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Detailed Geotechnical Investigation Around In-Place Mat Foundation Including T-Bar and Cpt Comparisons

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Abstract

The Maleo Producer is a converted Bethlehem JU250 mat-supported jack-up unit, which was installed in July 2006, on a soft, normally consolidated clay foundation some 40 km (25 mi) south east of Madura Island and approximately 25 km (16 mi) south of Puteran Island, offshore Indonesia. The unit was connected to a wellhead platform, and gas production began in late 2006. An initial site investigation performed in 2003 indicated that the undisturbed soil conditions consisted of a soft normally consolidated clay profile, with an undrained shear strength of 2 kPa (40 psf) at the mudline, linearly increasing with depth at a rate of 1.22 kPa/m (7.83 psf/ft) down to a depth of around 14 m (46 ft), below which a slightly stronger clay was encountered. The issue of on-bottom stability of the unit and its resistance to overturning were questioned by the classification society (ABS) as part of the reclassification of the rig. The behavior of the foundation under extreme storm loads and seismic events could be more reliably predicted by the designer, and more readily accepted by ABS, if new soil data were available. Two types of soil data were required 1) soil data for foundation design and re-analysis under and around the mat and 2) soil data for seismic analysis of the installation. This paper describes the extensive site characterization undertaken to prove the stability of the Maleo Producer facility during both the design storm and seismic events.

Introduction

The Maleo Field is located in Indonesian waters about 40 km (25 mi) south east of Madura Island and approximately 25 km (16 mi) south of Puteran Island (Figure 1), within the Madura Offshore Production Sharing Contract (PSC) area.

The Maleo Producer is a converted Bethlehem JU250 mat-supported jack-up unit (formerly the CD10) ABS Class Number 7900120. The unit was installed in July 2006, and was connected to a wellhead platform. Gas production began in late 2006 (Figure 2).

Description of the Installation

The installation is in approximately 57-m (187-feet) water depth. The hull is supported on three cylindrical steel legs, 3.66-m (12-ft) in outer diameter. The legs are supported on an "A" shaped mat (Figure 3) that rests on the seafloor. The mat is 64 m (210 ft) long, 52 m (170 ft) wide and 3-m (10-ft) thick. It has 0.6-m (2-ft) deep skirts (extensions of the mat side walls) that extend along all edges of the mat (around the outside mat edges, inside the slot at the aft end and around the inside edges of the 18 m x 33m (59 ft x 108 ft) cut-out within the three legs beneath the hull (Figure 3).

A 14-in (366-mm)-diameter gas export seafloor pipeline connects the installation (from the starboard side of the mat) to the 26-in. (660-mm) East Java seabed pipeline approximately 7 km (4.3 mi) to the south.

Details of the structure's geometry, preload history, and design load conditions were provided by Stewart Technology Associates (2006 a&b), as documented in Ooley and Stewart (2008).

Initial Geotechnical Site Investigation

The soil conditions around the Maleo platform site were originally investigated by Fugro in 2003. The site investigation consisted of one 100-m (330-ft) sample hole, one 100-m (330-ft) PCPT hole, four 20-m (66-ft) PCPT holes, and associated static laboratory testing. The results are presented in a log of boring, reproduced in Figure 4.

A report presenting the results of this initial investigation was presented in PTKRS Report No. 03008J-3 Issue 3, dated August 2003. This report characterized the soils as normally consolidated clay, with an undrained shear strength of 2 kPa (40 psf) at the mudline, linearly increasing with depth at a rate of 1.22 kPa/m (7.83 psf/ft) down to a depth of around 14 m (46 ft), after which a slightly stronger clay was encountered.

New Geotechnical Site Investigation

Geotechnical Data Required

The issue of on-bottom stability of the unit and its resistance to overturning were questioned by the classification society (ABS). The behavior of the foundation under extreme storm loads and seismic events could be more reliably predicted by the designer, and more readily accepted by ABS, if new soils data were available.

No seismic soil data were specifically requested of Fugro in the 2003 site investigation and no soil cores were available four years later. Detailed soil data were now required to perform the necessary non-linear finite element structural analyses and response spectrum analyses for various intensity seismic events. Geotechnical data were required from the site at a distance of no more than 120 m (400 ft) away from the Maleo Producer mat edge on either the bow or port sides (thereby completely avoiding the export pipeline and the wellhead platform). Continuous cone penetration data and shear wave measurements down to a depth of 100 m (330 ft) below the mudline were needed.

Samples from an adjacent hole taken every five feet were required for subsequent laboratory dynamic and static tests. Additionally, possible soil disturbance caused by the placement of the structure onto the soil at the site required quantification. Analysis efforts to predict the strength characteristics of the soil following the installation and pre-load operation were made but doubts existed as to the amount of disturbance that existed and as to the present soil strength characteristics. Therefore, the new geotechnical investigation was intended to provide as much data about the soil beneath, around, and below the mat as possible. The mat's zone of influence, and more importantly the depth range of interest, extended to at least 10 m (30 ft) below the present mat bottom plate. That translated into approximately 12 m (39 ft) below the mudline assuming the mat penetration estimate was correct.

Thus, two types of soil data were required:

1) Soil data for foundation design and re-analysis under and around the mat, and
2) Soil data for seismic analysis of the installation.

And at least three types of in-situ measurements were desired:

1) T-bar tests,
2) CPT tests, and
3) In situ vane tests.

Site Investigation Objectives

The new site investigation to obtain additional soil data was completed by Fugro in early 2007, with the following two main objectives:

- Confirm the strength parameters under and around the mat to analyze the platform stability against overturning during storm loading, and
- Obtain samples that could be tested to determine the dynamic soil properties to be used in the seismic analyses of the Maleo platform.

