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CASE HISTORIES PAPER
JACKUP RIG SPUD CAN PENETRATION: A 6,000 TON LOAD TEST

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ABSTRACT

One of the most exciting geotechnical problems for the offshore engineer is the prediction of mobile jack-up rig spud can penetration. Jack-up drilling rigs are used to drill offshore oil and gas wells in water depths up to about 100 m. The rigs are supported by circular "spud can" foundations fitted at the end of extendable platform legs. Upon arrival to the site the jack-up extends the legs to the sea floor and self-elevates out of the water. This action forces the spud cans into the seabed until soil capacity is attained. Prior to jacking the rig out of the water, a geotechnical borehole is made from the rig to verify soil conditions and estimate bearing capacity and leg penetration. The geotechnical engineer makes predictions of foundation capacity in real time; the predictions are then verified by the actual behavior of the footing under the 6,000 ton preload. This paper presents experience with bearing capacity predictions versus field measurements from over 15 offshore sites. Relatively simple closed form bearing capacity formulas are shown to provide good predictions for real behavior of these large scale foundations.

INTRODUCTION

Offshore geotechnical engineering is one of the most exciting fields in our profession. The combination of unusual soil conditions, extreme loadings, and challenging structures offer unique opportunities to test the limits of our understanding of foundation behavior. A good example is the case of mobile jack-up rigs. Jack-ups are large, self elevating platforms used to drill offshore oil and gas wells (Fig. 1). These rigs are the backbone of shallow water petroleum development, used world wide to complete wells in water depths up to about 100 m (300 feet). The units provide a completely self sufficient drilling system, from the physical drill works and mud system to pipe storage and accommodations for the drill crew and support staff. The advantages of the system are clear; these self contained drilling factories can be mobilized to any area of the world to provide high quality economic well installation.

Mobile jack-up rigs are essentially a floating barge equipped with extendable "legs". The hull of the rig is usually triangular, with one extendable leg at each corner of the hull. The rigs are of the order of 30 to 50 m in plan dimension, with total weights of the order of 100 MN (11,000 tons). The legs are 100+ m long, and are equipped with a circular "spud can" at the bottom. Dimensions of the spud cans vary from rig to rig, but they are often of the order of 14 m diameter (46 feet). The spud cans have a conical point to increase horizontal restraint at sites with small penetration (Fig. 2). When the legs are extended to the sea floor the spud cans act as temporary foundations for the structure, providing both vertical support and horizontal and moment restraint against wind and wave loadings.

Fig. 1. Jack-ups are large, self elevating platforms used to drill offshore oil and gas wells.

Operationally, the rig is towed to the site by tugs in floating mode, with the legs retracted. When the rig is in position the legs are lowered and the vessel is "jacked up" out of the water. Extending the legs forces the spud cans into the seabed until sufficient soil capacity is attained. During leg penetration the foundation has a factor of safety of one (soil at failure). To provide a sufficient factor of safety for rig operation, the foundation is preloaded by adding sea water ballast in special tanks within the hull. The foundation is preloaded to about 1.5 times the expected operational load. Typical preloads are of the order of 40 MN (4,000 tones). The ballast is then discharged and drilling can commence.

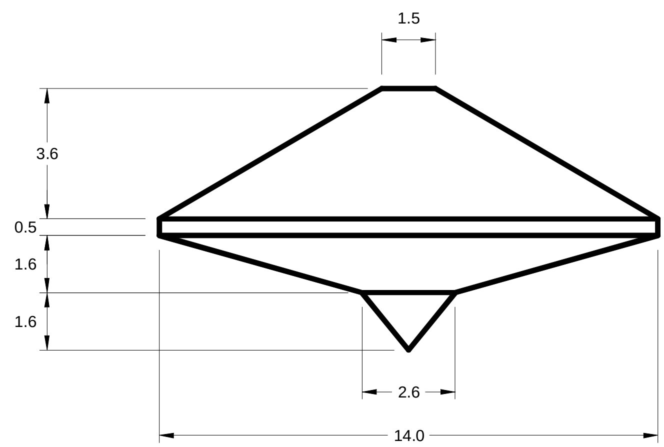

Fig. 2. Typical example of spud can vertical section. Measures are in meters.

