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Challenges in offshore geotechnics in Southeast Asia

Des chalenges en géotechnie marin en Asie Sud-est

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ABSTRACT

The first part of this paper describes the offshore oil and gas exploration activities in Southeast Asia. Typical subsurface conditions in the Sunda Shelf in Southeast Asia are highlighted and hazards in oil and gas exploration caused by the peculiar soil profile and parameters in the region are identified. These hazards include the punch through failure of spudcan supporting mobile jack-up rigs during installation and difficulties in removing the spudcans during extraction. The second part of this paper describes the results of centrifuge model study carried out at the National University of Singapore on punch through hazards during installation of spudcans in layered soils and performance of spudcans during extraction. The study on spudcan punch through reveals that a plug consisting of the overlying stiff soils develops when a spudcan punches through the underlying soft clay layer. Owing to such failure mechanism, conventional bearing capacity theories are not applicable to predict the spudcan punch through phenomenon. The study on spudcan extraction reveals that the suction developed at the spudcan base is the major component in the breakout resistance of spudcan with long operation periods.

RÉSUMÉ

La première partie de cet article décrit les activités de l'exploration du gaz et de pétrole marin en Asie Sud-est. Les conditions typiques du subsurface dans la region Sunda Shel en Asie Sud sont misent en valeur et les hasards d'exploration du gaz et de pétrole causées par le profil et les parameters particuliers du sol dans la région sont identifiées. Ces hasards incluent rupture du caisson de support du plateforme auto-élévatrice pendant l'installation et les difficultés d'enlever le caisson de support pendant l'extraction. La deuxième partie de cet article décrit les résultats d'une etude d'un modèle de centrifuge obtenu a l'Université Nationale de Singapour sur les hazards de rupture des caissons de support pendant l'installation dans des sols stratifiées ainsi que la performance des caissons de support pendant l'extraction. L'étude sur les rupture des caissons de support révèle qu'un bouchon consistant du sols rigide de recouvrement se devloppe quand un caissons de support rompre à travers la couche de l'argile douce au-dessous. À cause de cette mécanisme de rupture les théories conventionnelles de la capacité de la portée ne sont pas applicable pour prédire le phénomène de rupture du caissons de support. L'étude sur l'extraction du caisson de support révèle que la succion développée à la base du caisson est la composante majeure de la résistance à la rupture du caisson de support avec des longues périodes d'opération.

1 INTRODUCTION

Southeast Asia is one of the active regions in the world for the offshore explorations of oil and gas. Various types of drilling rigs are employed in the region and different geotechnical problems exist for the installation and operation of each type of rigs. Mobile jack-up drilling units, which can operate at seas up to 120-m deep and are supported by 3 to 4 independent spudcan legs, are commonly used in Southeast Asia. McClelland et al. (1982) stated that jack-up units face much greater accident exposure than most engineering structures and about one-third of jack-up accidents were due to foundation problems. In addition, owing to peculiar subsurface profile and properties in the region, Osbourne and Paisley (2002) reported that it is not uncommon for punch through failure to occur during spudcan installation and preloading. On the other hand, great difficulties can also occur when extracting spudcans from one location to another (McClelland et al., 1982). As mobile jack-up units are commonly employed in Southeast Asia and these units face much greater accident exposure, this paper will specifically address the geotechnical challenges concerning the installation and extraction of spudcans supporting jack-up units.

The first part of this paper reviews the gas and oil exploration activities within the Sunda Shelf region in Southeast Asia. Geology and subsurface conditions are then examined to highlight the situations where potential spudcan punch through hazards can take place. The second part of this paper describes the centrifuge model test program at the National University of Singapore (NUS) to investigate the spudcan punch through phenomenon in dense sand overlying soft clay and to examine the influence of suction on the extraction of spudcan. The test results and the practical significance of the findings are reported in this paper.

2 OFFSHORE EXPLORATIONS IN SOUTHEAST ASIA

US Geological Survey provides details of oil and gas exploration activities worldwide. Steinshouer et al. (2004) presented a report to the US Geological Survey on maps showing geology, oil and gas fields in East Asia, Southeast Asia and Australasia. Their data reveal that Southeast Asia is one of the active energy exploration regions in the world as a large number of oil and gas explorations are currently in operation. The major offshore oil and gas exploration fields are located in the south coast of Thailand, east coast of Malaysia, north coast of Java and Borneo islands and east coast of Vietnam. Figure 1 shows selected major oil and gas exploration fields in Southeast Asia.

Rigzone.com (2004) provides details of offshore rigs in use and their utilization rate by region inclusive that in Southeast Asia. Drilling rigs commonly used in Southeast Asia include mobile jack-up drilling units, semi-submersible rigs, platform rigs, drill barges, drill ships, tender rigs and inland barges. Figure 2 summarizes the types of offshore drilling rigs used in