Therefore, in addition to the borings and in situ measurements outside the mat perimeter, it was highly desirable to obtain data from below the mat. This is conventionally considered to be a daunting task. The locations posing the least difficulty were immediately adjacent to the outside edges of the mat, within 0.6 m (2 ft) of the mat sidewall. Two locations at the mid-side of the bow and port edges of the mat were preferred, with one location at the port bow mat corner. These boring locations are identified on Figure 5.

Borings and/or in situ testing within the mat cut-out and in the mat slot (Figure 5) were considered to be "feasible". The possibility existed to deploy either a Seacalf® wheeldrive or a Roson® type of T-Bar/CPT/VST seabed system from the deck of the Maleo Producer that would sit in one of the large openings of the mat. After careful consideration, it was decided to use the Roson® system, as it was substantially lighter and more maneuverable than the Seacalf®. The Maleo Producer rig cranes were made available for deployment and operation of the geotechnical investigation equipment.

Measurements of mat depth of penetration into the seabed were also required. Penetration measurement results would ideally be reported as measured depths below original mudline at each mat corner. Additionally pore water pressures would be of benefit and samples for lab tests were desired.

Seafloor Elevation Reference

As previously stated, the main purpose of the site investigation was to determine soil strengths beneath the mat. The site investigation, undertaken in April 2007, provided a wealth of undrained shear strength (Su) data from a combination of T-bar, piezocone and vane tests. Soil strength profiles vs. depth at various locations around the mat and up to 18 m (60 ft) away from the mat edge were obtained.

It was recognized that a soil mound would have developed around the mat as the soil was displaced from beneath the mat and heaved up along its side. A previous study on a mat rig was reported by Young et al. (1982) for two locations where soft clays existed in the Gulf of Mexico, which confirmed that a soil mound may heave up to a few feet and extend as far as about 12 m (40 ft) from the edge of the mat.

Figure 6 presents schematically (assuming uniform soil conditions and a classical bearing capacity failure mode) how soil heave will develop initially close to the mat, then as the mat penetrates how the failure mode will extend further out. Hence the final soil heave should be greatest adjacent to the mat, and reduce with distance away from the mat. Note that for the specific soil profile at the Maleo location (which is almost normally consolidated), the shear zones would be expected to be much shallower than the classical mode indicated, as the failure mechanism should be confined to the near surface, weaker materials. Under ideal conditions (undrained and plane strain), the volume of heaved soil above the natual seabed should be equivalent to the displaced volume of the mat below the seabed, ignoring the small contribution of elastic free-field displacements. This is illustrated idealistically on Figure 7.

Therefore, the need to correct the seafloor datum for the various CPT and T-Bar tests performed around the platform mat was recognized, in order to be able to make meaningful comparison between the soundings near and far from the mat. Serendipitously, a sharp spike was observed to occur in both the CPT and T-bar data at a depth of about 11.6 m (38 ft) below the seabed. This was believed to represent a very useful horizontal marker stratum (see Figure 7) that was deep enough not to have been affected by the zones of plasticity that would have formed during penetration of the mat into the seafloor.

The most reliable vertical reference elevation for the borehole logs was the mat top plate where the Roson elevation relative to the mat was precisely known. The five boreholes taken with the Roson perched on the edge of the mat top plate gave direct measurements of soil strength profiles beneath the mat (at a distance of 450 mm (28 in.) from the outside mat edge, and one borehole, BH4, near the mat edge inside the mat cut-out). The depth logs for boreholes BH7 through BH17, taken with the Roson set directly on the sea bed soil, can be closely related to the nearby mat top plate elevations.

Borehole depths relative to the mat top plate were accurately interpreted by Fugro. For boreholes off the mat, the Fugro data seem to show the Roson instrument (cone, T-bar, or vane) always starting in the soil although the typical height of each instrument above the base of the Roson bottom frame is around 700 mm (28 in.). Stewart (2007) notes that the Roson could be expected to sink into the seabed by about 0.5 m (20 in.). This effect would alter the interpretation of soil heave around the mat, but would not affect the interpretation of shear strength with depth below the mat, as the strength profiles were ultimately corrected using the deep marker stratum as an elevation benchmark.

By using this marker stratum as a common elevation datum, it became possible to estimate the thickness of the soil mound by adjusting the reference depth of each CPT and T-bar sounding to match the location of the spike on each data profile. The resulting profiles of a soil mound are shown in Figure 8. The inferred mound profile appears reasonable for a mat penetration of about 1.8 m (6 ft) below the original seafloor in terms of the volume of the displaced soil matching the volume of the mound. Further interpretation of the mat bottom relative to the soil profile indicates that the mat is at least 2m (6.5 ft) below the original seabed.

Shear Strength Values Beneath and Around the Mat

A total of 7 CPT and 8 T-bar tests were conducted at distances ranging from 0.6 to 18m (2 to 60 ft) from the edge of the mat. Figures 9 and 10 show the collective results of all the CPT and T-bar tests, respectively, on individual plots to indicate the spatial variability in soil strengths. The two figures indicate that all the data are very similar, using values for N_k of 17.5 and 10.5 to reduce the CPT and T-bar data, respectively.

The ratio between the T-Bar and CPT cone factors (10.5/17.5=0.6) is somewhat on the low side compared with published data from Lunne et al. (2005), where ratios of $q_{t\text{-}bar}/q_{net}$ from several soft clay sites were reported to vary between about 0.7 and 1. Although, the ratio implied from the Maleo data ($q_{t\text{-}bar}/q_{net}$ ~0.6) is not dissimilar to the data from Onsoy reported in the Lunne et al. paper.

The average undrained strength profiles, interpreted from the CPT and T-bar data, are compared on Figures 9 and 10 to illustrate the range in spatial soil properties. The results show a very tight band, which indicates that the soil strengths are spatially uniform. The average strength profile selected for the overturning stability analyses increases linearly with depth from 1.0 kPa (21 psf) at the seafloor to 15.5 kPa (324 psf) at 12.0 m (39.4 ft). This new strength profile increases linearly with depth at a rate of 1.2 kPa/m (7.72 psf/ft). This rate of strength increase is very similar to that from the strength profile that Fugro previously interpreted as 1.22 kPa/m (7.83 psf/ft) from the earlier two borings. This profile indicates that the soil strength at the bottom of the mat is at least 3.4 kPa (71 psf).