The process is very interesting from a geotechnical point of view. Consider the spud can foundation as it is being jacked into the seabed. At initial touch down the soil bearing capacity is less than the reaction force applied by the drill rig. The spud can penetrates the soil, causing failure and plastic flow of the underlying soil. At some point the soil bearing capacity is sufficient to resist the applied load, and the rig begins to lift out of the water. Due to the very soft soil conditions offshore penetrations of 10's of meters are not unusual.

Fig. 3. A view of the drill floor of a jack-up rig during building of the drill strings, previous to start sampling.

The geotechnical challenge arises when there are non-uniform soil conditions. The most critical examples are cemented strata, or layers of sand underlain by soft clays. In this case the bearing capacity of the spud can on the strong layer is significantly greater than the capacity if it is founded on the underlying soil. If the capacity of the strong layer is exceeded during the loading, the footing will punch through the strong layer and penetrate rapidly into the soft formation. When the speed of penetration exceeds the jacking rate, the rig tilts and the leg is overstressed. In extreme cases punch through can lead to overturning of the rig.

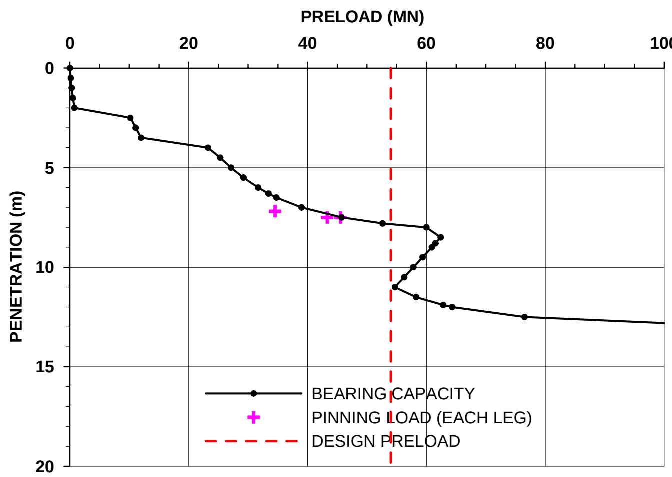

Fig. 4. Example of prediction of leg penetration curve.

Prior to jacking the rig out of the water, a geotechnical borehole is made from the rig to verify soil conditions and estimate bearing capacity and leg penetration. The primary goal is to check for risk of punch through. The boring is made using the rig draworks. Sampling is conducted using the wireline tools operated through conventional 5½ inch API drill strings (Fig. 3). The geotechnical engineer makes predictions of foundation capacity on board in real time (Fig. 4). These predictions are then verified by the actual behavior of the footing under the preload. This paper presents experience with bearing capacity predictions versus field measurements from 15 offshore sites, which locations are shown in Fig. 5.

METHODOLOGY FOR SPUD CAN PENETRATION ANALYSIS

The geotechnical analysis of the spud can foundation is straight forward. The vertical bearing capacity of the spud can foundation is evaluated considering a number of possible penetration depths, and the resulting curve of foundation capacity versus leg penetration is plotted. The planned preload is compared to the predicted capacity to determine the expected penetration depth. Punch through risk is assessed by checking the resistance at eventual strong layers in the profile. The industry standard approach follows the SNAME (1998) recommendations, based on simple bearing capacity formula with minor modifications for offshore conditions. The following sections outline the formulae used for vertical bearing capacity.

