CHAPTER 95

SCOUR UNDER A VERTICALLY OSCILLATING LEG

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ABSTRACT

Mishaps with jack-up oil rigs could be caused by scour beneath their legs as they oscillate vertically, either on site or when being shifted to or from site. This action was replicated in the laboratory by moving cylindrical feet to and from a sandy bed at frequencies appropriate to the scale of the model. By retaining equal Reynolds numbers for the sand grains, whose size was commensurate with prototype material, the period of oscillation had to vary with the leg diameter. By adopting a suitable size scale, a range of periods was determined from knowledge of resonant motions of rigs in relatively deep water. Erosion was recorded which appeared sufficient to cause mal-distribution of load in the structure. Even when oscillations occurred in a leg penetrating the bed, no support was available due to liquifaction of the soil. The two pilot studies herein described indicate the need for a comprehensive research program on the subject, due to the large investments in jeopardy.

INTRODUCTION

Among the various offshore mobile drilling units, the jack-up rig has become increasingly popular. From a survey by Howe in 1968[1] there were 92 such units in a total of 192 at that time. However, this form of rig has suffered a high incidence of mishaps. As seen in Table 1 they have accounted for 60% of the major accidents, excluding those due to blowouts. In this context a major accident is defined as damage of at least US$1.0M or total loss. Of these half were suffered on site, through storm action, normal conditions or moving on or off site, the last accounting for two thirds of this category.

Howe stated: "A problem plaguing early pile-supported jack-up rigs was excessive leg penetration in soft soils. At least 2 of these rigs tipped over because of apparent soil failures while preparing to move off location".

TABLE I. Mishap incidence with oil rigs 1949-68 - after Howe[1]

Type of Rig		Submersible	Jack-up	Ships & Barges	Semi-Submersible	Totals
On Location	Blowouts	1	3	1	-	5
	Severe Storm	2	1	2	2	7
	Normal Conditions	1	2	-	-	3
	Moving On or Off	1	6	-	-	7
Under Tow		-	6	1	1	8
Totals		5	18	4	3	30
% of Total Accidents (Ex-Blowouts)		16	60	12	12	100
% of Total Exposure		29	43	23	5	100

It appears that motion of the legs near the seabed can produce an unstable condition[1]. Rigs are particularly prone to this when load is being partially taken by a floating carrier, but even when in position such a structure can suffer resonant swaying, which can lift legs from the bed a matter of centimeters. It will be shown in this paper that these oscillations, with periods from 3 to 10 seconds, can scour significant holes beneath legs, even in non-cohesive soils of large grain size.

PROTOTYPE LEG MOTIONS

Harleman et. al[2] have stated that the first modal frequencies of tall offshore towers are 0.1 cps or higher, or a period of 10 seconds or less. This is based upon the motion of structures fixed at the bed as might apply to a piled structure (see Figure 1A). Jack-up rigs are normally founded on the seabed, or if tied by piles will be free to oscillate when being shifted on or off site. In this event a certain degree of rocking can ensue which causes repeated lifting of the legs from the floor.

This resonant motion is depicted in Figure 1B, the frequency of which can be determined simply if it is assumed that the mass of the structure is concentrated at the deck and small angles of tilt are considered. The equation of motion is then

$$\frac{d^2\theta}{dt^2} = \pm \frac{B\,g}{2[L^2+B^2/4]} \qquad \text{- - - (1)}$$

where θ = instantaneous angle of tilt from the vertical

L = height of the deck centre of gravity from the sea bed

B = horizontal distance between legs

g = acceleration due to gravity

t = time

This represents a periodic, but not simple harmonic motion, the period of which is given by

$$T = 8[(L^2 + B^2/4)\theta'/Bg]^{\frac{1}{2}} \qquad \text{- - - (2)}$$

where θ' is the extreme angle of tilt in radians (see Figure 1B).

Typical dimensions for deep-water jack-up rigs according to Howe[1] are: L = 100 metres, B = 50 metres, giving $T = 37.3\sqrt{\theta'}$. For a leg to rise 0.5 metre from the bed $\theta' = 0.01$ radians (0.57°), so that T = 3.7 secs.