A heavy blue straight line indicates the project team consensus opinion of the general Su profile selected for evaluating the mat bearing capacity based upon the results of this site investigation. In the depth range of main interest beneath the mat bottom, the consensus line seems reasonable from this figure.

Figure 10 shows the T-bar data plotted for BH1 and BH3 borings, from the mat top plate and outside the mat at the port forward corner. The vertical reference datum is the mat top plate elevation at BH3.

The consensus line appears to reasonably represent the Su data for boring BH3 beneath the bottom of the mat. For the three boreholes near the mat where the soil has heaved up around the mat, the consensus line cannot represent the existing soil strengths from the top of the mat down to seven feet beneath the existing mudline, however.

Cyclic TBar Data and Remolded Strength

A number of cyclic T-Bar tests were undertaken to determine the remolded soil strength. A comparison of these data is presented on Figure 11 for Tbar tests undertaken at Boring BH3 (next to the mat in the affected area) and Boring BH10 (some distance away in nominally unaffected seabed). Here, the data from Boring BH3 have been corrected to account for the soil heave discussed previously.

It can be inferred from these data that the cyclic T-Bar residual strength forms a relatively consistent trend with depth, across the two boreholes considered. In fact, in the upper meters, the correlation between the TBar residual is probably better than that for the monotonic T-Bar resistance. This demonstrates that there are zones within Boring BH3 that appear disturbed and, thus, exhibit a lower monotonic strength than at equivalent depths in Boring BH10, though the residual strength is similar. This partly remolded material is, therefore, less sensitive.

Conclusions

An extensive site investigation around the foundation of the Maleo producer was carried out in order to determine the in place capacity of the system and its response to seismic loading. This was a challenging site investigation due to the proximity of the borehole locations to the existing foundation, necessitating corrections to the data to account for soil disturbance and seabed heave. Physically locating the Roson® system on the edge of the mat in order to carry out continuous CPT testing extremely close the the outer skirt of the foundation was a challenging task, but was carried out very successfully. Good quality data was acquired that enabled a consistent view of the in situ soil strength to be developed (once seabed elevations were referenced to a deep marker stratum).

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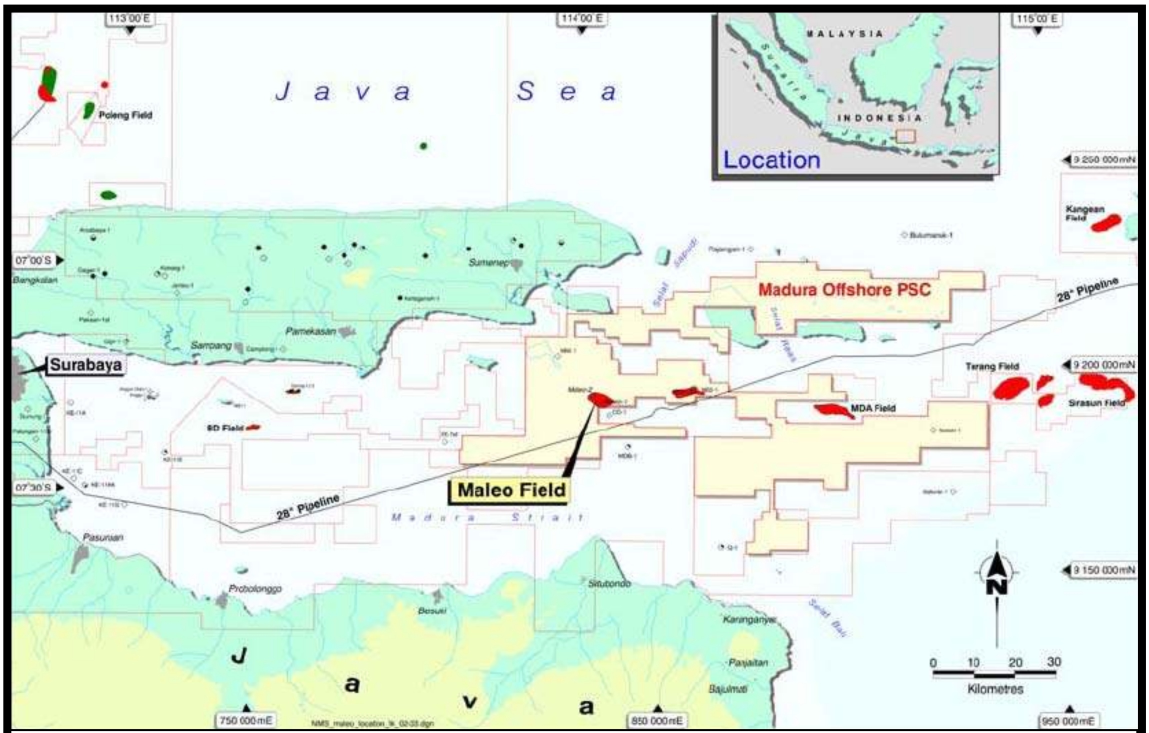

FIGURE 1 – Maleo Producer Location Plan

FIGURE 2 – First Gas – Around September 2006
Flare tower is on port side. Cranes are on both port and starboard sides.