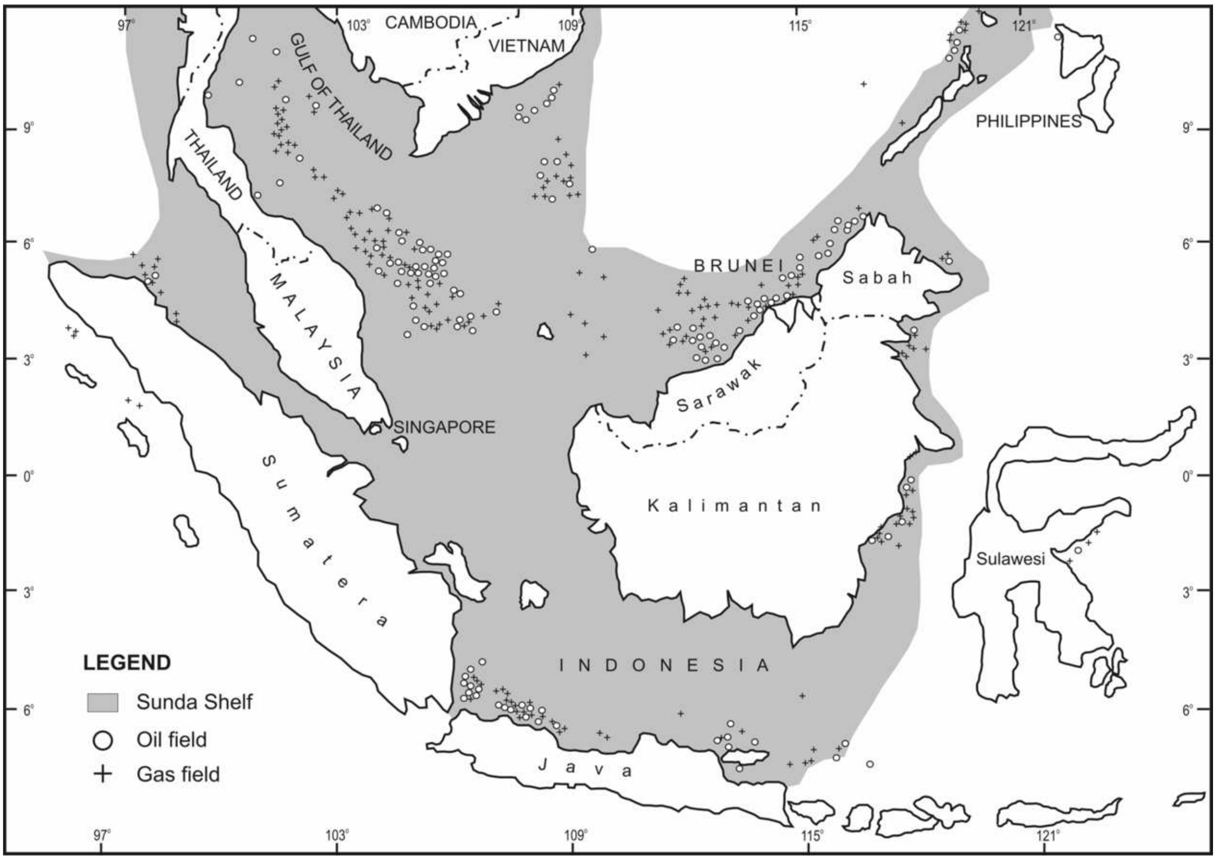


Figure 1. Map of Sunda Shelf and selected major oil and gas exploration fields in Southeast Asia

Southeast Asia and their respective number currently in operation.

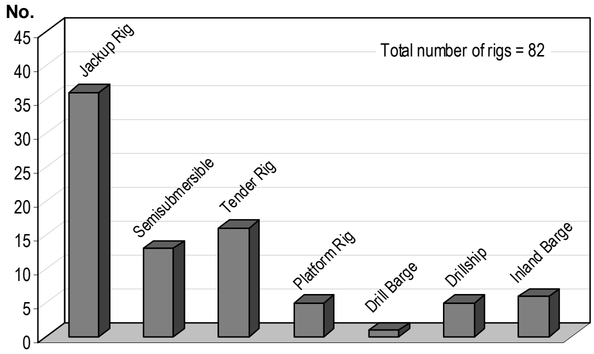


Figure 2. Utilization of offshore rigs in Southeast Asia
(source: www.rigzone.com)

It is evident that jack-up units are by far the most commonly employed drilling rig for energy exploration in the region. The utilization rate of jack-up units in Southeast Asia is shown in Figure 3. The data reveals that a large number of such units are still under construction or ready to be employed for drilling highlighting the use of such jack-up units in the region will further increase in near future.

A photograph of a mobile jack-up unit is shown in Figure 4. These jack-up units are commonly employed for drilling in waters up to 120 m deep and usually supported by 3 to 4 independent legs with individual foundation termed “spudcan”, as shown in Figure 5. The diameter of a spudcan typically ranges from 10 m to 20 m. After the completion of drilling at one location, the entire jack-up unit will be relocated to another drilling location by extracting the spudcans from the seabed. The operation modes of a jack-up unit can hence be categorized into 4 stages: namely (1) afloat, (2) installation and preloading, (3) drilling operation and (4) extraction, as depicted in Figure 6.

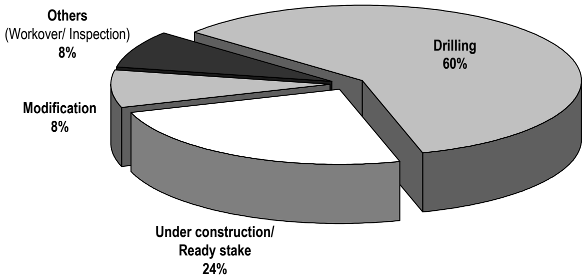


Figure 3. Utilization of jackup rig in Southeast Asia
(source: www.rigzone.com)

McClelland et al. (1982) described the operation modes of a jack-up mobile unit in some detail. They further elaborated on the possible installation and operation hazards of jack-up units. These hazards generally include the inability to carry preload at maximum leg penetration, punch through during preloading with large additional penetration, soil scouring, inability to extract the spudcan footings and seafloor instability.

3 SUBSURFACE PROFILE AND CONDITIONS

Much of the seas in Southeast Asia belong to an area termed the Sunda Shelf. Figure 1 shows the extent of the Sunda Shelf covering an area of about 3 million square km. Castleberry II and Prebaharan (1985) described the formation of the Sunda Shelf in detail. The Sunda Shelf in Southeast Asia was exposed during the worldwide lowering of the sea level in the last major glacial episode. During the subsequent rise in sea level over the past 20,000 years, marine clays have been deposited over much of the shelf.

Figure 4. Photograph of mobile jackup rig (courtesy of Keppel Offshore and Marine Ltd.)

