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CENTRIFUGAL MODEL STUDY OF SPUD-CAN PENETRATION IN LAYERED SOIL DEPOSIT

ETUDE DE MAQUETTE CENTRIFUGE POUR PENETRATION DE CAISSON DE SUPPORT A TRAVERS DEPOTS STRATIFIES

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SYNOPSIS : Results of a series of twelve continuous penetration tests with three sizes of model footings carried out on a medium-sized geotechnical centrifuge at an acceleration level of 80 g are presented. The experiments simulate the penetration of spud cans of offshore drilling rigs in deep beds of sand and stratifed deposits involving sand layers of different thicknesses overlying clay. The limited parametric study indicates the possibility of a punch-through of the footings when the thickness of the surface sand layer is less than around 1 to 1.5 times the footing diameter. For larger sand thicknesses, the peak resistance would occur below the sand surface. At deep penetrations, the sand plug formed below the footing is found to have a marked influence on the penetration resistance. The experimental data have underscored the need to develop a plausible failure mechanism and a computational model consistent with large deformations.

INTRODUCTION

Jacket-type drilling rigs used for oil exploration in offshore areas are jacked up above the water level against the weight of the hull which may be ballasted with sea water. In order to ensure safety of the rig under offshore environmental conditions, the footings of the legs, called the spud-cans, are load-tested prior to commencement of drilling operations with the specified proof load which is higher than the normal operating loads. Since the rigs generally have legs of fixed length, problems arise during installation in stratified offshore deposits.

If a soft soil underlies a hard stratum, the resistance to leg penetration in the upper layer may, at some depth, suddenly show a tendency to decrease with penetration due to the influence of the underlying soft layer. Consequently, the rig will undergo faster rates of penetration leading to uncontrollable, often catastrophic, settlements. In offshore parlance, this phenomenon is known as "punch-through".

For smooth and successful installation of a rig it is necessary to have a reliable and accurate estimate of the variation of penetration resistance of the spud-cans at any given location. An accurate prediction helps in anticipating possible events like punch-through during penetration, and more importantly, it would be possible to judge if at all it is possible to jack up a given rig at a particular location.

CURRENT METHODS OF ANALYSIS

Two methods of analysis are presently in use for this problem. The first method is based on the concept of stress distribution and the applied load on the footing is considered distributed over an imaginary footing of larger size at the interface. The relative increase in the size of the loaded area is obtained by assuming an arbitrary angle of dispersion at the edge of the real footing. The recomendations made by various authors in respect of the angle of dispersion do not take into account either the relative stiffnesses of the two soils involved or the range of depth, in relation to the footing size, at which this mechanism is valid. Moreover the failure modes observed in experiments do not correspond to those associated with an enlarged loaded area at the interface. The second method of analysis proposed by Hanna and Meyerhof (1980) considers penetration of a truncated pyramidal block of sand into the underlying soft clay. It is believed that at failure, the block of sand expands laterally giving rise to a passive pressure on its vertical sides. However in the absence of a properly defined mechanism of failure during footing penetration, the numerical computations cannot be expected to yield reliable estimates of failure loads.

REVIEW OF PREVIOUS WORK

Attempts have been made by several research workers to conceptualise the failure mechanism through laboratory experiments. Dembicki & Odrobinski (1973) have indicated the development of considerable heave at the level of the sand-clay interface for sand thicknesses of about twice the foundation width. Tcheng (1957) and Vesic (1975) observed the formation of a sand plug with vertical sides below the footing.

In recent years centrifuge modelling has been used to study this problem. Model footings were tested by Herdy & Townsend (1983) on sand overlying clay at acceleration levels of 20 to 50 g. They observed heave of clay over an area of 5 footing diameters. James & Tanaka (1984) and James and Shi (1988) have reported centrifuge tests on a dry sand bed. They observed reduction of bearing capacity compared with 1-g model possibly due to dilatancy of sand at field stress levels.

Craig & Chua (1991) have summarized the work done at the University of Manchester, U.K. on penetration of spud-cans of jack-up rigs. It was noted that for small penetrations upto about 0.25 B in sand, the observed bearing pressures were approximately in agreement with those computed using Hansen's bearing capacity factors for shallow footings.