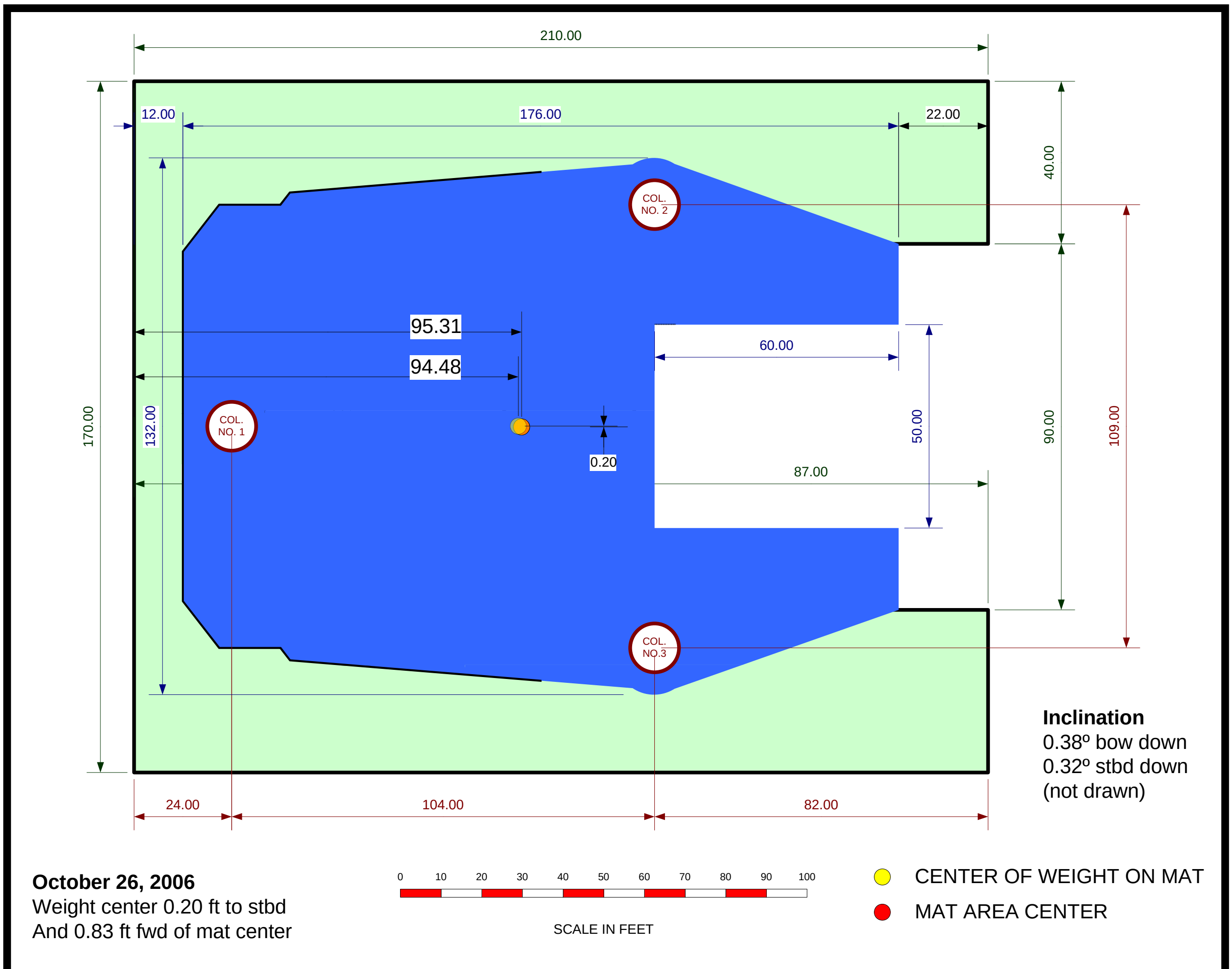

FIGURE 3 – Plan View Showing Principal Dimensions with Hull in Blue and Mat in Green. All dimensions are in feet.