The resonant input to produce such rocking could be provided by normal wind generated waves. For example 10 second waves propagating through this 50 metre wide structure in say 30 metre depth of water would exert sequential forces on the legs with a period of 3.7 seconds.

Larger vertical lifts of the legs could take place with longer periods of oscillation.

WATER PARTICLE VELOCITIES

Assuming that a leg moves vertically from the bed to some height 2A above it, this implies an amplitude of oscillation A with some period T. As seen in Figure 2 some scour (S) will ensue the size of which must be defined at some radius; in this case it was taken at the periphery of the leg. Maximum scour occurred between this radius and the centre of the leg.

If it is also assumed that the vertical velocity of the water adjacent to the foot is equal to that of the foot, is zero at the bed, and is linearly distributed between, the horizontal water velocity (U) at the radius r is then given by (3)

$$U = -Vr/2R \qquad - - - \quad (3)$$

where R = height of the foot above the bed at any instant.

It is seen from Figure 2 that

$$R = S + A(1 + \sin 2\pi t/T \qquad - - - \quad (4)$$

if sinusoidal oscillation is assumed and t is the instantaneous time from the mean level
The vertical velocity of the foot $V = \partial R/\partial t$ which from equation (4) becomes

$$V = (2\pi A/T) \cos 2\pi t/T \qquad - - - \quad (5)$$

Substituting for R and V into equation (3) gives

$$U = -\frac{\pi r}{T}\left[\frac{\cos 2\pi t/T}{(S/A) + 1 + \sin 2\pi/T}\right] \qquad - - - \quad (6)$$

By differentiating equation (6) with respect to t and equating to zero the maximum velocity becomes

$$U_{max} = \pm \frac{\pi D}{2T} \Big/ \sqrt{(\frac{S}{A} + 1)^2 - 1} \qquad - - - \quad (7)$$

where D = diameter of the leg

The relationship of U_{max}, D/T and S/A is illustrated in Figure 3. It is seen that as soon depth increases so maximum velocity decreases, indicating that some equilibrium will be reached when particles are no longer disturbed.

Equation (7) is dimensionally homogeneous, but it is worthwhile to approach the parameter problem from dimensional analysis, from which it can be shown that the following terms are relevant

$$\pi_1 = S/D, \quad \pi_2 = A/D, \quad \pi_3 = d_s/D, \quad \pi_4 = Dd_s/\nu T,$$

$$\pi_5 = (S_s - 1)gd_s^3/\nu^2$$

where d_s = median diameter of the sediment

ν = kinematic viscosity of the water

S_s = specific gravity of the sediment (assuming that of the fluid is unity) so that $S/A = f(A/D,\ Dd_s/\nu T, d_s/D, (S_s-1)gd_s^2\ /\nu^2)$ - - - (8)

If equation (7) is approximated by

$$U_{max} = \pm\ \pi DA/2TS \qquad - - - (9)$$

the Reynolds number of flow for the sediment particles is

$$R_n = \frac{\pi DAd_s}{2TS\nu} \qquad - - - (10)$$

indicating that $S/A = f(Dd_s/\nu t)$, which is similar to π_4 above.

SCALING LAWS

From equation (7) it is seen that similar S/A ratios will ensue in model and prototype if $(D/T)/U_{max}$ ratios are similar. For sediments of similar characteristics in prototype and model similar U_{max} values should be employed. This demands that $(D/T)_r = 1$. A similar conclusion is reached from equation (10) if d_s/ν is to remain constant.

It was necessary to decide on a prototype diameter which any model leg purported to represent. In tests at the Asian Institute of Technology[4] a scale of 1:50 was assumed, so that legs of diameter 2.54, 5.08, and 7.62 cms represented prototype values of 1.27, 2.54 and 3.81 metres respectively. Amplitudes used were 2.11, 3.71, 5.56 and 7.5 mm, representing prototype values of 10.55, 18.55, 27.80 and 37.50 cms.

As noted already, the prototype periods of oscillation can vary up to 10 seconds. A range of 2.5 to 10 was tested which, because of the 1:50 scale and $(D/T)_r = 1$, became 0.05 to 0.2 seconds. The AIT tests were also conducted with three sediments of median diameter 0.018, 0.043 and 0.085 cms. Fresh water was used throughout for which the average ambient temperature of 30°C gave ν = 0.0085 stokes.