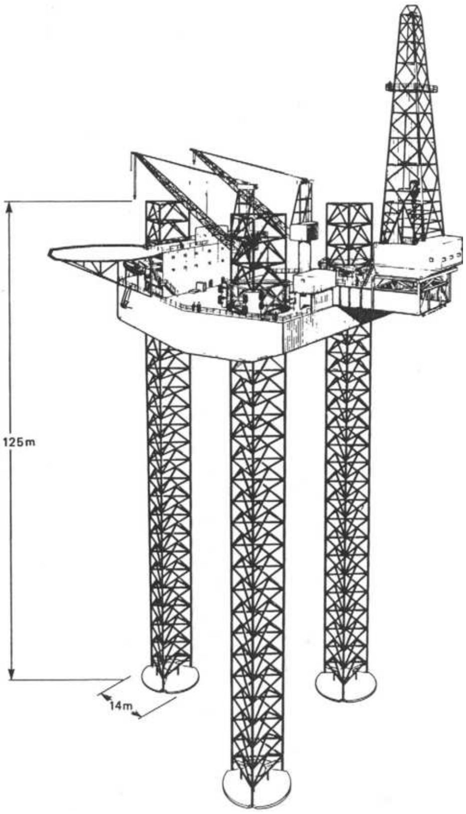


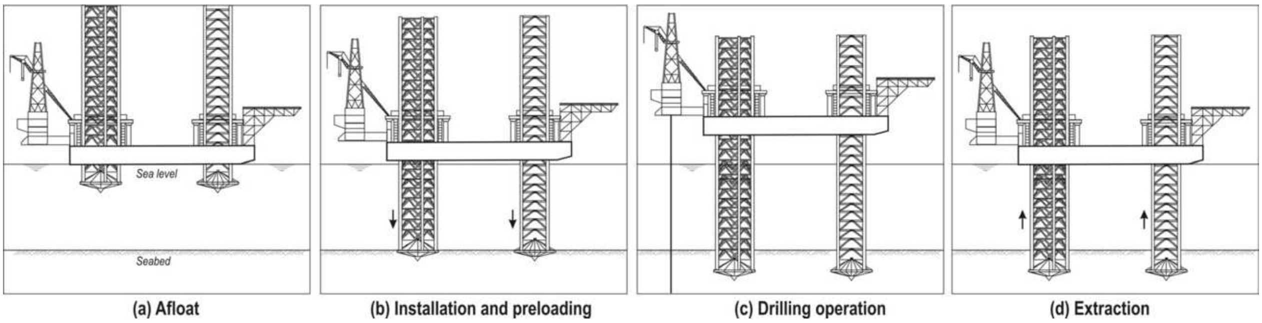
Figure 5. Typical jack-up unit (after Reardon, 1986)

Castleberry II and Prebaharan (1985) proposed a soil model for the Holocene and Pleistocene deposits of the Sunda Shelf shown in Figure 7. The upper soil layer is termed as Member A which generally consists of underconsolidated to normally consolidated marine clays of different thicknesses deposited during the last marine intrusion. They postulated that the thickness of Member A depends on the proximity to a sediment source, water depth and seafloor gradient. In some areas within the Sunda Shelf, a relatively thin stiff clay crust exists within Member A, as shown in Figure 7. These crusts are usually found less than 6 m below the seabed. Castleberry II and Prebaharan proposed that the crusts were formed during periods of exposure and desiccation and postulated a model for the crust evolution, as illustrated in Figure 8. The lower soil layer is termed as Member B which generally consists of normally consolidated to overconsolidated alluvial or marine clays.

Two examples of subsurface shear strength profile obtained recently from 2 separate offshore drilling sites in Southeast Asia are shown in Figures 9(a) and (b), respectively. These figures reveal that relatively stiff clay crusts exist at shallow depths of 6 m and 10 m, respectively. Beneath the crusts, the soil shear strength can be significantly smaller than that of the crust. When a spudcan is installed in such subsurface situation, a larger load is necessary to jack the spudcan through the stiff clay crust but the underlying soft clay may not have sufficient resistance against the penetrating spudcan resulting in plunging or punch through of the spudcan. When one spudcan of the jack-up unit experiences punch through while the other spudcans do not experience large additional penetrations, the jack-up unit would experience severe tilting as shown in Figure 10. This may cause failures in the installation and preloading process of the spudcans and demands time-consuming and costly remedies and repairs before the installation of the jack-up unit can resume.

Dier et al. (2004) analyzed over 50 incidents of failures of jack-up units worldwide and summarized the causes of failures, as shown in Fig. 11. They noted that spudcan punch through failures represent 53% of all incidents. Punch through problems can be further subdivided: (a) 8% of all incidents are associated with punch-through caused by hurricanes, (b) 14% with punch-through during preloading, and (c) 31% with no stated underlying punch-through cause. They also reported that out of 24 fatality cases, 19 are due to punch through failure.

Osbourne and Paisley (2002) reported that the risks of punch through hazards for mobile jack-up drilling units appeared to increase considerably in Southeast Asia in recent years. On average, punch through of spudcan has occurred at an alarming rate of 1 incident per annum with the estimated monetary cost ranging from US$1 million to US$10 millions to fix each incident. They recommended that a historical review of punch through cases in Southeast Asia to be made in relation to the subsurface profile and properties of each case and the development of 'best practice' guidelines for jack-up unit site assessment.



(a) Afloat (b) Installation and preloading (c) Drilling operation (d) Extraction

Figure 6. Typical operation modes of a mobile jack-up unit

As the operation of jack-up units is generally mobile in nature, they are not designed for any site-specific condition (Poulos, 1988). The penetration depths of the spudcans may hence vary greatly depending on the seabed conditions. Extraction of an embedded spudcan may be difficult, especially in soft clays with deep penetration. McClelland et al. (1982) reported a case in Mississippi Delta region that the spudcans penetrate to a great depth of 55 m below the seabed and a huge effort is required to extract such deeply penetrated spudcans. It is definitely not economical if a rig operator cannot extract the spudcans or takes a long time to extract them.