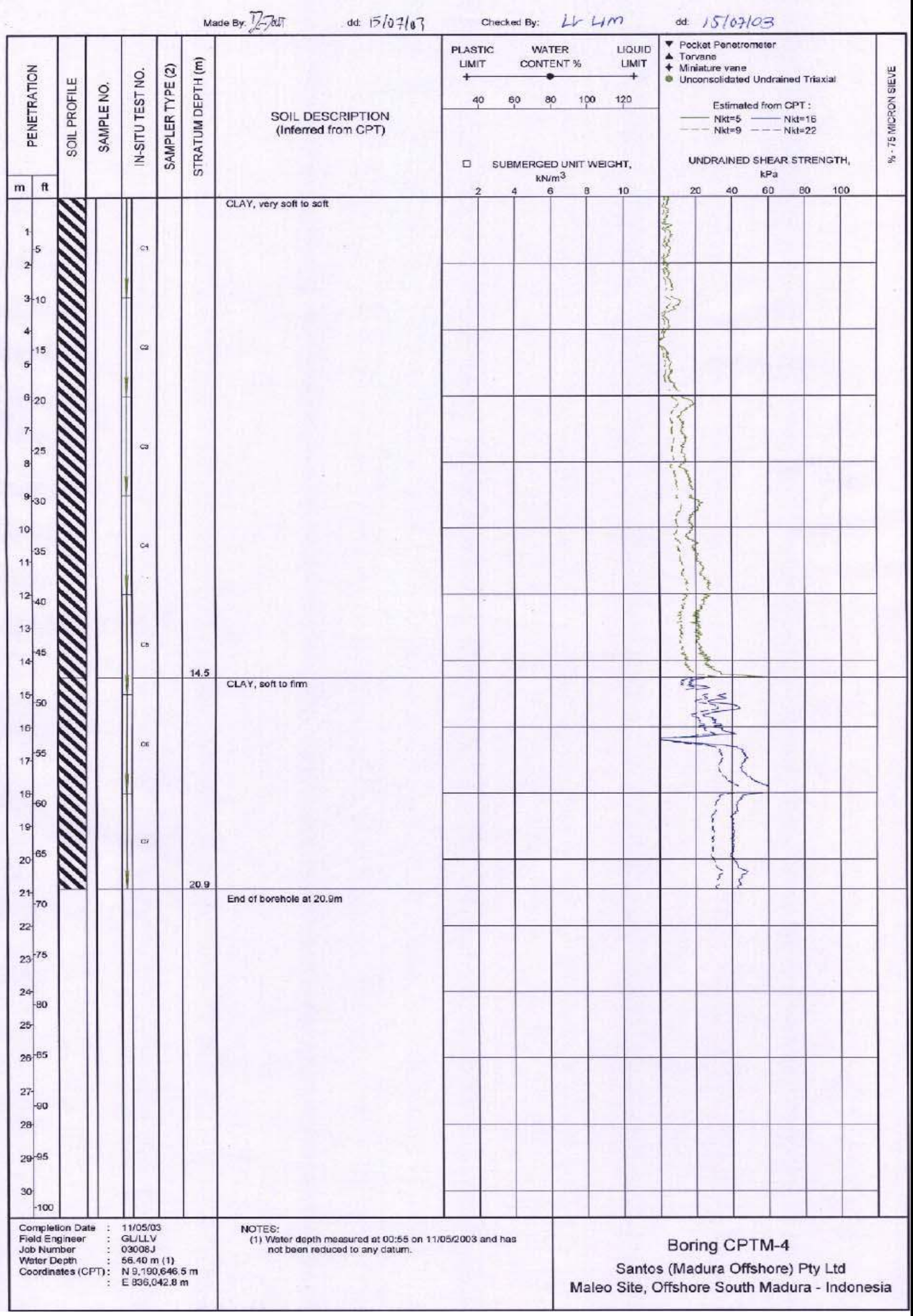

FIGURE 4: 2003 Soil Boring Log (reproduced from Fugro, 2003)

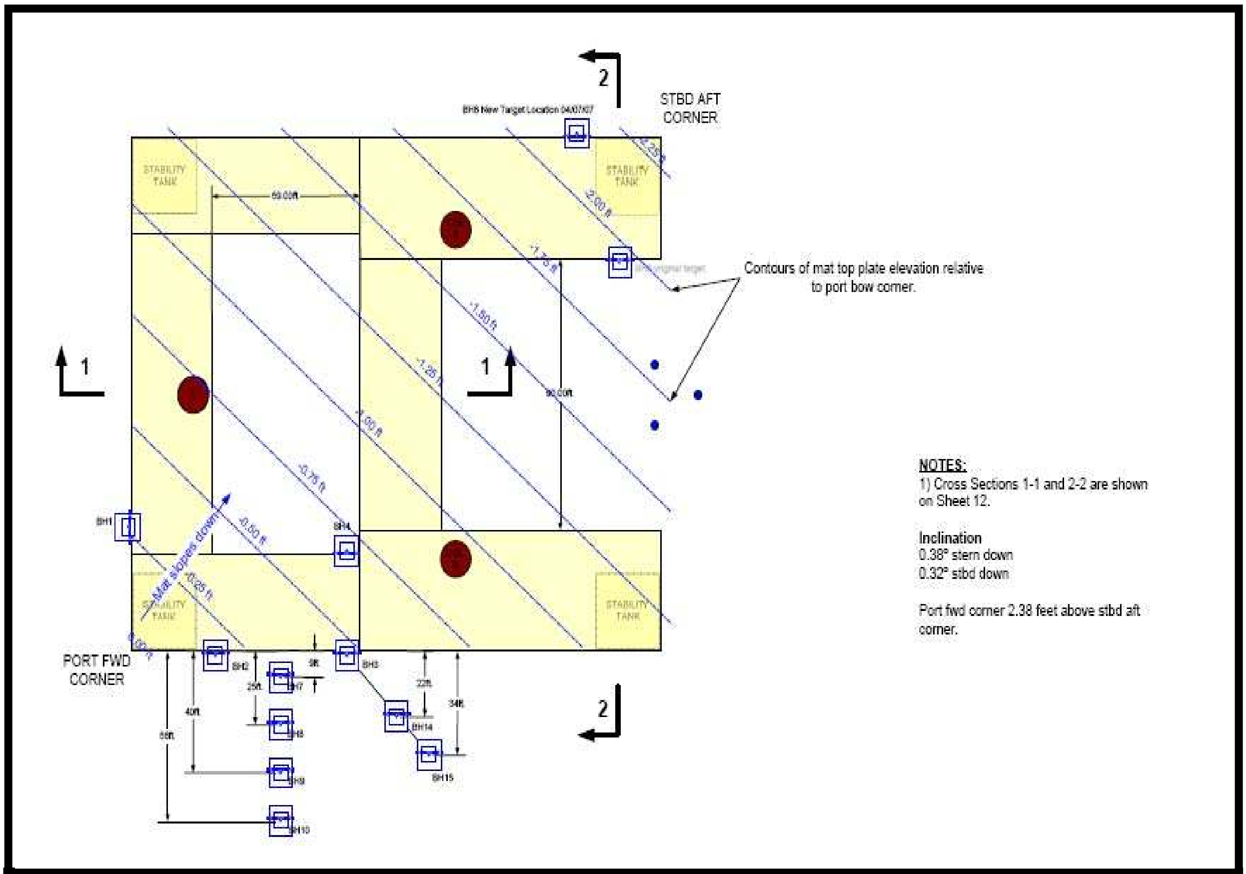

FIGURE 5: Target Boring Locations in Mat Zone Of Influence, All Within 2 Feet Distance From Mat Sidewalls

