SIMULATION OF FOUNDATION STABILITY OF A JACK-UP RIG

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ABSTRACT

The procedure for assessing foundation stability of jack-up rig (self-elevating drilling unit) on offshore soil has become increasing important as a result of the frequent incidence of rig damage and in some cases total collapse of the rig. In this investigation, computer simulation in assessing the foundation stability during a preload check of production jack-up rig is presented. Predicted results of two analytical methods are compared to establish the reliability of an initial theoretical assessment of the procedure. The methods used gave good agreement. A framework for these assessments ensures the safe operation of jack-up rigs in deeper waters.

KEYWORDS: Jack-up rig, foundation stability, preload check, environmental load

INTRODUCTION

With the exploration and exploitation of oil and gas gradually moving from onshore to offshore continental shelf and deeper sea adequate operational safety of offshore drilling rigs has to be employed to bring the oil and gas to the surface. According to a technical feature of Offshore Technology (1999), the offshore installation process is a critical factor for the commercial success of a subsea infrastructure. When drilling platforms first moved into coastal and offshore waters, rig movement and installation were not seen as very difficult tasks but when oil drilling adopted the jacking systems, simple solutions to determine foundation stability were no longer possible. Numerous incidents leading to total rig collapse occurred and stricter safety measures were adopted in the operation of jack-up rigs. According to Det Norske Veritas (1981), foundation failure has been the main cause of jack-up rig accidents ranging from loss of lives to a varying degree of damage to the structure and drilling equipment. Offshore drilling rigs have to be relatively stable during the drilling process, and at all times irrespective of soil, waves, water current and weather conditions.

The procedure and criteria for specific site assessment of mobile jack-up unit has lately been the subject of increased attention (Schotman and

Efthymiou, 1990). The main reason for the interest is due to the diversity of the current procedure and criteria and the need to harmonise them in view of the increased use of jack-up units in deeper and environmental unfriendly region like the North Sea.

Soil structure interaction is very important but extremely complicated and uncertain due to soil conditions, loading pattern and design of leg footings (Det Norke Veritas, 1985). Hence soil engineers are normally engaged to carryout soil analysis for any new site for the installation of a rig. One feature that has moved the rig to water depth of about 150m is the use of spud-cans (footings) fitted with 'skirts'. On most soil conditions, a skirt will increase the bearing capacity at the seabed and thereby increase the ability of the jack-up to meet higher environmental loads (Technical feature, Offshore Technology, 2000).

In location assessment, the foundation is generally considered to be acceptable if 100% preload capacity is available. In homogenous sandy soil, this may be possible but in many other cases it is not and installation may become potentially unsafe. Hence, a more rational framework underlying the assessment of foundation stability is required. The use of computer simulation model as an initial theoretical assessment is seen as a valuable tool and it is now playing a key role in the selection of field development concepts (Rowe, 1999).

For the theoretical analysis in this work, the principal particulars of a production jack-up rig are used in the simulation of the foundation stability. The basic criterion governing the stability of the rig is that the leg reactions and penetration must not exceed the permissible 100% preload value. In order to ensure that this condition is met, the design load of the unit is first calculated to ensure that the settlement or penetration is within limits. This load is the bearing capacity or ultimate bearing stress, which if exceeded may cause local failure of the rig.

DESCRIPTION OF THE MAIN SYSTEMS OF A JACK-UP RIG

A Jack-up rig shown in Figure 1is a self elevating drilling unit having a hull of sufficient buoyancy to transport the unit to a desired location, At the desired location, the hull is raised to a predetermined elevation above the sea surface on its legs are supported on the sea bed. The following main components and systems of the rig are briefly described.

Jacking system

Majority of the jacking systems of jack-up drilling units have three triangular or square legs (column) as shown in Figure 1, but some have four legs. Both the hull and the legs can be jacked up or down during rig movement. Electrical, hydraulic or pneumatic jacking systems are used to raise and lower the legs. At the end of the legs are fitted spud-cans with skirts, which increase the bearing capacity on the seabed.

Ballast and Preload System

This system consists of water tanks for preloading the rig. Some of the tanks are used as ballast water tanks for trimming the hull while afloat. The tanks are filled with seawater by submersible pumps and emptied by gravity.