4 CENTRIFUGE MODEL STUDIES

It has been established earlier that spudcan punch through hazards and extraction are two common problems encountered for jack-up drilling units. In view of this, centrifuge model studies have been carried out at NUS to evaluate the spudcan behaviour during installation and extraction. This is a part of the research programs initiated at the NUS's Centre for Offshore Research and Engineering (CORE) which was officially launched in September 2004 to facilitate multi-disciplinary research in offshore engineering. As much of the research program also deal with soft soils, the experience gained and the findings established by earlier research studies on soft soils carried out at the NUS's Centre for Soft Ground Engineering are extremely beneficial.

A photograph and a sketch of the centrifuge model setup for the present study are shown in Figures 12 and 13, respectively. It should be noted that the model soil profile consists of an upper dense sand layer underlain by normally consolidated soft clay, which is different from that in the Sunda Shelf subsurface conditions. As it is rather difficult to prepare a soil profile of stiff clay overlying soft clay for centrifuge testing, it has been decided that as a preliminary study, an alternate soil profile of dense sand overlying soft clay was first investigated. All tests were performed at 100g. A model container of 500 mm in diameter and 400 mm high was used. The kaolin clay slurry was thoroughly mixed under vacuum at 1.5 times its liquid limit and then consolidated under 100g for 8 hours. After self-weight consolidation of soil was completed, the upper dense sand layer was prepared by raining Toyoura sand at a constant drop height. The sand was then saturated by applying vacuum on the top and water was allowed to flow into the model container through a tube at the elevation of sand-clay interface.

In all cases, the spudcan was installed using a servo-controlled hydraulic actuator. During installation, the penetration resistance (load) was measured by a load cell and the spudcan penetration was measured by a long-travel potentiometer. The spudcan was instrumented with total and pore pressure transducers at the top and base of the spudcan, as illustrated in Figure 14. A set of miniature cone penetration test equipment was also mounted on the loading frame to measure the soil strength in-flight. The measured shear strength profiles reveal that the clay is normally consolidated except near the sand-clay interface which is subjected to sand surcharge.

For the tests involving spudcan extraction, the upper dense sand layer was omitted so that the spudcan would not punch through during installation. The soil preparation procedure is essentially similar to that described for the punch through studies except that there was no preparation of the upper sand layer.

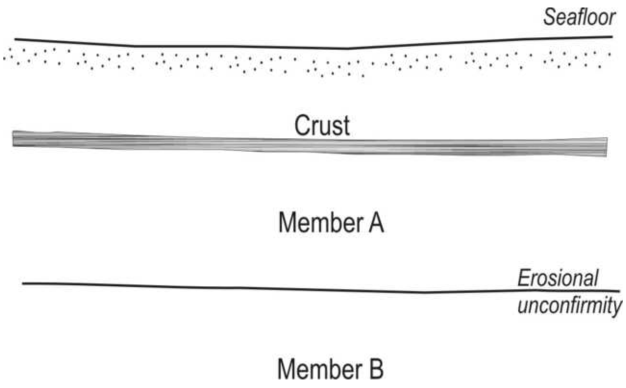
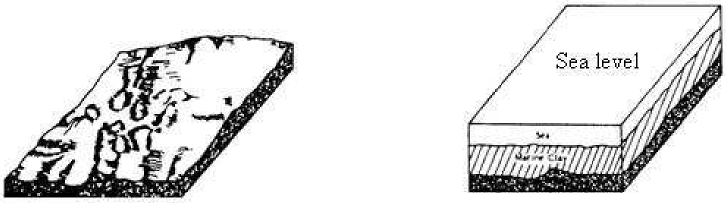
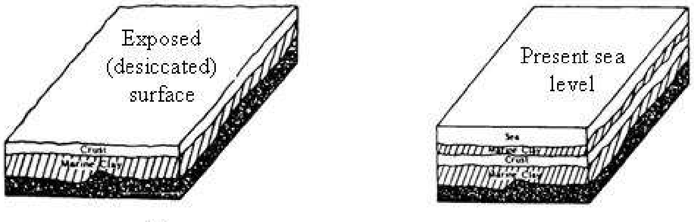


Figure 7. Soil model for the Holocene and Pleistocene deposits of the Sunda Shelf (after Castleberry II & Prebaharan, 1985)



(a)
Late Pleistocene
Erosinal Surface (Member B)

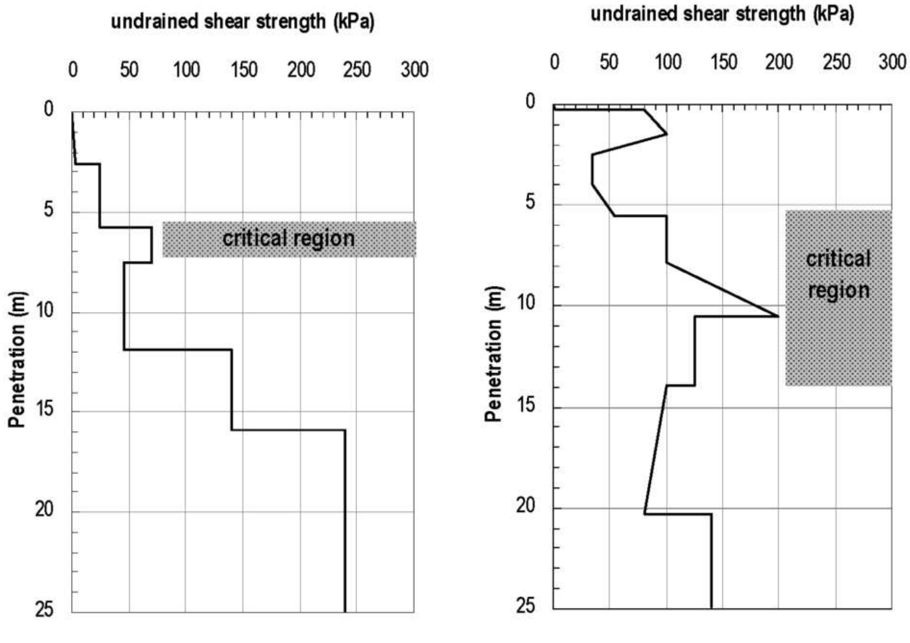
(b)
Initial Marine Transgression
Deposition of Marine Clay (Member A)