At the University of Western Australia[5] legs of larger diameter were used, namely 8.05, 10.62, 13.13 and 15.78 cms, which were oscillated over a similar range of A/D values as for the former tests (i.e. 0.0276 to 0.219). If these purported to represent the same prototype legs as before the scale approximates 1:20. The periods of oscillation were thus in the same prototype range as previously.

Only one median diameter of sand (0.0177 cms) was used but two different water densities of 1.155 and 1.194 were obtained by the addition of salt. The kinematic viscosities were altered very little. As will be seen, insufficient runs were made from which to draw any conclusions on the influence of the (S_s-1) and ν terms in the π_5 parameter.

EXPERIMENTAL PROCEDURE

The legs were attached to a sliding shaft which was activated by a crank arm off a rotating wheel. The amplitude and speed of motion could be varied through a variable speed drive. The number of oscillations were recorded by a tachometer and speed setting by stroboscope. Initial tests were conducted to find the time necessary for equilibrium scour profiles to be reached. This is an important element in such tests with sediment and might be the source of some of the scatter encountered in the results.

Prior to oscillating the legs the 7 cms thick sand bed was compacted by tamping under saturated conditions. The leg was attached with its minimum level set at the sand surface. The scour profile was subsequently measured by means of a horizontally traversing pointer gauge. A typical set of profiles is illustrated in Figure 4. At very high frequencies the profile became conical, in which case the movement of sand particles was intense and the resultant slope of the hole (from the leg periphery inwards) was at the angle of repose for the soil. These holes have been omitted from the analysis since the scouring conditions are quite different from the remainder of the tests. This is not to infer that this phenomenon does not warrant investigation, but the present study centered on incipient motion of particles in the equilibrium profile.

RESULTS

The obvious dependent ratio from equation (7) is S/A since it entered into the calculation of U_{max}. This was then tested against dimensionless parameters $Dd_s/\nu T$, A/D, d_s/D and $(S_s-1)gd_s^3/\nu^2$. As already noted too few results were obtained on these pilot studies to check the last parameter adequately. A regression analysis conducted on data from both test series resulted in an equation.

$$\frac{S}{A} = f\left\{\left(\frac{Dd_s}{\nu T}\right)^{1.061} \left(\frac{A}{D}\right)^{0.224} \left[\frac{(S_s-1)gd_s^3}{\nu^2}\right]^{-0.700}\right\} \quad --- (11)$$

which was then approximated to

$$\frac{S}{A} = f\left\{\left(\frac{Dd_s}{\nu T}\right) \left(\frac{A}{D}\right)^{\frac{1}{4}} \left[\frac{(S_s-1)gd_s^3}{\nu^2}\right]^{-\frac{2}{3}}\right\} \quad --- (12)$$

Results are plotted in Figures 5 and 6. The bulk of the data for d_s = 0.0177 and 0.018 are shown in Figure 5, where it is seen that the small change in median diameter produces a cluster around lines at slightly different slopes. The kinematic viscosities were 0.0113 and 0.0085 stokes respectively. At this stage it does not warrant the determination of an equation for either of these curves, only to note that scour can range from A to 7A. In terms of the prototype equivalents this could range from 10 to 200 cms for the diameters implied.

The few results for larger diameter particles are well defined by the two lines drawn in Figure 6. They indicate that for coarser sediments slight increases in the combined parameter, as occasioned by larger diameters or greater frequencies of oscillation, could result in excessive scouring for any given leg amplitude. The few points for (S_s-1) changes are inconclusive since they provided scatter similar to the results for $d_s = 0.0177$ in Figure 5.

It may be thought that this scouring action could be compared directly with incipient bed movement due to waves, of which Silvester and Mogridge[6] collected the many formulae derived. However, there is one significant difference in the conditions in that positive and negative pressures are exerted on the soil under the leg, which according to Bagnold[7] has a greater disturbing influence on larger sized grains. As the leg rises so is a suction applied to the surface of the bed and the particles placed in suspension are then forced outwards with the water in the subsequent downward motion. It does not take a great frequency to have the bed beneath the leg hidden within a fog of suspended sand.