Hoisting System

A hoisting system is used to lift or lower the drill stem and casing during the process of drilling a hole and lining it. It consists of draw works often called hoist, derrick or mast, crown block, traveling block and wire-rope drilling line. The drilling line connects the draw works to several pulleys or sheaves in the crown block and then to another sheaves in the traveling block.

Circulation System

The main functions of circulation of drilling fluid include the transportation of drill cuttings to the surface, clean the bottom of the hole, cool and lubricate the drill bit and stem as well as support the walls of the well and prevent formation fluid into the well. Mud pumps draw in mud through a suction line from the mud-pits or tanks and send it out to a discharge line through a stand pipe on the rig floor into a strong flexible rotary hose which joins the swivel through a drive at the drill stem to the bit where it jets out and removes cuttings away from the bits. Finally, the mud is lifted to the surface through an annulus to the mud return line from where it flows to a unit called shale-shaker. The circulating fluid may either be water, mud, oil, air, gas or a mixture of these fluids.

Rotary System

The function of the rotary system is to rotate and hold the drill string in the hole. It turns the drill string and its attachments. Rotating equipment include the kelly or top-drive, swivel, rotary table, drill string and the bit.

Power Generating and Transmission Systems

Diesel engines are normally used as prime movers on a rig for propulsion and electric power generation. Power is transmitted from prime movers to various machineries by mechanical or electric drives. Gears, clutches, pulleys, chains etc. are used in the mechanical drive system while for electrical drive, DC-DC or AC-DC units are used through a silicon controlled rectifier (SCR) system. In addition to the main drive, a rig usually utilizes AC motors to run auxiliaries that are powered by the main electric drive. The power requirement for drilling varies with the number of equipment, depth of well and the environment.

PROCEDURE FOR PRELOAD CHECKS

A jack-up rig relies on water ballast for stability during towing, elevation or lowering of the rig's columns (legs) to the seabed and operation at drilling location. Either an electric, hydraulic or pneumatic jacks is used to raise and lower the columns, which are cylindrical, square or triangular in design.

In order to prevent foundation failures during drilling, stormy weather, extreme wave and current situations, preloading operation is required. This is a process of pumping seawater into preload (ballast) tanks, which causes the spud-cans of the legs to penetrate further into the seabed thereby increasing the soil bearing capacity. The ballast water is added in stages to bring the weight of the unit to its normal working load. After a satisfactory preloading of the foundation, the hull is elevated to a safe seawater level, clear of extreme wave crest to enable the rig operate without wave disturbance.

The preloading provides a check on the bearing capacity of the soil that supports the unit. If the location has very soft mud, a mat is lowered to the bottom of the seabed to create foundation for the legs. The preload process is complete when the spud-cans have penetrated to a soil stratum with a bearing capacity sufficient to support the fully preloaded weight of the unit without further penetration. (Rapoport, et.al, 1989).

According to Schotman and Ethymiou (1990), the key advantage to the preload check is that it is simple to use but it has a number of drawbacks. The preload check in this simulation assumes that the soil capacity is determined only by the vertical loading using ballast water while in reality a small horizontal force from underwater current can play a significant role that may result in rig failure despite satisfactory preload requirement. Failure may arise if the shearing resistance of the soil and its strength capabilities are not properly evaluated. Other shortcoming includes the non-consideration of wind, wave and current effects. Self-elevating units are designed for various maximum water depths. For successful operation, a thorough knowledge of soil bearing capacity at the particular location, expected wind and wave-forces, tidal variation for the season of the year and maximum water depth are required.

THEORY

Determination of Leg Reactions

Assumptions:

1. That during the preload checks, the bearing capacity is determined only by the vertical loading.

2. No safety margins are given for environmental forces (wind, waves or current), degradation of soil and uneven application of the preload.

The three legs (jack-up columns) are designated: Bow (R_B), Starboard (R_S) and Port (R_P) as shown in Figure 2 while Figure 3 displays the plan view of the rig. The weight acting on the legs is due to preloading of the rig with ballast water into the preload tanks. During and after the preloading, both the longitudinal and transverse centres of gravity (LCG and TCG) must be within acceptable limit for stability to be achieved. Preload check of 100% is commonly used in jack-up foundation assessment. It therefore, requires that the foundation reaction during preloading is the total reaction at the legs and is expressed as

$$R_{fl} \geq R_B + R_P + R_S \qquad (1)$$

Where

R_{fl} = Foundation or bearing capacity

R_B = Bow leg reaction

R_P = Port leg reaction

R_s = Star board leg reaction

The loads to be transferred by the spud-cans of the legs to the soil follow from structural integrity of the assessment of the jack-up rig. Taking moment as shown in Figure 4, when the rig is at equilibrium, the reaction for the bow-leg is:

$$R_B = (W \text{ x. } (D_L + D_B - \text{LCG}))/D_L \ldots\ldots\ldots\ldots(2)$$