(c)
Marine Regression
Expose of Marine Clay – Formation of crust

(d)
Final Marine Transgression

Figure 8. Crust evolution model (after Castleberry II & Prebaharan, 1985)



(a) (b)

Figure 9. Two examples of subsurface shear strength profile in Southeast Asia

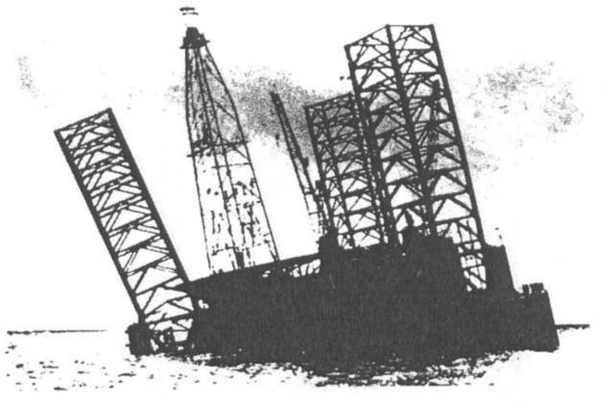


Figure 10. Failure of Triton II jack-up rig (after McClelland et al., 1982)

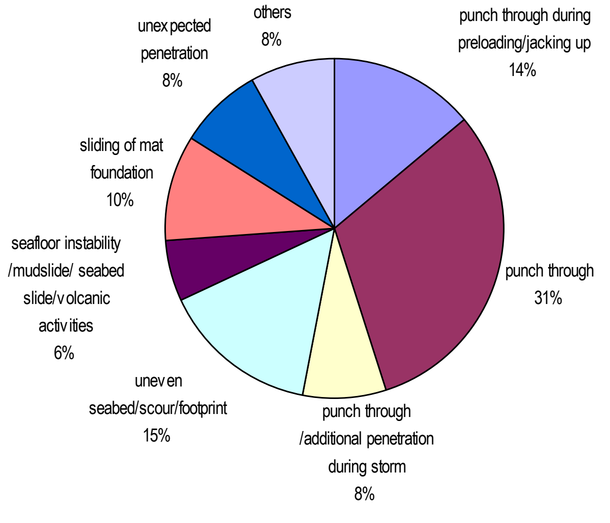


Figure 11. Case histories according to the cause of failure (after Dier et al., 2004)

5 SPUDCAN PUNCH THROUGH STUDIES

Once the sand was saturated for the tests involving spudcan punch through, the potentiometers were placed, the loading frame was mounted, and the model spudcan and miniature cone penetrometer were attached to the model setup. The model container was then subjected to 100g again until the clay was fully consolidated under the new sand surcharge. Once the soil consolidation was completed, miniature cone penetration test was carried out to measure the shear strength of the soil. The test was conducted at a location at mid-way between the model container centre and boundary such that it does not affect the subsequent spudcan test (located at the container centre) and is essentially free of the boundary effect of the model container. The spudcan was installed under load-controlled mode. Throughout the spudcan penetration process, the readings of the load cell and the potentiometers were monitored at frequent intervals.

Unless otherwise stated, all the test results are presented in prototype scale hereinafter. The penetration resistance (load)-depth responses obtained from a typical test is shown in Figure 15. In this test, the spudcan has a prototype diameter of 10 m and the upper dense sand layer is 7 m thick. As expected, Figure 15 shows that the load initially increases with penetration depth. Upon reaching a penetration depth of about 1.3 m, the penetration resistance reduces indicating that the spudcan has plunged. In order not to damage the servo-controlled actuator during the punch through process, the load cell was allowed to respond accordingly.

This is unlikely to be so in the field and the applied load on the spudcan would be maintained and the spudcan would immediately punch through a great depth into the lower soft clay before it came to rest. The recorded punch through load is marked by the dash line shown in Figure 15. The plunging depth is estimated to be about 7 m before the spudcan would not penetrate further, as indicated in Figure 15. Several other tests have recently been completed to examine the effects of upper sand layer thickness on the punch through process. These results will be reported in Teh et al. (2005). Further tests are also planned to investigate the punch through process of spudcan in stiff clay crust overlying soft clay.

Preliminary comparison between the measured spudcan punch through load and those predicted values from conventional bearing capacity theories (for example Hanna and Meyerhof, 1980) reveals that the theories are not applicable to predict the punch through load accurately. To examine the punch through mechanism in greater detail, the test was repeated using a half-cut spudcan in a rectangular model container with a transparent perspex front window. The test process was recorded by a series of photographs using a high resolution camera. Four photographs obtained from different test stages are shown in Figures 16(a) to (d). It is evident that a sand plug has developed beneath the spudcan base during the punch through process. Particle Image Velocimetry technique (White et al., 2001) is currently employed to analyze the failure mechanism of the punch through process with a view to develop a rational design method to predict the spudcan punch through phenomenon.