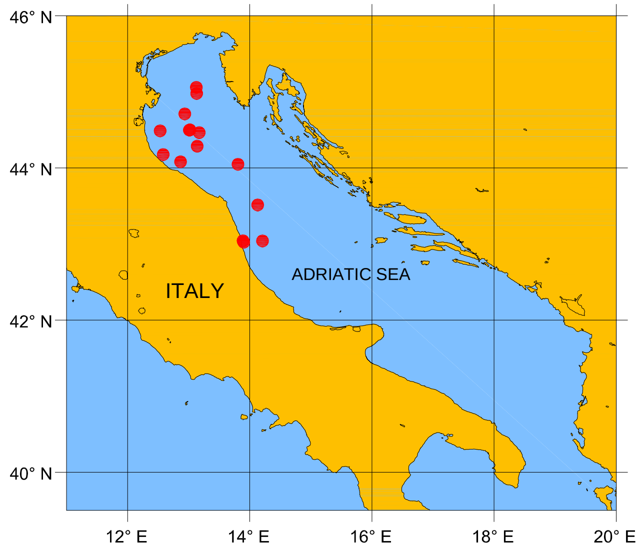

Fig. 5. Locations of offshore sites where were performed bearing capacities predictions versus field measurements.

The ultimate vertical bearing capacity (F_v) is defined as the maximum vertical load which the footing can support at a given penetration. F_v is computed assuming that there is no back flow of soil into the footprint above the footing. Figure 6a shows the general footing configuration and definition of dimensions.

Bearing Capacity in Clay

Ultimate vertical bearing capacity in clay is computed as:

$$F_v = (S_u N_c' + p_o')A \quad (1)$$

where:

F_v is ultimate vertical bearing capacity;
S_u is undrained shear strength;
p_o' is vertical effective stress at foundation level;
A is footing cross sectional area at foundation level.
N_c' is a bearing capacity factor.

Various empirical and theoretical methods are available to estimate N_c' (for example API, 1993; Vesic, 1975; Davis and Booker, 1973). These solutions are based on comparatively small diameter flat bottomed foundations typical of onshore applications. An alternative method to estimate N_c' for conical shaped footings in cohesive profiles with increasing shear strength has been developed by SNAME (1998). The SNAME methodology takes into consideration footing penetration, rate of strength increase of the clay, spud can geometry (cone angle) and the roughness of the footing-clay contact.

Bearing Capacity In Silica Sand

Bearing capacity in silica sands is computed using the Vesic (1975) formula:

$$F_v = \left(\frac{\gamma' B}{2} N_\gamma s_\gamma d_\gamma + p_0' N_q s_q d_q \right) A \quad (2)$$

where:

$$N_\gamma = 1.5(N_q - 1)\tan\phi$$

$$s_\gamma = 0.6 \text{ for circular footing}$$

$$d_\gamma = 1.0$$

$$N_q = e^{\pi \tan\phi} \tan^2\left(45 + \frac{\phi}{2}\right)$$

$$s_q = 1 + \tan\phi$$

$$d_q = 1 + 2\tan\phi\,(1 - \sin\phi)^2 \frac{D}{B}$$

and:

ϕ is drained friction angle of the soil;
D is footing embedment (depth);
B is footing diameter.

The empirical bearing capacity factors give reasonable agreement with model footings of less than 2.0 m diameter. Field experience, however, shows that the formulas tend to underestimate actual spud can penetration. To account for these "scale effects" the estimated triaxial friction angle for sands is reduced by 5° for leg penetration analysis.

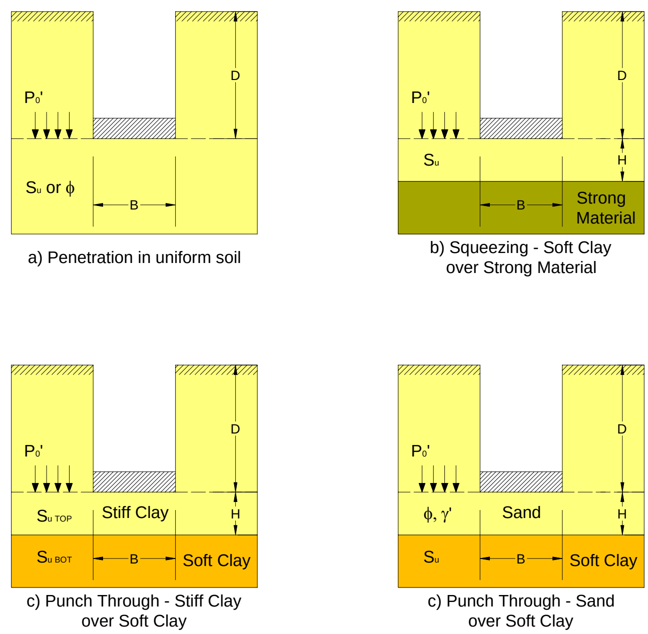

Fig. 6. Spud can bearing capacity and basic failure mode.