FURTHER OBSERVATIONS

Although the apparent scour dimensions as given above do not appear to be disastrous, they would provide a distribution of load on the legs quite different from those for which they and the whole frame were designed. But it should be remembered that in the current tests the leg oscillated only down to the original bed level. In practice a leg could well follow its scour hole down and so keep digging. In fact a test was conducted in which an oscillating leg was lowered into the sand surface with no apparent increase in its resistance to motion. The boiling of the soil indicated that liquifaction was taking place. This action probably prompted Howe's statement quoted in the introduction. It can be envisaged that coarse sand would suffer this loss of load carrying capacity more than fine sediment which would resist this fluctuating dispersion of water. However, prior to this buried condition the fine sediment would be scoured more by any given oscillating condition.

A curve developed for the time required to reach equilibrium scour (4) indicated that in one half to two days in prototype conditions a continuous oscillation could produce the results as indicated. This is well within the realms of storm duration when resonant oscillation could be set up.

Another phenomenon observed in the tests was a vortex generated up the sides of the leg. As illustrated in Figure 7 this had an upward velocity adjacent to the leg with a less well defined return flow out from this surface. This water motion carried sediment, placed in suspension by the suction and high velocities beneath the foot, up the sides of the leg and outwards to some radius before its fall velocity exceeded the upward stream. The radius of the scour equated that of the observed horizontal dimension of the vortex plus the radius of the leg. For finer sediments the mound radius exceeded this sum and for coarser material it was smaller.

The generation of this vortex is possibly due to the pressure fluctuations produced at the outer periphery of the foot. As the leg moves upwards water is drawn in with a maximum horizontal velocity at the foot level. As the leg decelerates on its upward journey the pressure becomes positive, so forcing water out from the base of the foot. This outward flow interacts with the previous inward current, to force fluid up the side of the leg. By this circulation material is removed from the vicinity of the leg and placed in a mount surrounding it. Perhaps the volume of sediment removed may be a better criterion to correlate with leg characteristics rather than scour at the periphery of the leg.

TOPICS FOR FURTHER RESEARCH

The two pilot studies can only be instrumental in directing attention to this important problem. All the variables tested need much more data on which to draw conclusions and derive relationships. But the exigencies of natural oceanic conditions must not be forgotten, such as wave action with its mass-transport current near the bed boundary layer and ocean currents which create their own vortex structure. Posey[8] has alluded to the turbulent structure produced by wave action within the space frames of oil rigs and similar structures, which can scour major depressions under them. All these actions need to be researched in concert before any solution can be contemplated. Metering of sediment suspension around existing rigs would be a worthy investment. This would necessarily have to be carried out with sampling tubes fixed to the legs at the outset.

Specific problems requiring attention are :-

1. The actual motion of structures rocking on a floor require analysis and measurement since the sinusoidal oscillation used herein may distort the scouring action greatly, either through under-rating or in over-rating it.

2. More tests are required to find the influence of A/D, d_s/D, $(S_s-1)gd_s^3/\nu^2$ by using sediments of varying diameter and density with larger scale models.

3. The phenomenon of liquifaction needs researching since its influence could overshadow any scouring that takes place.

4. Future tests should incorporate measurements of velocities and pressures on the base of the foot and on the bed beneath it. This latter could be accomplished by a fixed bed shaped as a scour hole.

5. Experiments should be conducted in the presence of waves and currents, firstly with single cylindrical legs and later with the rig structure as a whole.

CONCLUSIONS

1. The history of mishaps with structures resting on the seabed would indicate a foundation source of failure which to date has not been fully appreciated.

2. The possible resonant oscillation of oil rig structures, with consequent lifting of feet from the floor, could produce scouring or liquifaction of the soil which can result in a dangerous load redistribution.

3. Water particle velocities and pressure fluctuations beneath a leg oscillating vertically, with frequencies experienced in nature, can be sufficient to remove sediment from beneath the foot.

4. Scour can be related to leg dimensions and sediment characteristics by suitable dimensionless parameters, the final form of which requires much more experimental investigation.

