravelly clay with occasional cobbles.

At borehole (BH8 – whilst this is the same nomenclature as in Example 2 it is a different site) the top 3 m of seabed consists of very silty, fine sand. Beneath the top layer of sand is a 6 m deep layer of slightly laminated, slightly sandy clay. Within the clay dominant area of the site some of the borehole data shows a sand veneer extending only around 0.1 m below the surface. Beneath this veneer of sand is another 0.1 m deep layer of very gravelly, sandy clay and underlying this layer is a 6.1 m thick layer, also of very gravelly, sandy clay. Underneath this are alternate layers of sand and clay.

The rectilinear tidal currents over the site have peak spring and neap current speeds reported to be 0.67 m/s and 0.34 m/s. The 1-year return period significant wave height, H_s, is 4.8 m at the offshore edge of the site, with a corresponding peak wave period of T_p = 9.8 s. Based on the analysis of wave statistics a significant wave height of 0.5 m is only exceeded 25% of the time.

Prediction of scouring at BH8 using the method of Annandale gives a scour depth of 2.3 m, approximately, for normal hydrodynamic conditions (Figure 4). From bathymetric surveys of the site the scour depths in the vicinity of the borehole have been shown to vary over time but are typically in the range of 1 m to 3 m (Figure 5). Figure 5 also shows a general change in seabed scour depth over time due to bed erosion and infilling. The clay layer acts to inhibit scouring beneath the upper sand layer as discussed previously by Whitehouse *et al*. (2008).

4. Discussion

Three case examples have been presented demonstrating the application of the Earth Materials approach of Annandale (1995; 2006). The studies represent first order assessments supported with some post-construction surveys of scouring. Uncertainty in scour prediction and assessment arises from a number of factors. These include metocean and soils data, the modelling methods applied, details of the structure and the influence of the foundation installation phase. Methods based on purely sand soils cannot be applied with certainty at those sites where a range of soils are found as they are conservative predicting a maximum scour depth (e.g. Equation (4)), which of course may be appropriate for design.

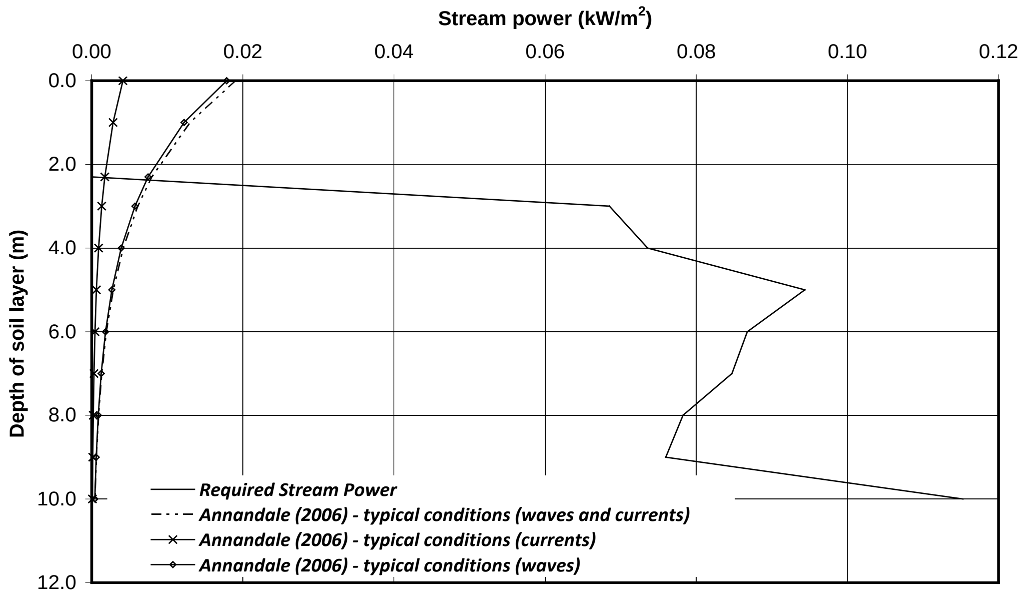

Figure 4: Plot showing the extent of scour for typical hydrodynamic conditions at BH8 – Example 3