Bearing Capacity in Layered Soils

The presence of non uniform soil layers can adversely affect spud can bearing capacity. Three basic failure modes can be identified: general shear, squeezing of soft material, and punch through into softer layers (Fig. 6). Evaluation of capacity in these cases is described below.

General Shear. When soil layers are of similar strength the spud can penetrates by inducing general shear in the subsoil (Fig. 6a). An equivalent undrained shear strength or drained friction angle is established for each layer, and bearing capacity is computed as described above.

Squeezing of Soft Layers. Figure 6b shows the condition of a layer of soft clay underlain by a stronger material. When the spud can is far above the strong layer the bearing capacity is that of the soft clay. As the footing penetrates and approaches the firm layer the capacity increases, ultimately reaching that of the stronger soil. The capacity of the footing as it approaches the strong layer is computed as:

$$F_v = \left[\left(a + \frac{bB}{H} + \frac{1.2D}{B} \right) S_u + p_0{}' \right] A \qquad (3)$$

where:
S_u is undrained shear strength of soft clay;
H is thickness of soft clay below footing;
a empirical factor taken as 5.0;
b empirical factor taken as 0.33.

The lower and upper bounds of F_v are the bearing capacity in the soft clay and the bearing capacity on the stronger layer, respectively. For constant strength profiles, squeezing begins to increase bearing capacity at a distance T above the strong layer:

$$T = \frac{bB}{N_c' - a - \frac{1.2D}{B}} \qquad (4)$$

Punch Through of Firm Clay into Soft Clay. Punch through is a risk whenever a spud can bears on a strong layer underlain by a weaker strata. Figure 6c shows the case of a firm clay overlying a softer clay. Bearing capacity is computed as:

$$F_v = \left[3\frac{H}{B} S_{u,top} + N_c s_c \left(1 + 0.2\frac{D+H}{B} \right) S_{u,bot} + p_0{}' \right] A \quad (5)$$

where:
H is thickness of firm clay below footing;
$S_{u,top}$ is undrained shear strength of upper clay;
$S_{u,bot}$ is undrained shear strength of lower clay;
N_c is bearing capacity factor taken as 5.14;
N_q shape factor, taken as 1.0 for ϕ=0

The upper and lower bounds for F_v are bearing capacity of upper and lower layers, respectively.

Punch Through of Sand over Soft Clay. Bearing capacity of a footing on a layer of sand overlying soft clay (Fig. 6d) is given by:

$$F_v = F_{v,bot} - AH\gamma' + 2\frac{H}{B} \left(H\gamma' + 2p_0{}' \right) K_s \tan\phi A \qquad (6)$$

where:
$F_{v,bot}$ is bearing capacity of underlying layer;
H is thickness of sand layer;
γ' is submerged unit weight of sand layer;
K_s is coefficient of punching shear.

The coefficient of punching shear K_s is based on the work of Hanna and Meyerhof (1980). A lower bound approximation of K_s is given by:

$$K_s \cong \frac{3S_u}{B\gamma' \tan\phi} \qquad (7)$$

CASE STUDIES

This paper presents a set of 15 case studies of jack-up leg penetration in the Adriatic Sea. The cases include 4 different jack-ups used at the sites. The spud cans of these rigs varied from 11.8 to 14.6 m in diameter, and the preloads were from 31.1 to 54.1 MN (3,500 to 6,000 ton).

Geologic Setting

The test cases were located in the central and northern Adriatic Sea (Fig. 4). The Adriatic Sea is an epicontinental semi-enclosed basin characterized by a rectangular shape elongated in the north-west to south-east direction. The gradient of the shelf is very low in the northern and central part (40 m per 100 km) and steeper in the southern sector (Trincardi et al., 1994). The northern Adriatic Basin can be considered the submarine continuation of the Po basin over a continental shelf area. Here, 7000 m of sandy and argillaceous beds deposited during the Pliocene (Celet, 1977). Most of the sediment is derived from erosion of the Alpine and Apennine chains. These materials are transported to the north eastern Adriatic by the Po river and, subordinately, by other rivers including the Adige, Brenta, and Reno. Currently, the Po river supplies the majority of the sediment, about 20 million tons per year (Colantoni et al., 1979). These sediments are redistributed by marine currents, with the coarse material deposited along the coast and the finer material carried longer distances offshore.