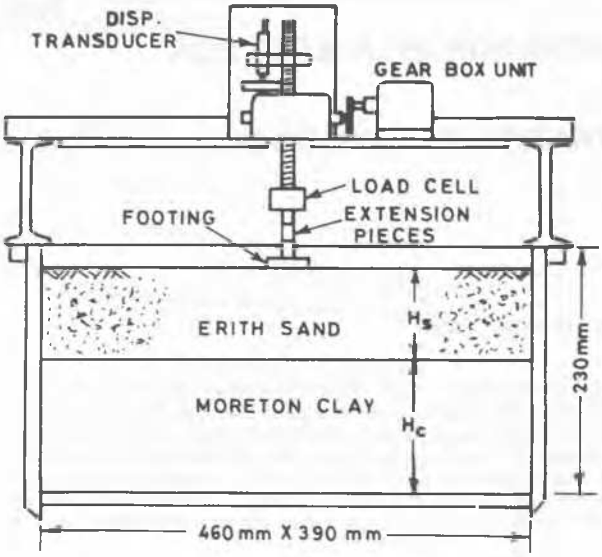

Fig. 1 : Model arrangement in centrifuge basket

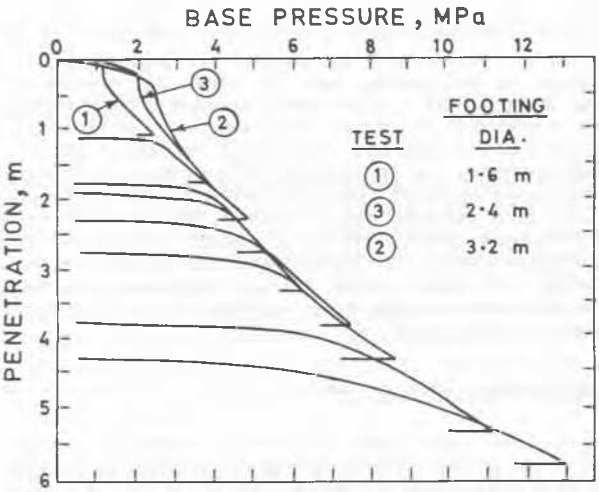

Fig. 2 : Prototype results for model footings on sand at 80 g.

In clays, the predicted ultimate loads showed a reduction of 8-15% relative to the observed data.

In tests involving sand overlying clay, the Hanna and Meyerhof method of analysis was found to predict lower bearing pressures. It was suggested that a more realistic value of failure load at deep penetrations may be obtained by including the shear resistance on the confined sand plug which moves with the footing and also an equivalent depth which takes into account the non-horizontal upper and lower boundaries of the sand stratum.

The review of the available information on this problem indicates that firstly there is a need for developing a plausible mechanism of failure during continuous penetration of footings in stratified soil deposits. It should then be possible to develop appropriate computational procedures for prediction of penetration resistance with depth.

EXPERIMENTAL STUDY

To clarify certain ideas about the resistance to continuous penetration of footings in two-layered soil deposits involving sand overlying clay, a series of model tests was carried out in a medium-size centrifuge in the University of Liverpool. U.K. A description of the centrifuge is given by King, et al. (1984). The machine essentially consists of two buckets, 390 mm x 460 mm x 230 mm deep, hinged at the ends of a revolving arm at an effective radial distance of 1.16 m. Acceleration levels of about 200 g could be attained at 400 rpm. Model footings, 20 mm, 30 mm and 40 mm in diameter and 10 mm in thickness were used with roughened base and sides. The thickness of the upper sand layer was varied between 40 mm and 120 mm giving sand thickness to footing diameter ratios, Hs/B, in the range of 1 to 6. At the acceleration level of 80 g used in the experiments, the corresponding prototype dimensions are as given in Table 1.

Moreton clay having liquid limit of 42 and plasticity index of 24 was carefully placed and hand-compacted in small quantities at an average water content of 20.7%. The clay as placed had a bulk unit weight of 21.16 kN/m^3 and degree of saturation of 85-90%. Under undrained conditions, the shear strength parameter c_u was 31 kPa and angle of shearing resistance ϕ_u was about 10° to 15°.