6 SPUDCAN EXTRACTION STUDIES

As the upper sand layer was absent for the tests involving spudcan extraction, the spudcan would not plunge during installation. After the spudcan was installed to about 19 m depth, an operation working load of ranging from 25% to 75% of the installation load was maintained on the spudcan for various specific time periods. Miniature cone penetration test was conducted to measure the soil strength profile before the spudcan is extracted. During the entire test process, the spudcan load and displacement, total and pore pressures at the top and the base of the spudcan were monitored at regular intervals.

Figures 17(a), (b) and (c) show respectively the development of spudcan load and displacement, total vertical pressures and pore water pressures obtained from a typical test. In this test, the spudcan diameter is 12.5 m. The penetration resistance is recorded to be 30.9 MN at the final penetration depth of 18.9 m. The operational working load is maintained at 75% of penetration resistance for 53 days. The prototype time scale in Figure 17 is presented by assuming soil consolidation is the dominant event such that prototype time is equal to model time multiplied by the square of the gravitational field. It should be noted that the presentation of time is solely for convenience and this scaling law is only applicable to the operation period and may not be valid for the installation and extraction periods.

Figure 12. Photograph of centrifuge model setup

Figures 17(b) and (c) reveal that the total vertical and pore pressures at the top of spudcan increase almost linearly with penetration depth. However, the magnitudes of total vertical and pore pressures at the spudcan base are considerably larger than those at the top. The maximum increase in pore pressure generally occurs at the centre and decreases radially outwards. During the spudcan operation period, the pore pressures at the spudcan base dissipate with time while those at the spudcan top do not experience significant changes.

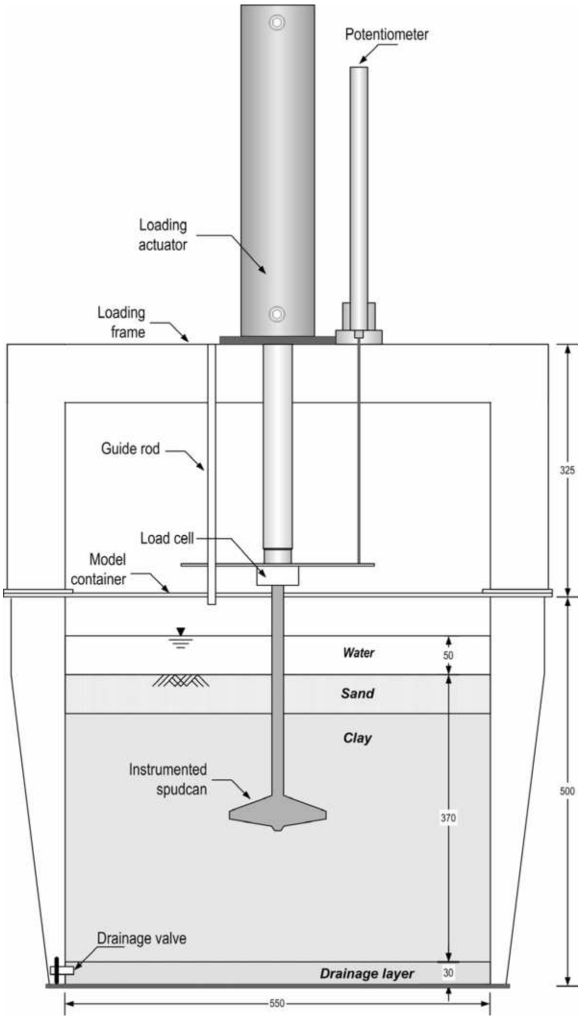


Figure 13. Centrifuge model setup

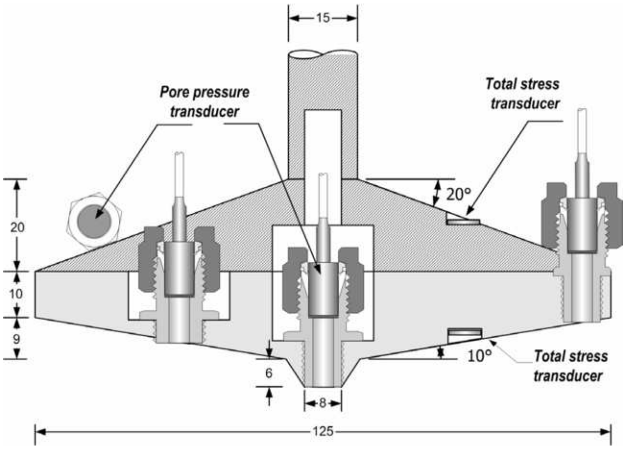


Figure 14. Model spudcan

Extraction was carried out using displacement control mode by releasing the compressive load on the spudcan and subsequently applying a continuous upward movement to the spudcan which results in tension load, as illustrated in Figure 17(a). The extraction created immediate increases in total vertical and pore pressures at the top of spudcan and reach the peak values after a 0.5-m upward displacement, see Figures 17(b) and (c). A much larger reduction in total vertical and pore pressures at the spudcan base was noted. It is noted that the changes in pore pressure and total vertical pressure are of similar magnitude, suggesting that the applied uplift force is translated mainly to the change in pore pressure rather than in effective stress. A maximum uplift resistance of 19.5 MN was recorded at an uplift displacement of about 2 m (15% spudcan diameter). After which, the uplift resistance gradually decreases coupled with corresponding changes in total vertical and pore pressures at the spudcan base.

The maximum reduction in pore pressure takes place at the centre and decreases radially outwards. It is believed that the spudcan base experiences an artificial downward pressure upon extraction with the development of negative excess pore pressure or suction. Craig and Chua (1990) attributed the reduction in the uplift resistance to water entering the interface between the soil and the spudcan base breaking the suction at the interface. A mass of relatively stiff clay was observed stuck at the top of the spudcan after spudcan extraction, see Figure 12.