Plio-Quaternary geologic and geomorphologic processes have significantly changed the geography of the Adriatic Sea. During the Quaternary glaciations, sea level changes led to migration of the coastline, which was accentuated by the low shelf gradient. After a slow regression, the Adriatic reached a minimum elevation of 120 m below the current level during the most recent (Würmian) glaciation, about 18000 years B. P.. The entire shelf was exposed to subaerial conditions and a fluvio-lacustrine plain developed. In these conditions erosion predominated, although local zones of deposition occurred. The successive rise in sea level, the Flandrian transgression, rapidly flooded the alluvial plain. During this process the continental deposits were partially eroded, reworked and covered by a thin stratum of marine sediments. The channels and incisions present on the alluvial plain were filled with sediments by the advancing sea. The maximum marine intrusion occurred about 5000 years B. P. At this point the currently existing coastal zones of the Po and Venetian plain were submerged (Correggiari et al., 1996).

Figure 7 shows the present sediment distribution in the Adriatic Sea (Brambati et al., 1983; Stefanon, 1984; Trincardi et al., 1994). Sedimentation shows a trend parallel to the coast. Active Holocene deposits are confined to a narrow zone along the western (Italian) coast of the Adriatic. Further offshore sedimentation is almost absent, and the thin sandy cover of the Flandrian transgression still outcrops. Three typical sections through the basin margin are shown in Fig. 8 (Cattaneo, et al., 2003). In the northern sections delta front sands grade to the pro-delta Holocene wedge. At the seaward extension of the wedge older Pliocene formations subcrop. Moving south, the pro-delta wedge is more pronounced.

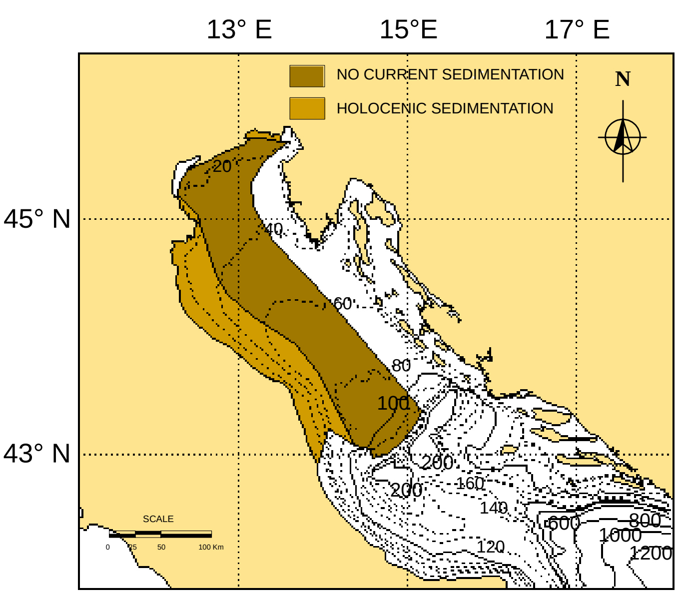

Fig. 7. Holocene sedimentation in the Northern Adriatic Sea.

The implications of the area geology for jack-up siting are that sites fairly near the coast are expected to have significant pro-delta clays overlying older competent materials. The pro-delta deposits are primarily highly plastic normally consolidated clays, although silty and sandy layers are frequently encountered. Further offshore the stronger formations are found near the surface and leg penetration is minimal.