The upper layer of required thickness was built up by vibrating thin layers of dry Erith sand with the help of a hand-held vibrator. The sand is fine-grined and uniform, having an effective size of 150 microns and uniformity coefficient of 1.5. About 80 per cent by weight had prticle sizes between 150 and 250 microns. The unit weight of the sand when compacted was around 16 kN/m^3 corresponding to a relative density of 76%.

The model footings were placed on the sand surface and continuous penetration during flight was achieved by means of a gear box unit, as shown in Fig. 1, giving an effective model penetration rate of 0.5 mm per minute. The experiment had to be done in several stages on account of limited travel of 20 to 25 mm of gear box-transducer assembly. The results of 12 tests for the three selected model footings are shown on Figs. 2 to 5. The enveloping curves for all the stages in each test are also shown. The data are summarised in Table 1.

RESULTS AND DISCUSSION

Penetration In Deep Bed of Sand

Three tests were carried out for prototype footing diameters of 1.6 m, 2.4 m and 3.2 m in 16.8 m deep bed of dry sand. The observed base pressures during continuous penetration are shown in Fig. 2. It is seen that at relatively shallow penetrations, the base pressures are larger for larger footing diameters, but at greater depths, the curves are indistinguishably similar. This shows that footing size influences ultimate bearing capacity only at shallow depths, but at deeper penetrations, the predominant effect is that of surcharge which is independent of footing dimensions. Computations made using Meyerhof's bearing capacity factors gave good comparison with experimental results for shallow depths but were 25 to 30% higher than observed bearing pressures at deeper penetrations. A friction angle of 42°, considered reasonable for the dry, Erith sand at 76% relative density, was used in the computations. It should be appreciated, however, that considering the various

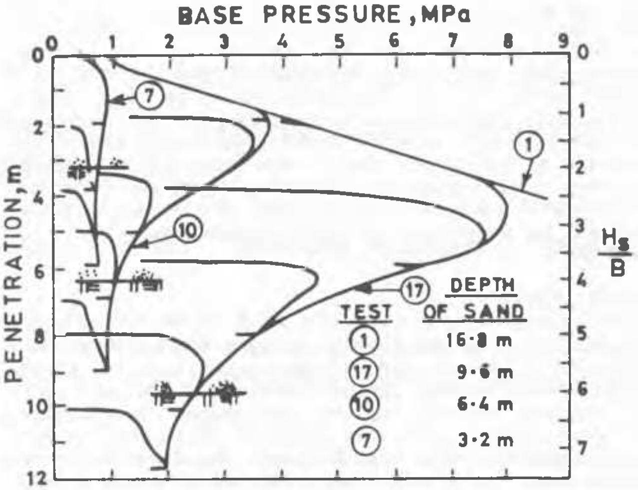

Fig. 3 : Prototype results for 20 mm dia model footings at 80 g.

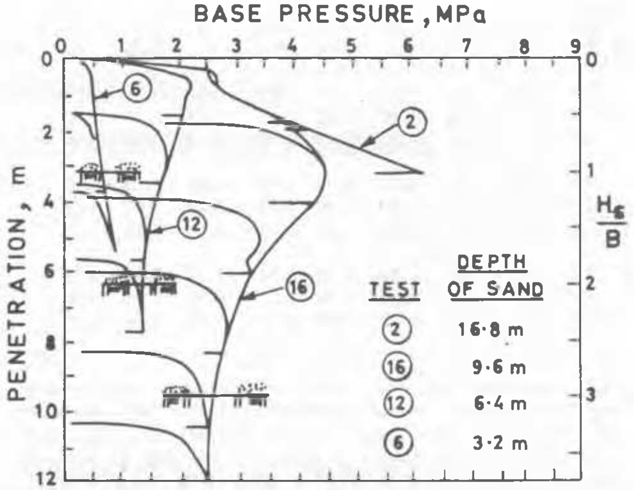

Fig. 5 : Prototype results for 40 mm dia. model footings at 80 g.