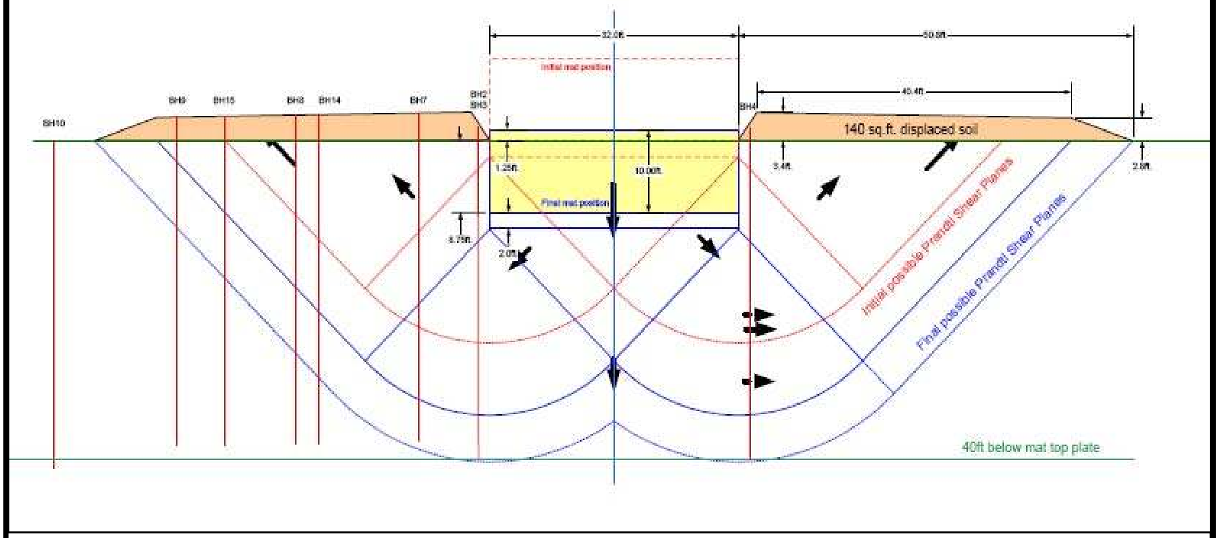

Figure 6: Schematic of Mat Penetration and Displaced Soil Heave Around Mat.
Based on Finite Element Analyses Performed by Sage USA (Templeton et al., 2008)

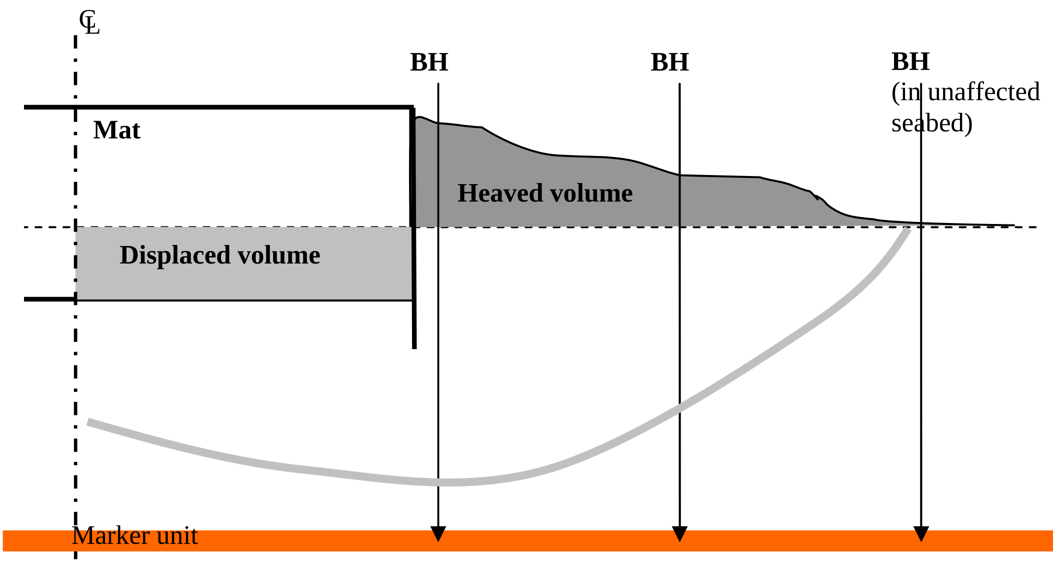

FIGURE 7: Schematic of Mat Penetration, Heave Volume and Marker Bed

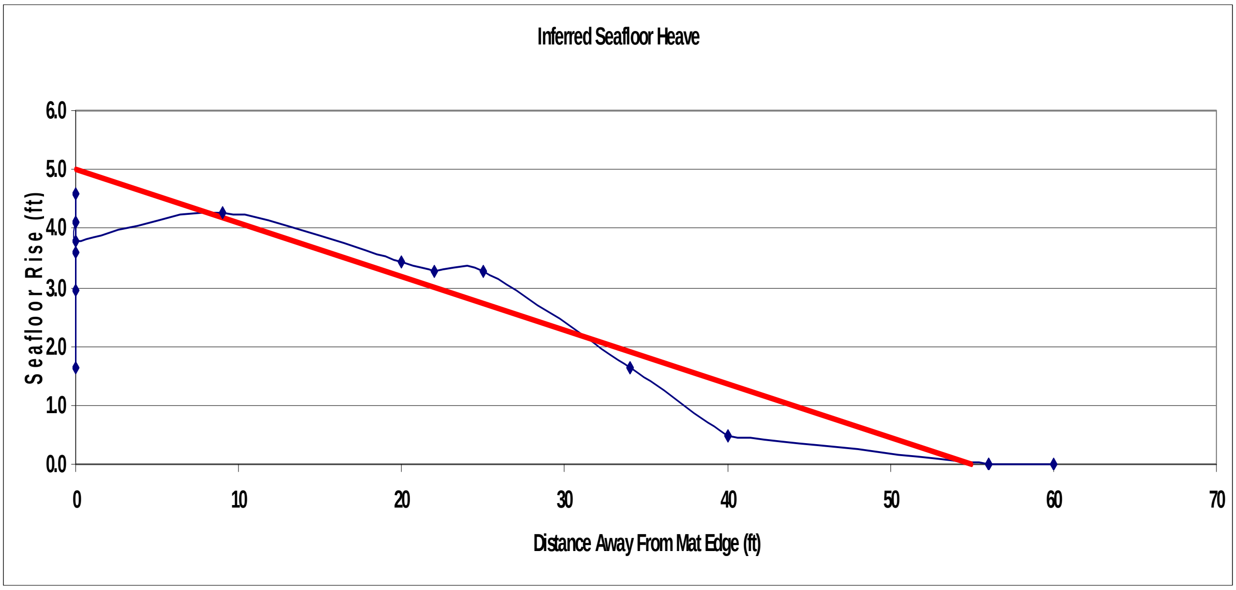

FIGURE 8: Soil Heave Inferred from Seafloor Upward Shift Based on CPT and T-Bar Tests