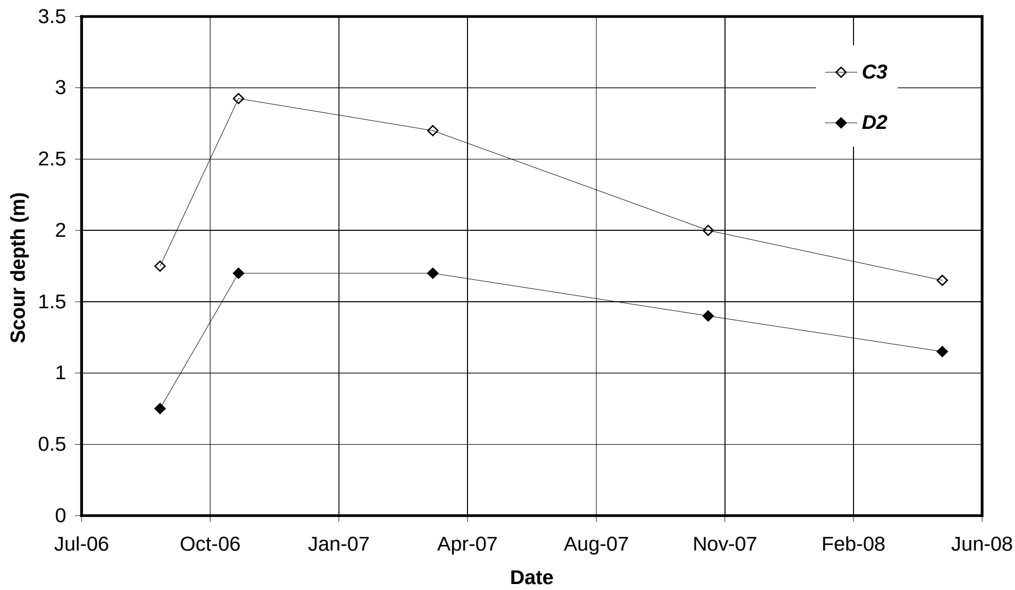

Figure 5: Variation of scour depth over time at two foundation positions

The method of Annandale has great potential for predicting scour in complex marine soils, but to reduce uncertainty in its application requires further detailed testing for a wide range of conditions. For scour assessments in general it is very important to know the surficial soil characteristics and data analysis starting from 1 m below the seabed or deeper in a foundation site investigation may not be representative of the surface sediment properties required for a scour assessment. However, knowledge of the sediment properties below the bed level will be important for predicting scour development with depth through the seabed. The quality of assessment will depend on the number N and thickness of soil layers distinguished and characterised within the depth range to at least S_{max} (Equation (4)). Geotechnical parameters such as SPT blows may be accurate to within ± 25 %, whilst for clays there will be some uncertainty in the values typically obtained as part of site investigations for bed density and vane shear strength, with accuracy in the order of ± 5%. Uncertainty will also arise from spatial variability within and between samples at a given site, and temporal variation in sediment properties. The influence of layering in sandy and silty soils or the presence of a veneer of mobile sediment overlying, for example, stiff clay can be taken into account in the scour assessment if detailed site survey data is available. The rate of erosion has not been evaluated and hence the prediction is of potential depth.

5. Conclusions

Scour is a physical process related to the movement of sediment by the flow of water away from a structure. The soil conditions are described by geotechnical parameters, therefore, scour is of a geotechnical nature as it relates to the reduction in ground level around a structure. Soil mechanics testing provides workable definitions of the complete spectrum of soil types from pure cohesionless sands to clays.

The approach of Annandale (1995; 2006) has been used to assess the scour potential at three contrasting offshore locations. The approach allows for the physical properties of the soil to be considered and although the method does not directly take into account the chemical properties of the material, the mass strength number, M_S, represents the relative influence of chemical bonding properties of the soil through the unconfined compressive strength. The method represents an engineering methodology that can be applied using information obtained during geotechnical site investigations. Key considerations for application include:

- The requirement for good information on the soil properties with depth through the seabed, including grain size distributions, density, undrained shear strength, internal angle of friction, etc from the seabed surface to the depth (at least) of S_{max}.
- Knowledge of the metocean conditions for both typical and extreme events.

Furthermore:

- The method relies on previously calibrated formula for the stream power at the seabed P_1 and shape of the curve P_n with depth in the soil. The curve retains values of $P_N = 1.3P_a$ at the base of the scour hole at depth S_{max} and theoretically scouring may continue (if $P_R < 1.3P_a$). Hence an alternative approach is to solve for $P_R = P_N$ at $S/S_{max} = 1$, which is being considered by the authors elsewhere (paper in preparation).
- The determination of the development of scour through time in complex marine soils requires further research, especially for soils with multi-modal grading distributions and with distinct layering.
- It is important to determine any adjustment to soil properties that might occur during foundation installation that could affect resistance to scouring.

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