Where:

W = Weight acting on rig

D_L = Longitudinal distance between the bow and stern legs

D_B = distance of the extreme point of bow to the centre of the bow leg

LCG = Longitudinal centre of gravity of the rig

When the rig is at equilibrium, the clockwise moment and the anti-clockwise moment, are equal, hence viewing from the stern side of the rig as shown in Figure 5, and taking moment parallel to the longitudinal centreline through the port leg, the starboard reaction is obtained as:

$$R_s = [W \text{ x } (D_r/2+\text{TCG}) - R_B \text{ x } D_r/2]/D_r \ \ldots.(3)$$

Where

D_T = Distance between the port and the starboard legs

TCG = Transverse center of gravity of the rig

In a similar manner, taking moments about an axis through the starboard leg results in an expression for the port leg reaction given as:

$$R_P = [W \text{ x } (D_r/2\text{-TCG}) - R_B \text{ x } D_r/2]/D_r \ \ldots.(4)$$

The important difference in the two expressions for the reaction of the starboard and port legs is the sign for TCG, which could be positive or negative depending on the position of the weight. When the weight is on the port of the centreline, TCG is negative and vice versa. Therefore, that portion of the weight borne by the port leg is greater than that borne by the starboard leg. Similarly when TCG has a positive value, the starboard leg reaction is greater.

Computation of LCG and TCG

$$LCG = \frac{\sum M_L}{W_T} \qquad (5)$$

The longitudinal center of gravity is computed as

where:

M_L = longitudinal moment

= (Added weight of ballast water x its LCG + weight of the rig x its LCG)

W_T = total weight of ballast water and rig

while the transverse moment of gravity is given as:

$$TCG = \frac{\sum M_T}{W_T} \qquad (6)$$

Where

M_T = Transverse moment

= (Added weight of ballast water x its TCG + weight of rig x its TCG)

DETERMINATION OF FOUNDATION CAPACITY

The reaction forces resulting from the structural analysis are compared with the bearing capacity of the spud-can foundation under combined horizontal and vertical loading. Schotman and Efthymiou (1990) expressed the foundation or bearing capacity to withhold vertical load as

$$\frac{R_{F2}}{\gamma_F} \geq \gamma_D V_D + \gamma_V V_V + \gamma_E E_E \quad (7)$$

Where:

R_{F2} = foundation capacity to withstand combined vertical and horizontal loads

V_D = Vertical load reaction from fixed gravity load

V_V = Vertical load reaction from maximum variable load

E_E = environmental reaction load vector.

γ_F = Partial factor covering uncertainties in the estimation of R_F (= 1.1)

γ_D , γ_V, γ_E = partial factors covering uncertainties in fixed gravity load, (=1.0), variable load (=1.0) and environmental load (1.3) respectively.

Most of the foundation failures associated with extreme environmental loading do not result in direct damage to the spud-can footing. When further penetration into the soil occurs, most footing will increase their capacity (with the exception of punch-through failure), before a stable situation will be achieved. The associated displacements, however, may result in overstressing of the legs (local failure) or jack-up overturning (global failure). The failure criteria for spud-cans is thus better formulated in terms of allowable displacements than in terms of allowable loads (Schotman and Efthymiou, 1990).

RESULTS AND DISCUSSION

The weight of the ballast water used for the preloading increases with the predicted bearing capacity as displayed in Figure 6. The use of equation (1) without the inclusion of the extreme environmental load to determine the reaction at the rig's legs predicted a lower value when compared to those obtained with equation (7). It is established in this analysis that the environmental load is approximately 13.3 % of the total reaction at 100% preload capacity. This observation indicates that full dynamic response of the structures in irregular waves and current as well as detailed knowledge of the bearing capacity of the soil cannot be ignored. However, the inclusion of environmental load will require detailed oceanographic data of the location and weather condition.