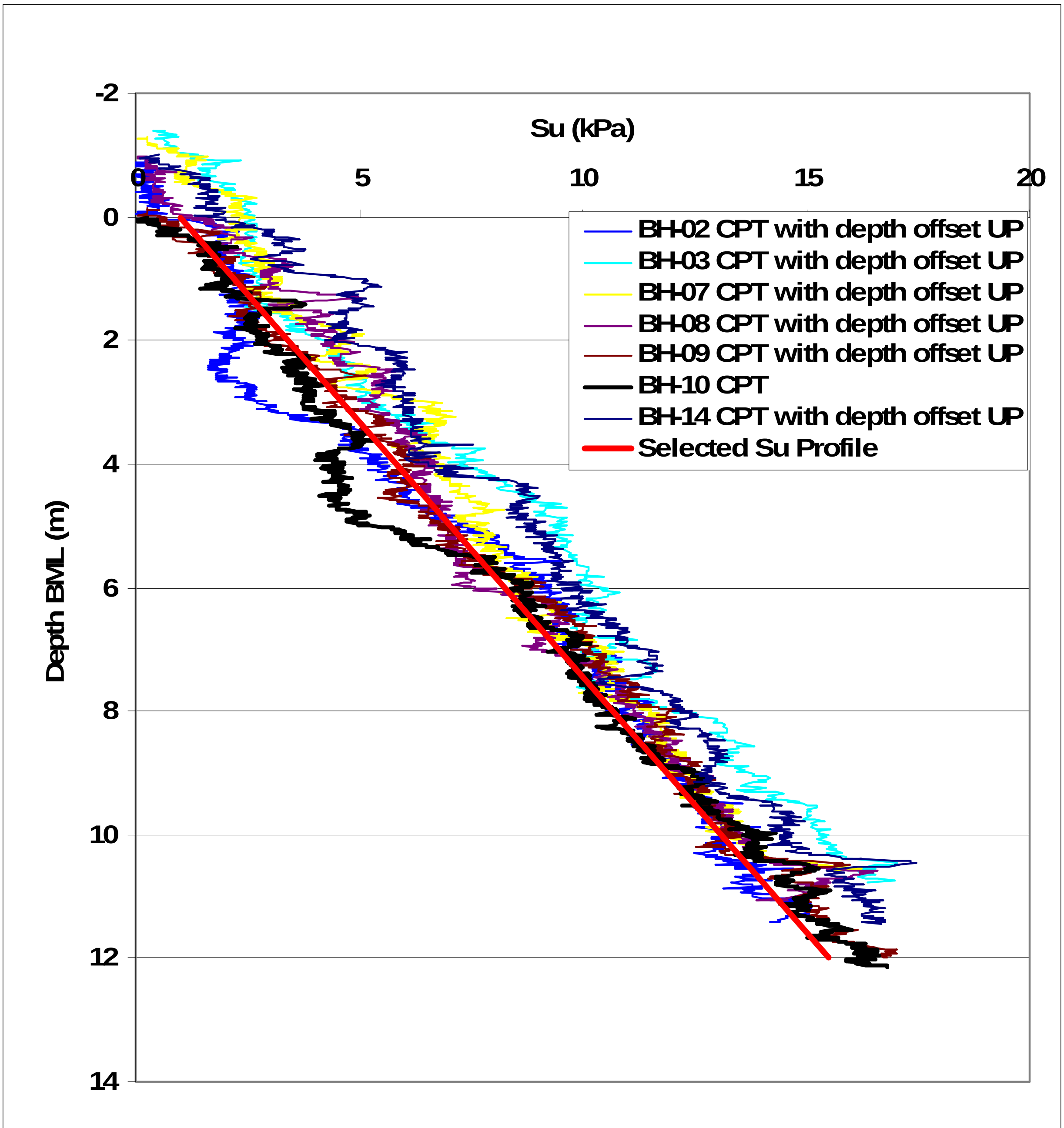

FIGURE 9. Plot of Su Interpreted from CPT BH-02, BH-03, BH-07, BH-08, BH-09, BH-10 and BH-14 Adjusted for Common Marker Statum Depth

Note: The red line shows the interpreted undrained strength profile used in the analyses of overturning stability.

