Discussion Session 2.4 / Séance de Discussion 2.4

Offshore platforms and pipeline foundations

Fondations des plates-formes et des oléoducts en mer

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Presented papers

Deep-water site investigation in soft sediments, *M.F Randolph, Univ. of Western Australia (Discussion Leader)*
Deep water geohazards for pipelines, *T.J. Kvalstad, NGI (Panellist)*
Recent advances in burial assessment for submarine pipelines and cables, *A. Puech, Fugro France (Panellist)*
Brazilian experience with suction piles, *J.R.C. Mello, Petrobras (Panellist)*

Randolph: Offshore geotechnical specialists tend to discuss their work within their own discipline, and I hope this session helps exchange experience between people working in onshore and offshore areas. Papers related to offshore foundations to the Istanbul Conference can be categorised into:

1. Shallow Foundations:
   - Capacity under V-M-H loading, *Poulos et al (Australia)*
   - Vertical bearing capacity, *Martin (Australia)*
2. Piles
   - Drivability parameters, *Alm/Hamre (Norway)*
   - Model instrumented pile design, *Mendoza et al (Mexico)*
3. Offshore Pipelines
   - Wave-induced break out of pipeline, *Gu et al (China)*
   - Pipeline penetration in clay, *Salençon (France)*
   - Pipeline forces in unstable slopes, *Scarpelli et al (Italy)*
   - Pipeline-soil interaction in sand, *Zhang et al (Australia)*

Deep-water site investigation in soft sediments, *Randolph*

As we go into deep water, we deal generally with soft deposits, especially in the upper few meters. The current in situ practice for determining the strength profile includes CPT and shear vane tests. CPT results need calibration (choice of cone factor, N_k) against laboratory tests on undisturbed samples, which are usually difficult to obtain in deep water deposits. The shear vane test is of limited potential in near surface soils, and also need calibration (correction factor μ). There are potential benefits in using flow-round penetrometers such as the T-bar, ball and plate penetrometers. The main advantages of such devices are:

- the projected area is about 10 times the shaft area, which increases the sensitivity of measurements;
- negligible correction is needed for overburden pressure;
- plasticity solutions allow estimation of the factor relating penetration resistance to shear strength, within ± 1%;
- the bearing capacity factor, N_k, is not affected by the rigidity index (G/s_u), or the at-rest coefficient of earth pressure.

Offshore results from both T-bar and CPT tests show that the T-bar exhibited relatively less scatter than the CPT. Both devices could give identical results at very shallow depths, but tended to deviate noticeably at greater depths. It is not clear whether this deviation is due to changing degrees of anisotropy and strain softening, to errors in the corrections for overburden stress and excess pore pressure, or to gradually changing cone factors.

Figure 1 shows that T-bar, ball, and cone penetrometers can give consistent results, if we use the same N_k factor of 10.5. This is a worry because the theoretical value for the ball should be 20 % higher than for the T-bar, and indicates that effects of strength anisotropy and strain softening need to be taken into account.

The second part focuses on combined loading of foundations in (V-M-H) space. I am wondering why our current design guidelines are still based on plain strain conditions, rather than starting with basic solutions for circular foundations, thus avoiding inaccuracies due to shape factors, which are strongly affected by strength non-homogeneity with depth. Most offshore foundations are skirted, with embedment depths where significant divergence occurs between Lower Bound and Upper Bound plasticity solutions, as the mode of failure changes from surface failure to that of a type of cavity expansion. Secondly, centrifuge modelling has shown that displacements equivalent to 1 or 2 m may be needed to mobilise the full bearing capacity – a factor that is often overlooked in adopting plasticity solutions of bearing capacity.

There is an urgent need to derive bound solutions to predict the yield envelope in V-M-H space for circular and other shaped foundations. One promising approach is to adapt plain strain mechanisms for strip foundations, allowing the mechanism to vary across the width of the foundation.

I conclude my presentation by raising the following three questions for discussion: (1) in terms of SI, how can we improve on strength profiling, avoiding reliance on laboratory tests on varyingly disturbed samples? (2) in terms of caissons and skirted foundations, is it time to re-cast traditional bearing capacity formulae to avoid factors for shape, depth etc? and (3) how confidently can we define yield envelope shapes in V-M-H space?