Figure 7 shows the reaction on each of the legs without the consideration of environmental load factor, as expressed in equation (1). While approximately equal reactions were obtained on the port and the starboard legs, the bow-leg gave a higher reaction. The knowledge of these reactions will assist in the distribution of load on the rig. Figure 8 demonstrates that the longitudinal centre of gravity increases while the transverse centre of gravity shown in Figure 9 decreases to maintain the stability of the rig as the preload check increases. The values obtained for these two centers of gravity fall within the designed values of the rig.

According to Rapoport and Alford (1989), analysis of boring samples from offshore locations indicates that soil properties vary considerably with depth and location. There are varieties of soil condition that could result in sudden uncontrolled penetrations of the legs. Generally these penetrations are associated with the spud-cans punching through the stronger soil layer into underlying weaker soil. Clay is termed cohesive soils and with proper amount of water they stick together and become plastic. It is known that stiff to medium clays pose fewer problems for jack-up rigs while soft clays allow deep penetration and may cause extraction problem after operation. Sands, silts and gravel are example of cohesion less soils and do not stick together. Figures 10 (a) and (b) show examples of load/penetration curves for very dense sand and soft clay. A thick layer of sand is capable of supporting heavy load with little penetration. However, if the layer is thin, a potential punch-through will exist. These curves follow the same philosophy as the one adopted for the preload check but they do not reflect the actual load/penetration behaviour after reloading, which is different from those depicted in Figure 10. The curve provides a means of planting and checking the elevating and preloading operations. Divergence indicates that the soil strength is different from that predicted.

CONCLUSION

A non-complex computer simulation for initial assessment of the integrity of jack-up foundation has been developed. The two methods i.e. the Bearing Capacity using the total reaction at the leg and the Foundation Capacity to withstand combined vertical and horizontal loads used in this simulation gave good agreement. The methods ensure complete compatibility with structural analysis and can be used to quantify the effects of load redistribution on the rig using ballast water. It is elucidated that full dynamic response of the structures in extreme waves and current situation is necessary in assessing foundation stability of a jack-up rig. The non-optimization of the partial factors used in equation 7 may have contributed to the environmental load of 13.3 % of the total reaction at the 100% preload capacity. From this analysis it has been further established that expected rig foundation stability can be evaluated from theoretical predictions and known soil data.

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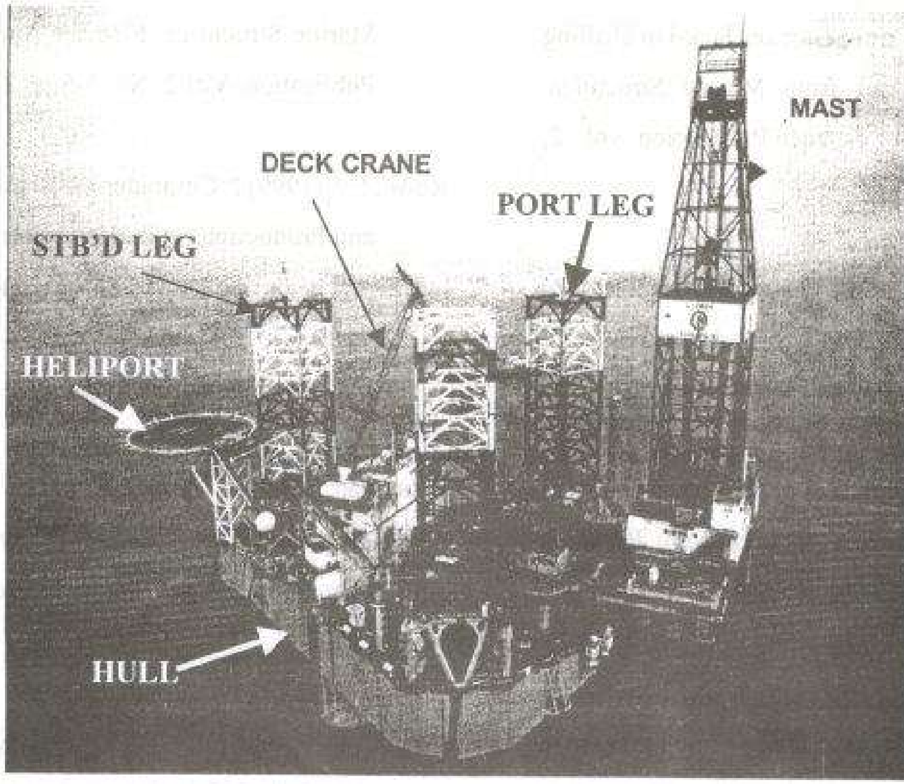