It is postulated that the uplift resistance consists of three major components; namely the effective self weight of the spudcan, the soil resistance above the spudcan and the resistance at the base of the spudcan. The results presented here refer to the net uplift resistance with the exclusion of the self weight of the spudcan. The soil resistance above the spudcan, termed as R_1, can be determined from the average total pressure measurements at the spudcan top. This is obtained by taking a weighted average of all total pressure readings at the spudcan top in relation to the tributary plan area of each transducer. The earlier interpretation reveals that suction at the spudcan base can be the major contribution in the resistance beneath the spudcan base.

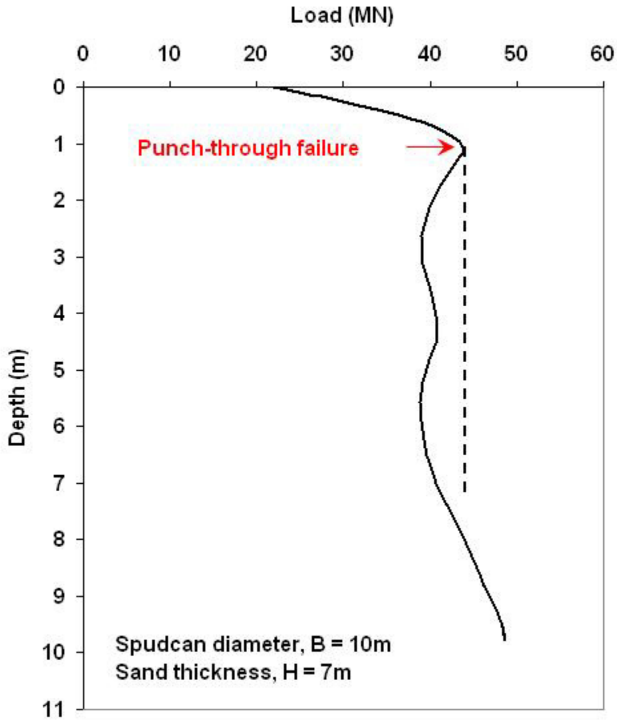
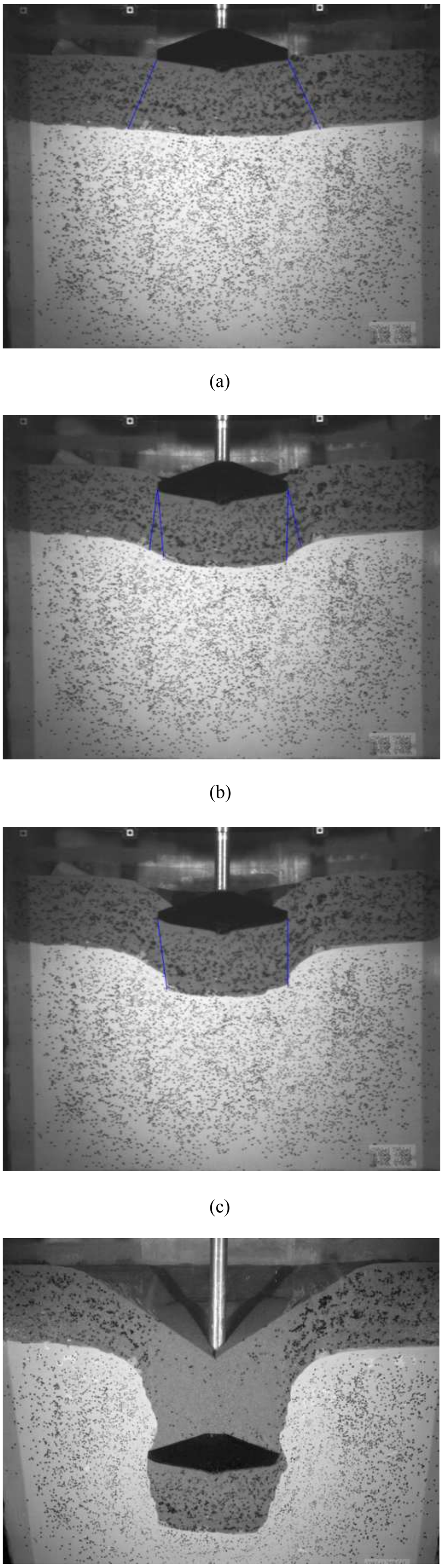


Figure 15. Typical spudcan punch-through test results



(a)

(b)

(c)

(d)