5. The scaling criterion would appear to be the Reynolds number for fluid velocity past the sand grains, which for similar model-prototype sediment and fluid results in a diameter to period ratio of unity.

6. The time to produce equilibrium scour profiles is well within the period during which storms can be experienced.

7. The removal of sediment by the vortex generated up the sides of an oscillating leg determines in part the diameter of the resulting mound.

8. There are many facets to the problem of scour beneath space frames in the very turbulent medium of the sea which require urgent attention from the oil industry.

9. Metering of sediment suspension near the sea floor could provide an immediate indicator of foundation problems.

ACKNOWLEDGEMENTS

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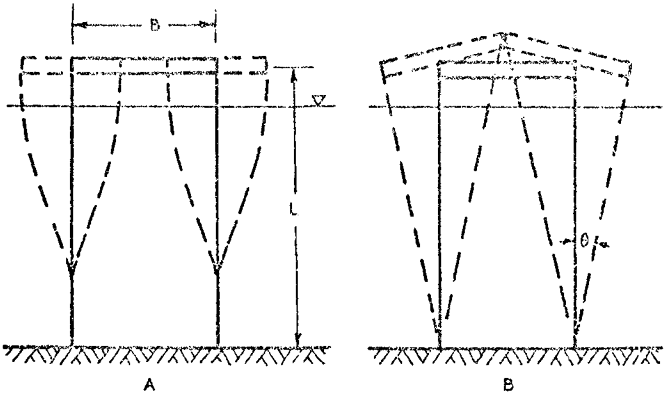


Figure 1 - Possible motions of structures in deep water.

Figure 2 - Definition sketch of leg oscillation and scour.

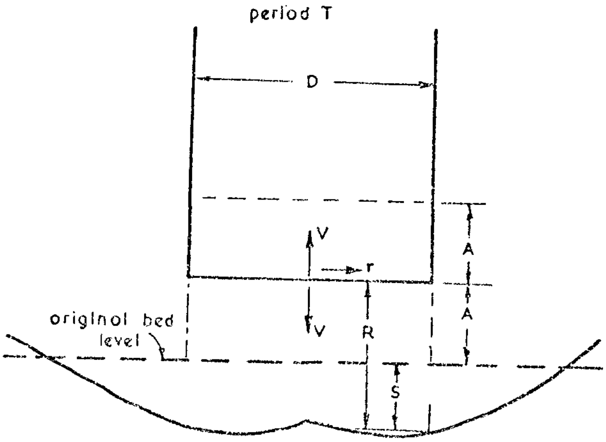
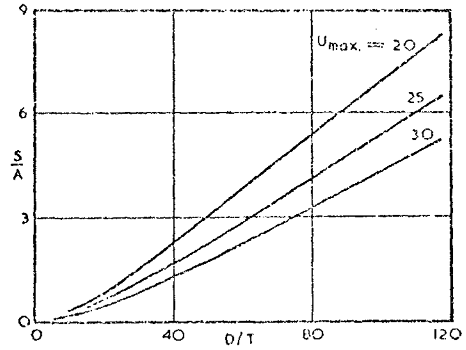


Figure 3 - Relationship between U_{max}, D/T and S/A.



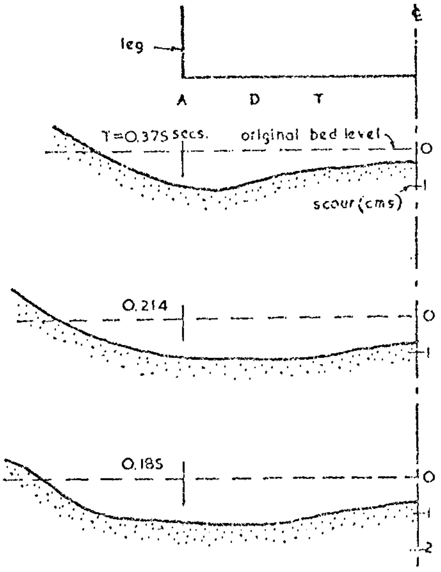
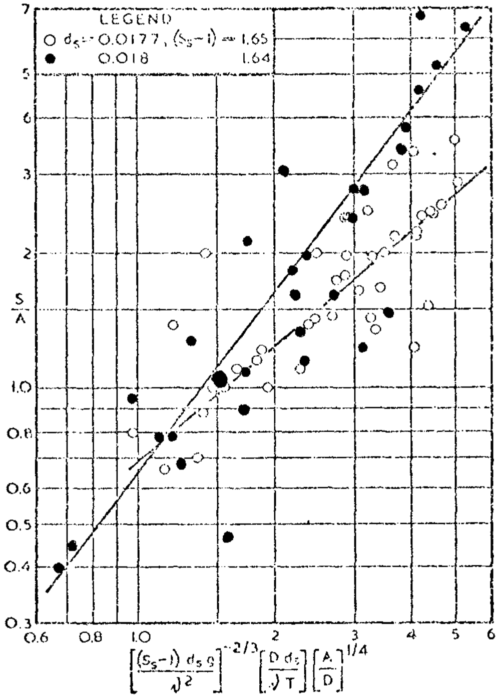