Figure 1: Pictorial view of a jack-up rig with square legs (Source: Offshore Tech. 1999)

Table 1: **Principal particulars of the simulated jack-up rig**

Length overall (with heliport)	86.42m
Length overall (without heliport)	67.02m
Width overall	61.02m
Dept of hull (at full width)	7.40m
Overall length of spud legs (ocean towage)	97.67m
Overall length of spud legs (field move)	124.35m
Longitudinal & transverse leg centres	39.00m
Bearing area of spud cans	146.80m^2
Load line draft	4,609.00m
Load line displacement (field move)	10,423 tonnes
Maximum draft prior to elevation	4,090.11m
Maximum displacement prior to elevation	9,261.00 tonnes
Required preload with all variables	3,264 tonnes

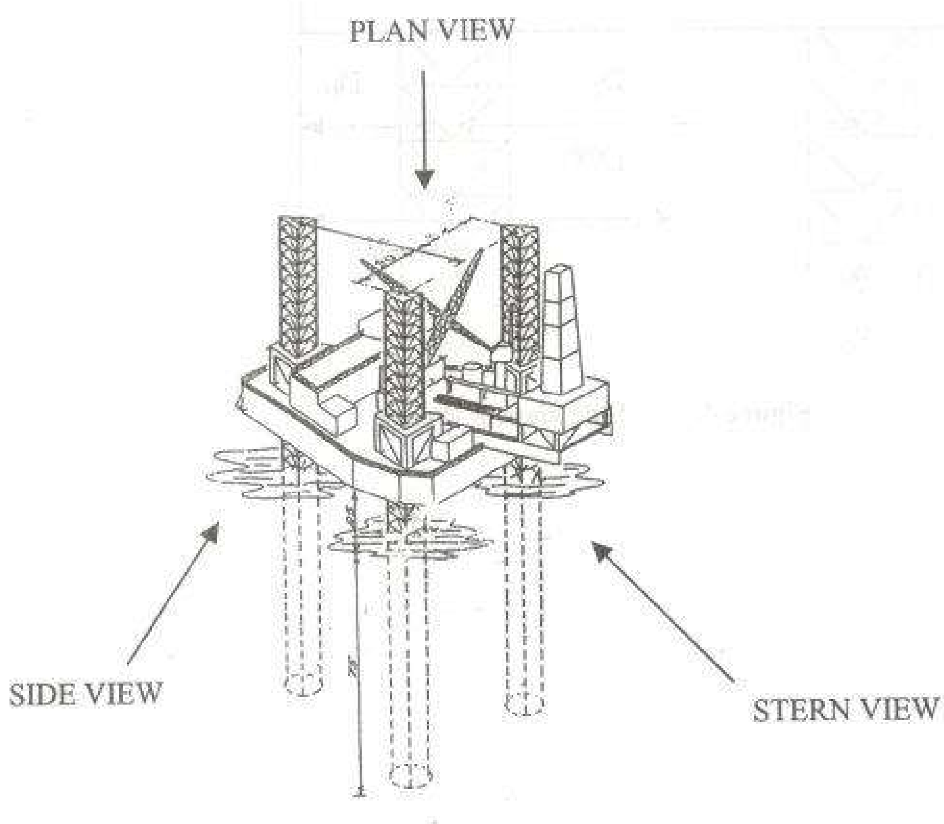

Figure 2: Independent leg unit of a jack-up rig

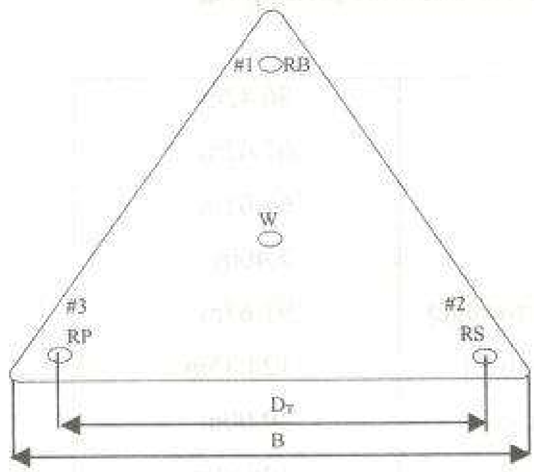

Figure 3: Plan view of jack-up rig