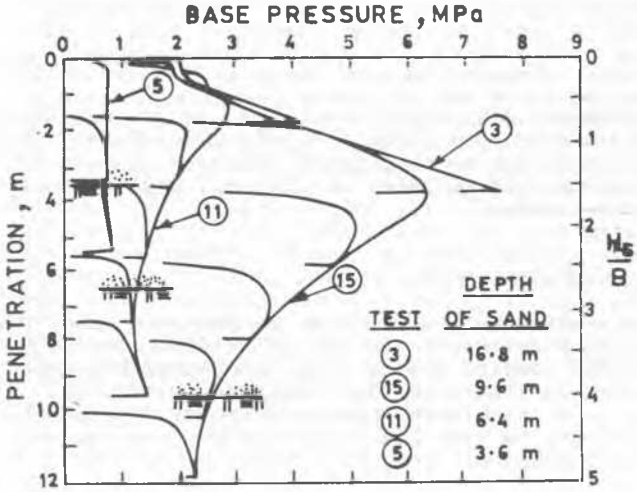

Fig. 4 : Prototype results for 30 mm dia model footings at 80 g.

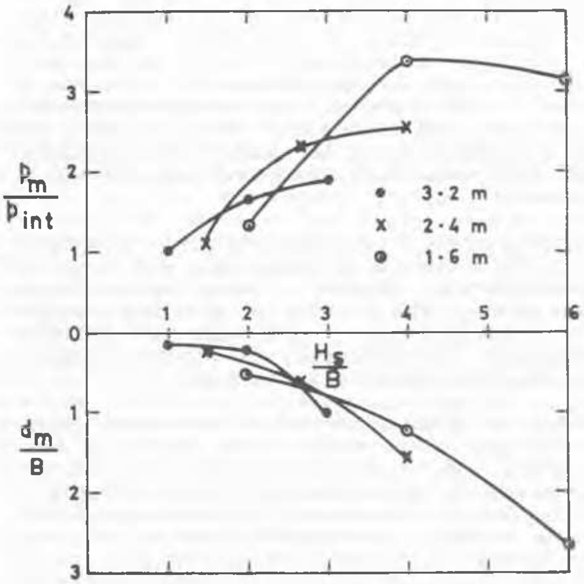

Fig. 6 : Variation of p_m/p_{int} and d_m/B with H_s/B.

basic phenomena that influence the shear strength of sands, the choice of an appropriate value of friction angle in a given situation is at best a matter of individual judgement. While the dilatant behaviour and effect of rate of shearing could be important aspects of material characterisation, what appears to be more pertinent in the present problem is the influence of the flow of soil below and around the footing on the failure mechanism during the process of continuous penetration. Once the failure mechanism is properly understood, it should be possible to develop an appropriate computational model in which the change in friction angle occurring as a consequence of large deformations is suitably incorporated.

Sand Overlying Clay

Results of experiments carried out with model footings corresponding to prototype diameters of 1.6 m, 2.4 m, and 3.2 m on sand beds of thickness varying between 3.2m and 9.6 m overlying clay are shown in Figs. 3 to 5. The salient numerical data from these tests are tabulated in Table 1 for reference.

The curves depicting variation of penetration resistance with depth observed in the tests indicate a common pattern. In beds of sand overlying clay, the resistance increases with penetration in a way similar to that in a deep layer of sand. But at some depth, d_d, below the surface, the rate of increase of resistance diminishes with penetration and a peak resistance, p_m, is observed at depth, d_m. Thereafter the base pressure continuously decreases to a value, p_{int}, when the base of the footing has reached the interface. With further penetration into the underlying clay, the base pressure will have the magnitude, p_f, corresponding to the maximum penetration, d_f.

Table 1 : Summary of experimental data (Prototype dimensions)

B m	H_s m	d_d m	p_d MPa	d_m m	p_m MPa	p_{int} MPa	d_f m	p_f MPa	h_{pl} m
3.2	9.6	1.6	3.7	3.32	4.58	2.55	12.16	2.55	2.16
3.2	6.4	0.14	1.0	0.80	2.24	1.35	7.88	1.44	2.14
3.2	3.2	0.0	0.0	0.51	0.53	0.73	5.82	1.00	2.72
2.4	9.6	2.4	5.0	3.81	6.33	2.50	11.88	2.33	1.44
2.4	6.4	1.0	2.6	1.50	2.90	1.25	9.46	1.42	1.80
2.4	3.6	0.0	0.0	0.60	0.79	0.73	5.39	0.89	1.76
1.6	9.6	1.8	4.0	4.30	7.90	2.50	11.76	2.10	1.04
1.6	6.4	1.3	3.3	2.00	3.70	1.10	8.96	1.06	1.00
1.6	3.2	0.0	0.0	0.86	0.97	0.73	5.96	0.84	1.24

At the conclusion of each test, observations were made of the size of the conical depression on the sand surface around the shaft, the heave of the surface of clay and the geometry of indentation in clay formed due to footing penetration. By making a vertical cut along the diameter of the indentation, the averge depth and shape of the sand plug below the footing were noted.