Figure 4 - Typical set of scour profiles for d_s = 0.0177 cms, A = 0.502 cms, D = 13.13 cms and T as shown.

Figure 5 - Scour ratio S/A versus a combined dimensionless parameter for the bulk of data.



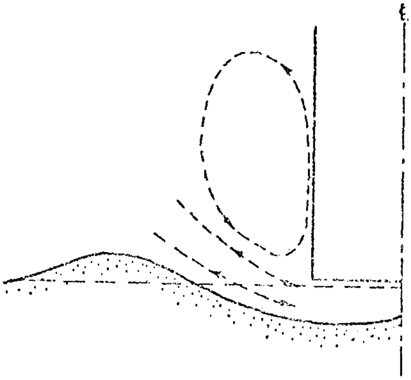


Figure 7 - Vortex formation around circular leg.

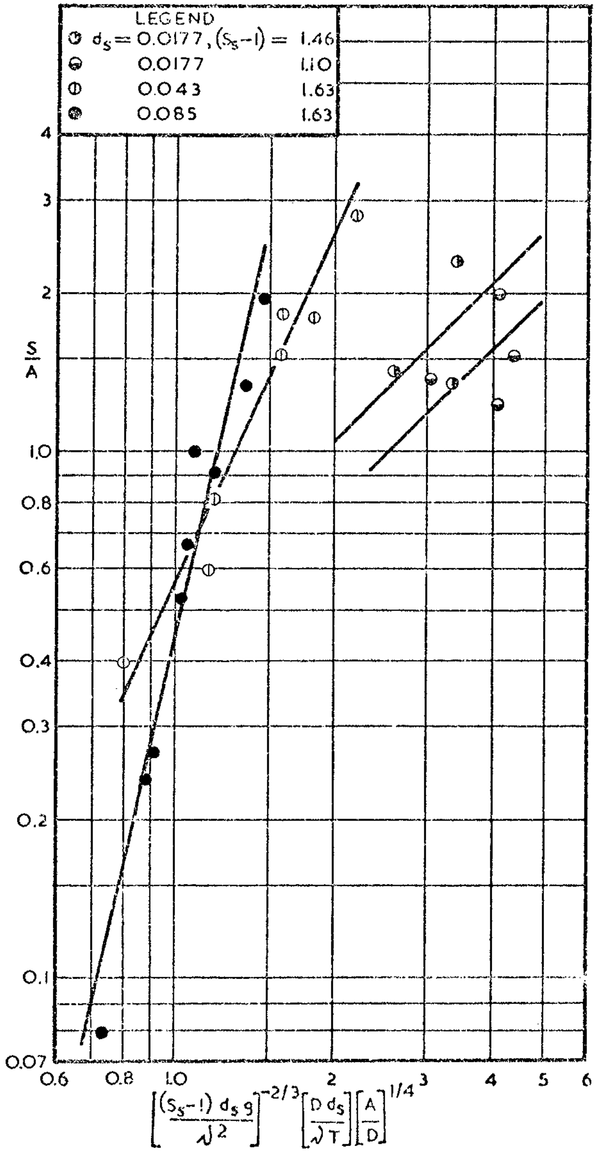


Figure 6 - Scour ratio S/A versus a combined dimensionless parameter for variations in d_s and ν.