Deep-water geohazards for pipelines, *T.J. Kvalstad*

There are four sources of hazards for offshore pipelines: (1) submarine slope instability, (2) mud and debris flow, (3) runout distance and velocity and (4) impact forces on pipeline.

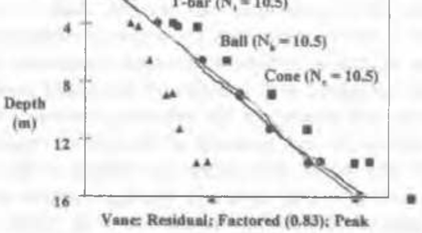

Fig. 1: Results form T-bar, ball and cone penetrometers

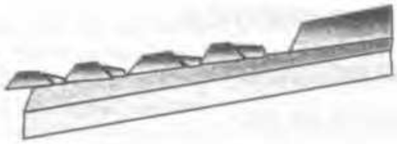

Fig. 2: Retrogressive failure of a continental slope

There are many examples of pipelines being affected by high- and low-velocity debris and mud flows. As more development of oil fields occurs on continental slopes, enormous slides are observed, with increasing gravity forces, even at shallow slopes of 0.5° to 3°. Figure 2 shows the retrogressive sliding mechanism observed on continental slopes and how they could pose threats to pipeline installations. The particular case study of the Storegga slide (8000 yrs BP) in Norway reflects a great source of hazard to potential pipeline routes in the vicinity of the Ormen Lange gas field, with its massive run-out of 800 km and volume of 5600 km^3. The high velocity associated with the dynamics of the slide enables hydroplaning and causes further degradation of shear strength. Eventually, the apparently rigid soil blocks turn into viscous fluid.

There are three mechanical approaches to modelling the sliding phenomenon, namely the dynamic wedge, Bingham fluid approach (BING) adopted by Jinag and Leblond, and Computational Fluid Dynamics (CFD). The aim of these models is to estimate the run-out distance, run-out velocity and impact forces on pipelines.

As to any of these mechanical models, there is a complexity in determining the appropriate soil parameters, which require both model testing and observational approaches.

In conclusion, I suggest that Computational Fluid Dynamic analysis is a promising approach for impact estimation. However, model testing at high velocities is required to verify computational results. Modelling inhomogeneous debris flow also needs more attention.

Recent advances in burial assessment for submarine pipelines and cables, *A. Puech*

There are many technical challenges facing the cable and pipeline industries in relation to burial assessments in terms of depth of burial, most appropriate burial method, anticipated performance of the recommended burial method, stability of trenches, stability of burial tool and anticipated wear of the burial equipment. The standard route selection survey methods are insufficient for burial assessment, including bathometry, side scan sonar, seismic reflection (boomer) and ground exploration. There is need for obtaining high-quality geotechnical data as well as continuous and reliable data along the route. This has led to introduction of the CPT and implementation of on-bottom continuous profiling techniques.

There are many advantages in the SEAROBIN technique, which is used for cable routing soil investigation, where PCPT tests are carried out and samples can be taken. This technique can work up to water depths of 2 km. There are many advantages in using the CPT to profile the strength of offshore deposits.

Currently, there are two main continuous profiling techniques: the first is based on electrical resistivity measurement (ERM) and the second on high-resolution seismic refraction systems (HRSRS). The ERM technique can acquire data in water depths of up to 2 km by measuring the apparent resistivity of the upper mass of marine sediments through continuous dragging of a cable equipped with a series of electrodes used for injecting current and measuring the resulting electrical field. The apparent resistivity is a measure of the overall resistance of a volume of soil whose dimensions are related to the electrode spacing. Using several electrode spacings enables measuring the variations of electrical resistivity with depth. The soil strength can be characterised by a formation factor (FF), which expresses the ratio between the soil mass resistivity and the sea water resistivity.

Following processing of the geophysical and geotechnical data, three types of burial assessment analyses are performed: (1) ploughing predictions, (2) interpolation of results along the entire route and (3) complementary assessment of burial conditions. The third type of analysis addresses a number of particular aspects such as local obstructions, cable or pipeline crossings, geohazards (slope stability, pockmarks, etc.), bearing capacity of seafloor, share wear etc.