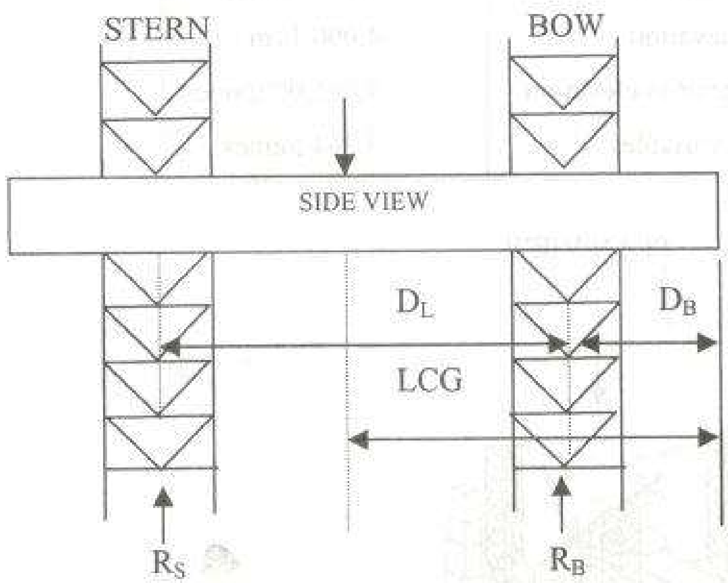

Figure 4: Side view of the rig

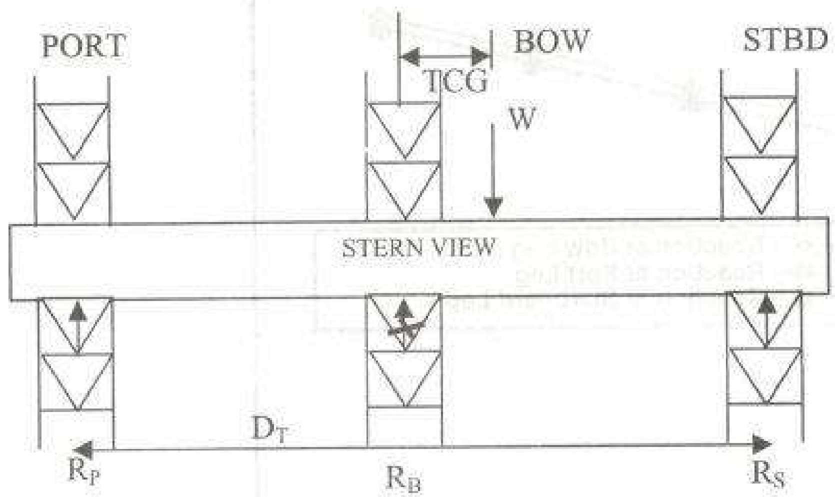

Figure 5: Stern view of the rig

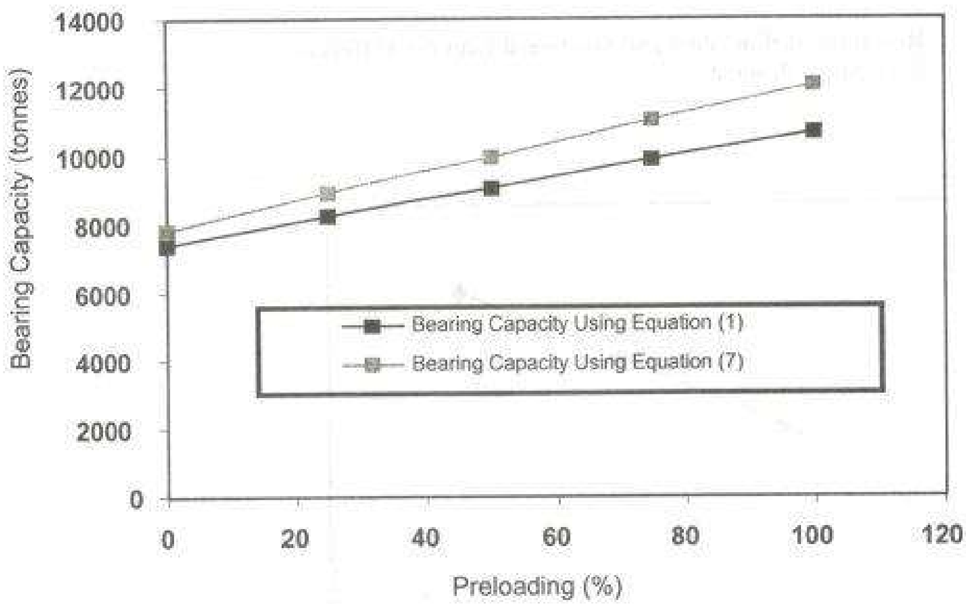

Figure 6: Comparison of the Variation of Bearing Capacity of Bearing Capacity (tonnes)

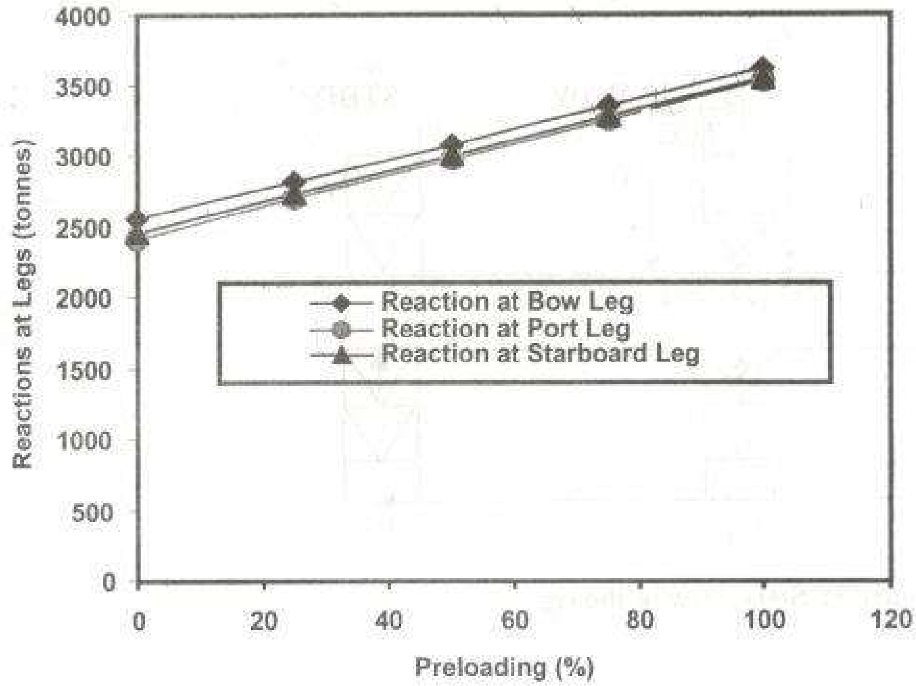

Figure 7: Reactions at Bow, Port and Starboard Legs for Different Percentage Preload