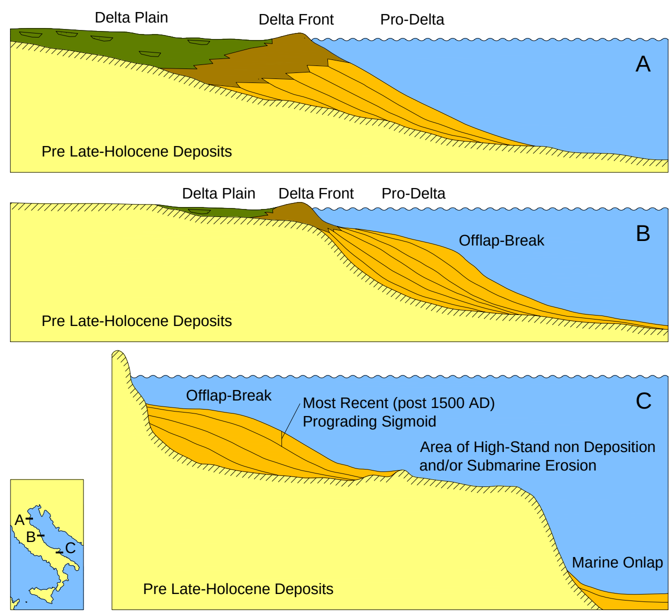

Fig. 8. Three typical sections through the Adriatic basin margin

Geotechnical Conditions

The soils in the northern and central Adriatic can be broadly separated into the following groups:

- Holocene Wedge Formation – Soft high plasticity normally consolidated clays with frequent silty interbeds, and occasional peat stringers. Undrained shear strength increases fairly linearly with depth;

- Plio-Quaternary Formations – Medium dense fine silty sands and silty clays. The soils are lightly to moderately overconsolidated by erosion and in some cases desiccation. The clays are low plasticity and have a strong silt component. The sands are fine, siliceous, subangular to subrounded, and contain limited quantities of mica. Again, the sand layers have a strong silt component. Strongly interbedded sequences are common at transitions between sands and clays. Undrained shear strength in the cohesive formations shows effects of light overconsolidation. Friction angles of the sands are consistent with a medium dense condition.

The greatest risks of punch through are in the pro-delta "Holocene Wedge". The presence of silty layers with partially drained behavior can lead to interruptions of penetration. If these layers are encountered near the maximum preload they can present a significantly hazard.

Predicted and Observed Behavior

Figure 9 shows the predicted and observed leg penetration at the 15 sites. In a few cases, where there were questions about the behavior of fine soil profile, a range of predictions was provided. In general the quality of predictions is good. There is a mild tendency to over estimate penetration, and only in two cases was the penetration significantly under estimated.

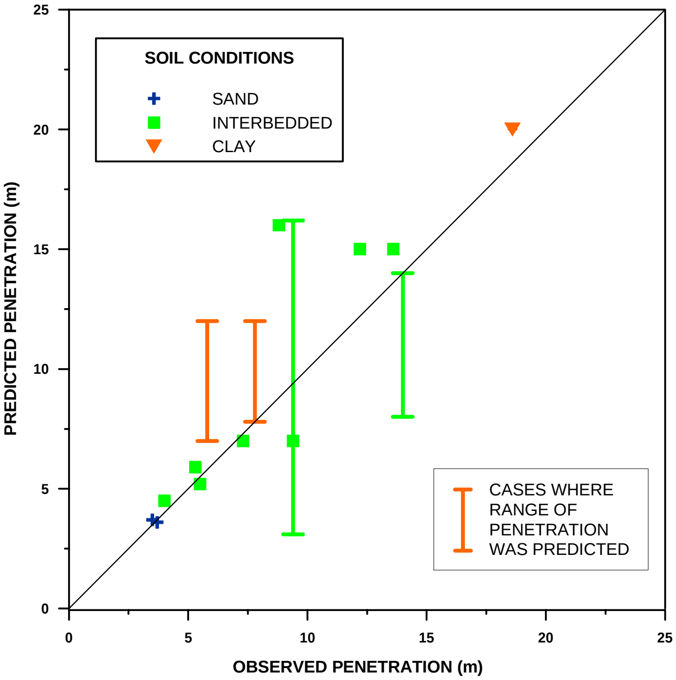

Fig. 9. Observed and predicted range of penetration for different soil conditions offshore sites.