Figure 16. Photographs taken at different stages of half spudcan test

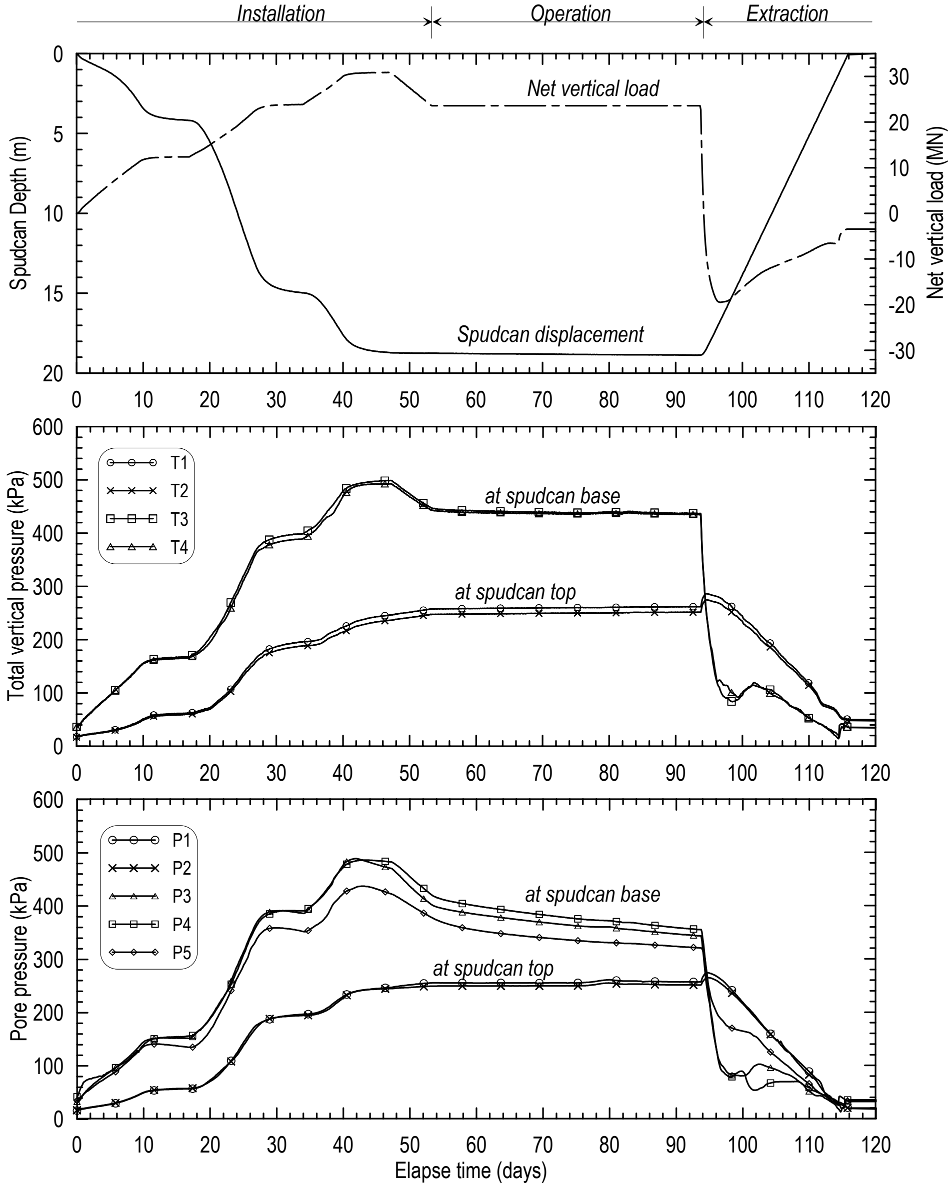


Figure 17. Time records of a typical spudcan extraction test

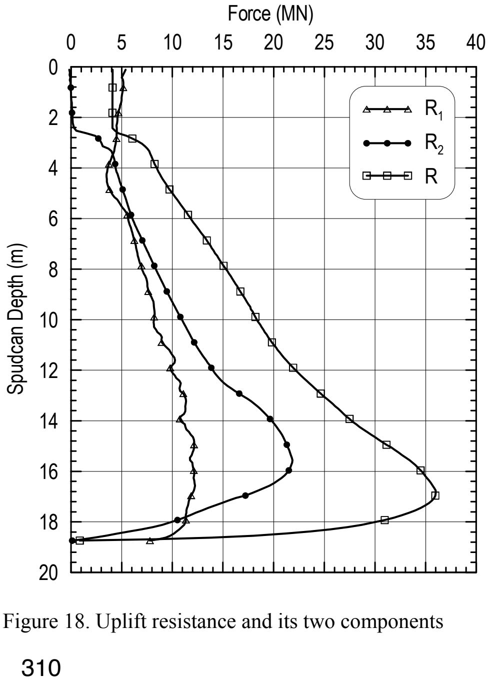


Figure 18. Uplift resistance and its two components

In view of this, the average suction resistance at the spudcan base, termed as R_2, is determined from the weighted average of all excess pore pressure readings at the spudcan base.

The development of net uplift resistance as measured by the load cell minus the spudcan self weight, R, and its two components R_1 and R_2 during the extraction process are shown in Figure 18. The arithmetic sum of R_1 and R_2 is found to be reasonably close to the load cell readings, revealing the method of interpretation in the present study is valid. Figure 18 illustrates that the suction at the spudcan base, R_2, is the major component of the uplift resistance.

Interpretation of more test data is currently in progress and will be reported in greater detail by Purwana et al. (2005). Preliminary findings reveal that the soil suction depends on the duration of the operation period. The longer the jack-up unit in operation, the larger the dissipation of excess pore pressure, resulting in greater amount of suction developed at the spudcan base upon extraction. Thus a larger uplift resistance is required to extract spudcans with longer operation periods.

7 CONCLUSIONS

In this paper, the offshore gas and oil exploration activities in Southeast Asia are reviewed. It is established that mobile jack-up drilling units are by far the most common type of drilling rig employed for offshore energy explorations in the region. These jack-up units are generally supported by 3 to 4 leg spudcans. By examining the geology, subsurface profile and properties of the Sunda Shelf in Southeast Asia, it is found that the presence of stiff clay crust within the soft clay stratum poses considerable punch through hazards for the installation and preloading of spudcans. Owing to the mobile nature of jack-up units, they are not designed for any site-specific conditions and hence their penetration depth varies greatly from site to site. It has been reported that difficulties often occur when extracting the spudcans from one location to another. In view of the above scenarios, this paper specifically addresses the geotechnical challenges concerning the installation and extraction of spudcans supporting mobile jack-up drilling units.

In order to examine the spudcan punch through hazards and extraction difficulties, centrifuge model tests have been conducted at the National University of Singapore. The model spudcan is extensively instrumented to monitor the changes in total vertical and pore water pressures at the spudcan top and base. For spudcan punch through studies involving dense sand overlying soft clay, it has been found that a sand plug develops beneath the spudcan base upon punch through. As such conventional bearing capacity theories are not applicable for the prediction of spudcan punch through load. For spudcan extraction studies, it is established that suction developed at the spudcan base is the major contributing resistance in the uplift resistance for spudcans with longer operation periods. Further studies are currently in progress to examine the mechanism of spudcan punch through and extraction in detail.

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