When the footings are penetrating the clay layer, the penetration resistance may be computed using the bearing capacity theories applicable to clay. Skempton's bearing capacity factors N_c, for instance, may be used for saturated clays under undrained conditions. In the present experiments, however, the degree of saturation of the clay at placement was about 85 to 90%. For this condition it was considered appropriate to use undrained shear strength parameters in the analysis. Computations made with ϕ_u equal to 10° to 15° and c_u equal to 31 kPa yielded ultimate bearing pressures which compared reasonably well with the experimental data.

The depth, d_d, at which the resistance-depth curve deviates from that of the deep bed of homogeneous sand is related to the sand thickness relative to footing diameter. From the values given in Table 1, it may be noted that for H_s/B equal to 6, the ratio d_d/B is 1.125 while for H_s/B equal to 2, the ratio is zero. However, the values of d_d given in Table 1 may be considered as approximate.

For planning the jacking-up operations, the important inputs are the estimates of the maximum base pressure, p_m that can be develop and the corresponding depth, d_m, and also the base pressure at the interface, p_{int}. The plots of p_m/p_{int} and d_m/B against H_s/B are shown in Fig. 6. It may be noted that as the thickness of the sand layer relative to footing diameter increases beyond about 1 to 1.5, the general trend is for higher values of p_m and d_m. But when H_s/B is less than about 1 to 1.5, the ratio d_m/B is very nearly zero indicating maximum resistance at very small penetrations. The corresponding ratio p_m/p_{int} is close to unity, which implies that the peak resistance can be only slightly greater than the expected resistance when when the base of the footing has reached the sand-clay interface. Thus for relatively thin sand layers, the footing tends to vertically punch through without load dispersion. A similar trend was also observed by Tcheng (1957).

The observations made at the conclusion of each test showed that a dense sand plug developed below the footing and moved integrally with it into the clay. The diameter of the plug was slightly larger than the footing doameter at the level of the base, decreased downward to nearly the footing size and had a capsule-shaped bottom. The average heights of the plugs, h_{pl}, observed in the various tests are given in Table 1. The average ratio h_{pl}/B for all the tests is approximately 0.7. It may be visualised that in a deep bed of dense sand, the sand plug is formed below the footing at shallow depths of penetration. But if the sand layer is of small thickness, the whole thickness of the layer would separate itself out from the surrounding sand and thus form a plug that descends into the clay. This is what seems to occur at H_s/B less than 1 to 1.5. A consequence of a sand plug of finite height moving integrally with the footing is that the failure load would need to be computed as the failure load at the level of the base of the sand plug. Appropriate allowance should be made for the frictional resistance on the sides of the plug and the footing in the penetration resistance computations.

CONCLUSIONS

The results of the experiments indicate the following conclusions : (1) In deep beds of sand, computations based on Meyerhof's bearing capacity factors compare well with the observed bearing pressures for shallow penetrations. At deeper penetrations, the computed values are 25-30% higher than the experimental values, indicating the need to incorporate the effect of large deformations in the computational model. (2) In stratified deposits involving sand over lying clay, the punch-through phenomenon sets in when the sand thickness is less than 1 to 1.5 times the footing diameter. For larger thicknesses of sand layer, the peak resistance occurs below the sand surface. (3) For the range of depth ratios H_s/B and the sand and clay used in these tests, the average height of sand plug formed below the footings is about 0.7 times the footing diameter. (4) Since the sand plug moves integrally with the footing, it is necessary to consider appropriate frictional forces on the sides of the plug and footing and the bearing pressure at the level of the bottom of the plug in the estimation of penetration resistance. (6) Further work is required to develop methods for determining the magnitude of the peak resistance to penetration and the depth at which the peak resistance may be expected.

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