Considering the cases by soil type, in sands the predictions were best. These reflect cases where the spud can tip penetrates the sand layer and the footing stops when the maximum section reaches the sand. In clays the penetration range was generally over estimated. As would be expected, interbedded soil profiles are the most difficult to predict. This is due to:

- Presence of silt layers which can show either drained or undrained behavior;
- The difficulty of applying simple bearing capacity assessment in layered conditions.

CONCLUSIONS

Based on 15 case studies of jack-up siting in the Adriatic, we can draw the following conclusions:

- In general jack-up leg penetration can be well predicted by simple bearing capacity equations;
- Spud can penetration in sands usually stops when the maximum section comes to bear on the sand layer;
- Leg penetrations can be large in normally consolidated clays. Penetration stops either at the base of Holocene Wedge or on silty / sandy interbedds;
- Predictions are most difficult in interbedded profiles, with the most critical cases being the presence of thin silty layers in soft layers;
- For practical purposes, the greatest risk of punch through is found in the Holocene wedge area.

REFERENCES

American Petroleum Institute (API) [1993], *Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms - Working Stress Design*, API RP 2A-WSD, 20th Edition, Washington, D.C.

Brambati, A., M. Ciabatti, G. P. Fanzutti, F. Marabini and R. Marocco, [1983], “A New Sedimentological Textural Map of the Northern and Central Adriatic Sea”, Bollettino di Oceanologia Teorica ed Applicata, Vol. 1, No. 4, pp. 267-270.

Cattaneo, A., A. Correggiari, L. Langone and F. Trincardi, [2003, “The Late-Holocene Gargano subaqueous delta, Adriatic Shelf: Sediment pathwars and supply fluctuations”, Marine Geology, Vol. 193, pp. 61-91.

Celet, P., [1977], “The Dinaric and Aegean Arcs: the Geology of the Adriatic”, in *The Ocean Basins and Margins*, Edited by Nairn, A. E. M., W. H. Kanes and F. G. Stehli, Vol. 4A, The Eastern Mediterranean.

Colantoni, P., P. Gallignani and R. Lenaz, [1979], “Late Pleistocene and Holocene Evolution of the North Adriatic Continental Shelf (Italy)”, Marine Geology, Vol. 33, pp. M41-M50.

Correggiari, A., M. Roveri and F. Trincardi, [1996], “Late Pleistocene and Holocene Evolution of the North Adriatic Sea“, Il Quaternario, Italian Journal of Quaternary Sciences, Vol. 9, No. 2, pp. 697-704.

Davis, E. H. and J. R. Booker, [1973], “The Effect of Increasing Strength with Depth on the Bearing Capacity of Clays”, Geotechnique Vol. 23, No. 4, pp. 551-563.

Hanna, A. M. and G. G. Meyerhof, [1980], “Design Charts for Ultimate Bearing Capacity of Foundations on Sand Overlying Soft Clay”, Canadian Geotechnical Journal, Vol. 17, pp. 300-303.

Meyerhof, G. G., [1972], “Stability of Slurry Trench Cuts in Saturated Clay”, Proceedings of the Speciality Conference on

Performance of Earth and Earth Supported Structures, ASCE, pp. 1451-1466.

Society of Naval Architects and Marine Engineers (SNAME), [1998], *Site Specific Assessment of Mobile Jack-Up Units, Technical and Research Bulletin 5-5A*, Rev. 1, Jersey City, NJ.

Stefanon, A., [1984], "Sedimentologia del Mare Adriatico: Rapporti tra Erosione e Sedimentazione Olocenica", Bollettino di Oceanologia Teorica ed Applicata, Vol. II No. 4, pp. 281-324.

Trincardi, F., A. Correggiari and M. Roveri, [1994], "Late Quaternary Transgressive Erosion and Deposition in a Modern Epicontinental Shelf: the Adriatic Semienclosed Basin", Geo-Marine Letters, 14, pp. 41-51.

Vesic, A. S., [1975], "Bearing Capacity of Shallow Foundations", *Foundation Engineering Handbook*, H. F. Winterkorn and H. Y. Fang, editors, 121-147, Van Nostrand Reinhold, New York.