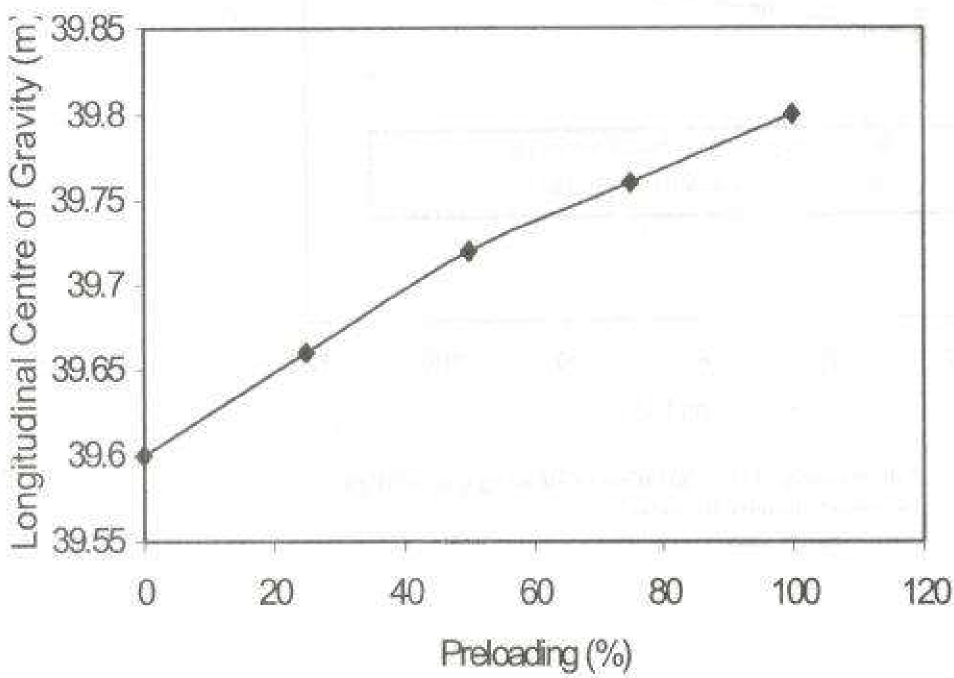

Figure 8: Longitudinal Centres of gravity during preloading

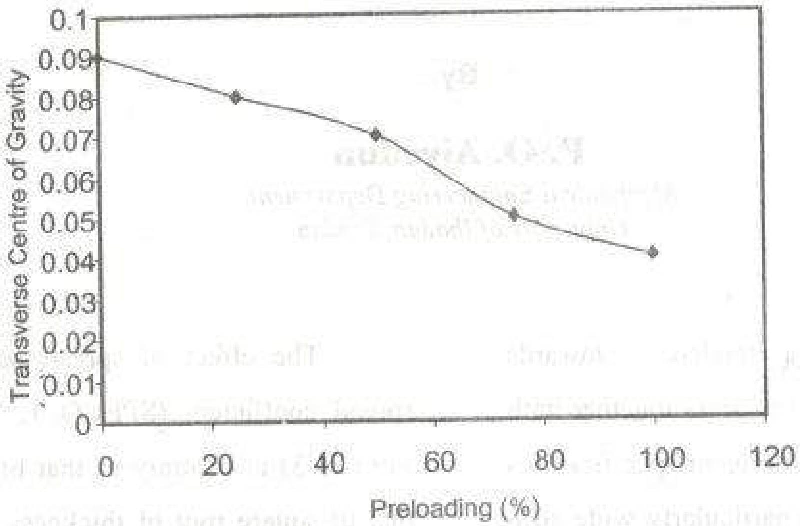

Figure 9: Transverse Centres of gravity during preloading

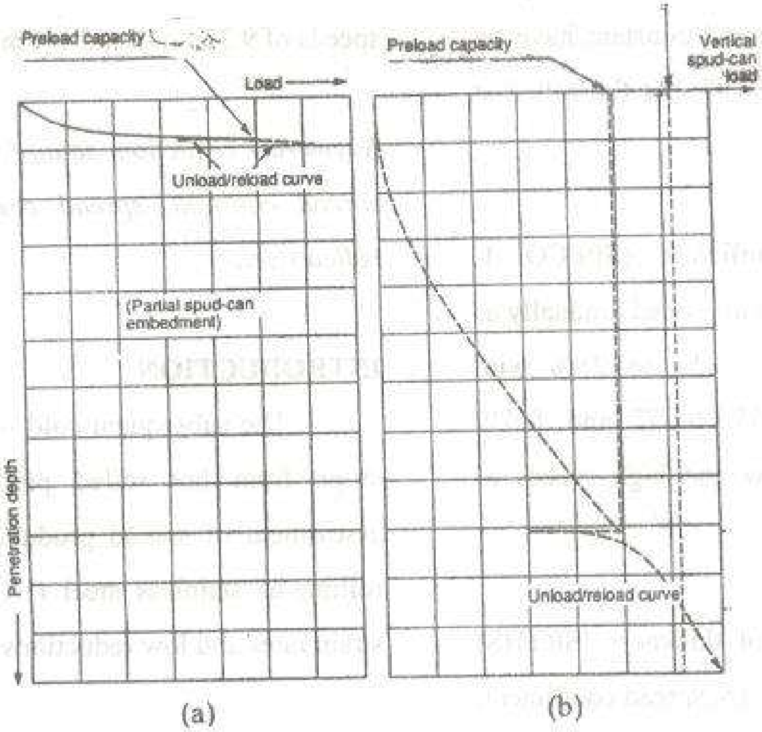

Figure 10: Comparison of load/penetration curves for typical sand and soft clay