It is important to integrate data from different techniques to define the characteristics of the sub-bottom profile required for burial assessment. Field results have shown that both the formation factor (*FF*) from electrical resistivity measurements and P-wave velocity from the seismic technique correlate with cone resistance q_c. These correlations help establish classification scheme for marine deposits.

In conclusion, further burial experience and back-analyses will assist in the near future to refine and improve burial assessment evaluations.

Brazilian experience with suction caissons, *J.R.C. Mello*

Suction caissons have been used in Brazil since 1996, at water depths up to 1025 m in soft clays. They were used effectively for the P-19 and P-26 semi-submersible production platforms, with anchoring pattern comprising sixteen piles each, as well as for other platforms. To avoid interference between platform anchoring systems, we adopted the taut-leg mooring solution for the semi-submersible anchoring systems, with mooring attack angle (related to the horizontal plane) close to 40°. However, for the FPSO anchoring systems, it was possible to adopt catenary mooring, with attack angle ~ 10°.

Suction caissons were also used in a shallow water project in the foundation reinforcement of the Ipanema Beach sewage pipeline, Rio de Janeiro. It is a 4.3 km long concrete pipeline (3.2 m o.d.) in water depths of up to 28 m, with pipeline joints 40-50 m apart, supported by discrete steel open-ended driven piles of 1.4 m o.d. The piles were used to guarantee that the 1970s pipeline would have the same slope for all segments. Due to the fatigue process, corrosion and micro fissures induced by the driving, some of the piles had broken, casting the two adjacent pipeline parts onto the seafloor. To solve this problem, two suction caissons (4 m o.d., by 4 m in length) were installed, with the pipeline in between. Suction pumps were used to advance the caissons beyond their self-weight penetration. Two supporting beams protruding from the top of the suction caissons were displaced to underneath the pipeline joint up to the position where they could be locked around the capital of the original pile. The pump flow was reversed to lift the caissons to the required position to support the beams. Grout was injected in the upper chamber of each caisson to avoid short term settlement.

Comments from the floor

To *Mello*: How would you account for possible rust of suction caissons and steel pipes?

Mello: There are some formulas used to predict the reduction in thickness with time as a result of rust. The rust is accounted for by adding equivalent thickness to the steel element.

To *Kvalstad*: Are these slope instability hazards associated with clay or sand?

Kvalstad : It could happen with very steep slopes in sand, and it happens also with clays at very low angles. There are case where inter-bedded clay layers of high sensitivity could exist in sand deposits, and these work as lubricant, facilitating sliding.

Kolk (Fugro): While there is room for improving the resolution of CPT, we also need to make sure that we obtain high-quality samples for routine SI. In the whole process of analysis of shallow foundations, we need to take the influence of cyclic loading and strain rate effect into considerations. There are significant approximations in our analysis, and we should not lose sight in the process of analysis.

Randolph: I agree; and it is clear that we have uncertainty of around 20% in current solutions, due to imponderables such as anisotropy, strain softening etc. However, I prefer to start with a rational approach based on simple soil models and then address the uncertainty, rather than start with solutions that themselves involve uncertainty.

In terms of SI, I have concerns about the reliability of electrical resistivity methods, particularly as much of the resistance occurs at the interface with the electrode rather than within the soil. In the seismic technique, would it be better to use the SASW method, to allow the much higher resolution obtainable from shear waves?

Kolk: I agree, but this is very difficult to achieve.

Randolph: Why?

Puech: Even with the P-wave, each cycle takes about 10 sec and we usually use 3 nodes, 20 m apart. Shear wave measurements would be much slower although could be achieved, but the P-wave approach is more efficient.

To *Randolph*: is there any concern about the stability of suction caissons?

Randolph: In deep water, the vertical capacity often governs. We need to be careful in adopting standard design methods for piles in estimating shaft friction for caissons, because of their extremely low wall thicknesses. This reduces the degree of cavity expansion, and hence the opportunity for effective stress and strength recovery adjacent to the caisson walls.