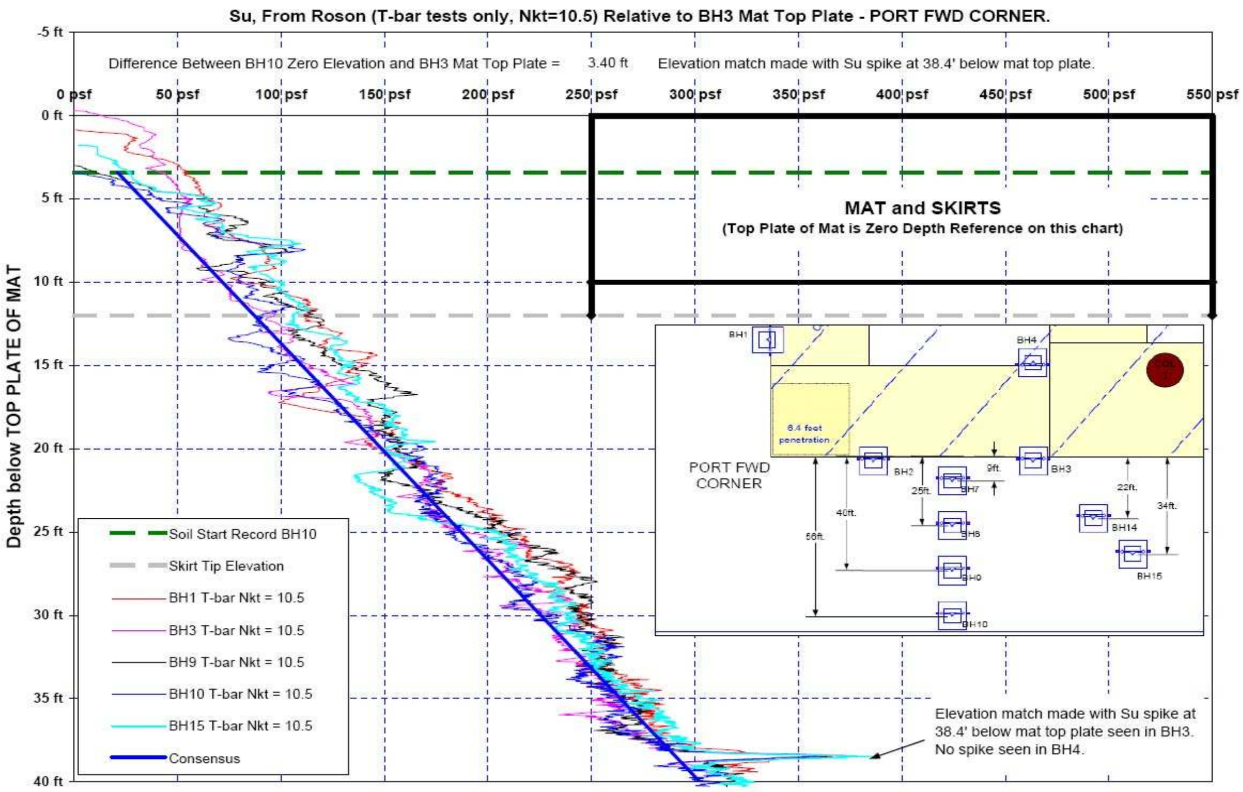

FIGURE 10 – Su Data from T-bar Tests on and Around Port Forward Corner

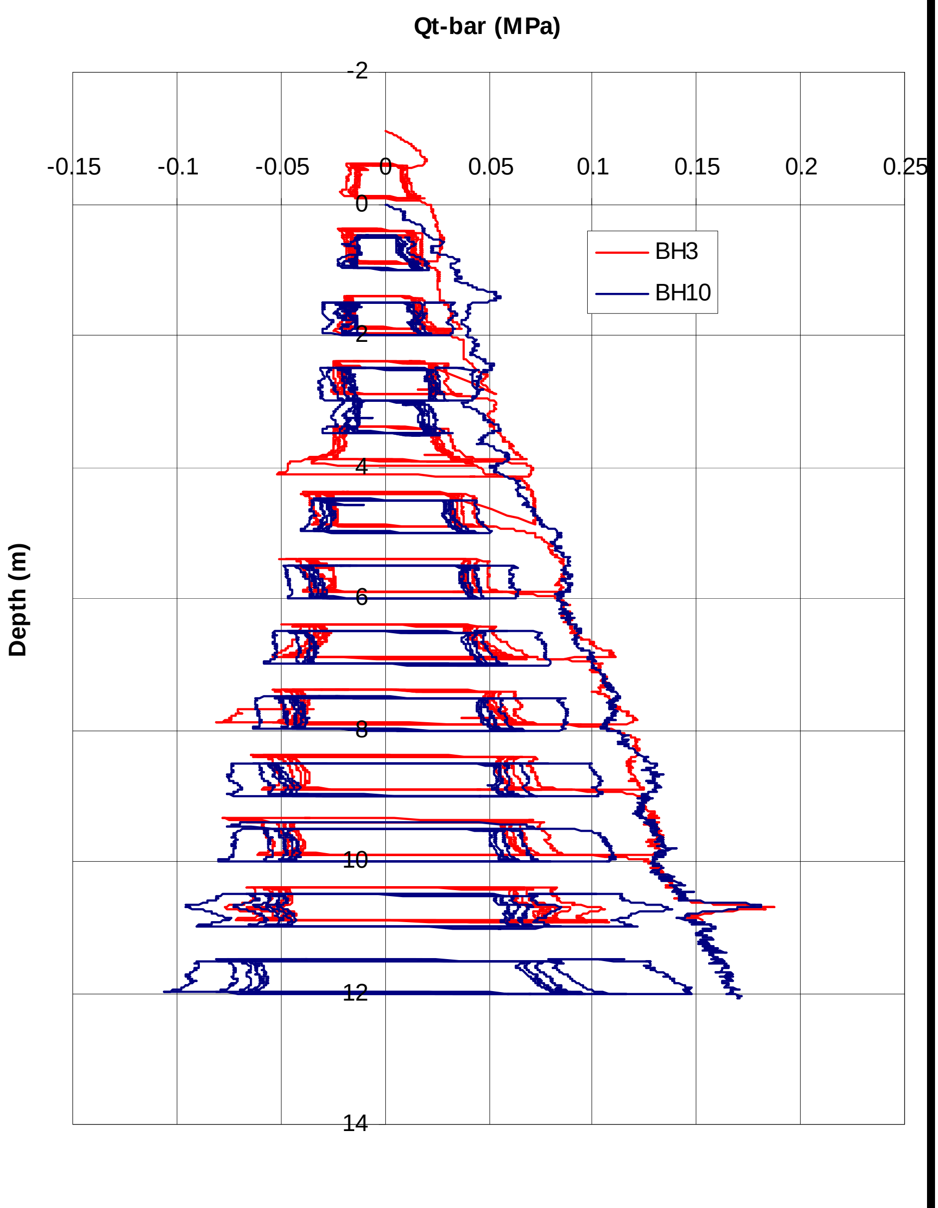

FIGURE 11: Typical Cyclic T-Bar Test