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V.D. S. Raju
Indian Institute of Technology, Madras, India

R. Sundaravadivelu
Indian Institute of Technology, Madras, India

V. G. Idichandy
Indian Institute of Technology, Madras, India

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V. S. Raju
Professor, Ocean Engineering Centre, Indian Institute of Technology, Madras, India

V. G. Idichandy
Associate Professor, Ocean Engineering Centre, Indian Institute of Technology, Madras, India

R. Sundaravadivelu
Assistant Professor, Ocean Engineering Centre, Indian Institute of Technology, Madras, India

SYNOPSIS Two offshore piles of 1000 mm diameter with 1 m socketing into rock in 15 m water depth have failed during construction. The analysis of failure considering wave and current forces, structural and foundation capacities and vibration measurement on freshly concreted and well set piles is discussed.

BRIEF DESCRIPTION OF FAILURE

Two adjacent offshore piles of 1000 mm diameter have failed during the construction of a berthing structure off the west coast of India. All the piles are founded with 1 m socketing into the rock strata and steel liners are used till the top of the rock strata. The piles are located in open sea. When 50% of the piles required for the berth are completed, one pile fell and another titled. The failure of these two piles have taken place one month after concreting, while remaining piles nearby did not fail. 11 steel liners of piles ready for concreting fell and 9 others tilted.

The cut off level and bed level for the broken pile is +4.3 m and -11.8 m, respectively. The fallen pile was found to be broken 400mm below the bottom of steel liner. Three out of fourteen reinforcement bars were snapped at the broken concrete face and the rest slipped out of concrete (Fig.1).

SEABED PROFILE AT SITE

The soil profile is given in Fig.1. The thickness of soft marine clay above the rock was 3.65m for fallen pile, 2.72 m for tilted pile and more than 5 m for piles nearby. The rock is classified as slightly weathered, Grade II.

ENVIRONMENT CONDITION AT THE TIME OF FAILURE

The sea was moderate to rough with wind speed of 18 to 22 knots and wave heights of 1.8 to 2.2 m on the day of failure. The high tide and low tide levels are +3.50m and +1.49m respectively.

The wave force on 1000 mm diameter pile in 15 m water depth estimated using MORISSONS Equation (1950) is shown in Table 1 for different wave periods and heights.

TABLE 1 WAVE FORCE ON 1000 mm PILE

Wave		Total force in KN
Period in Sec.	Height in m	
6	2.4	12.2
6	1.6	7.1
6	0.8	3.1
5	2.4	11.9

The current forces on 1000 mm diameter pile for currents of 0.55, 1.1 and 1.65 m/sec are 2.9, 11.5, 25.8 KN respectively.

ESTIMATION OF FOUNDATION CAPACITY OF PILES UNDER LATERAL LOADS

The lateral capacity of pile when the concrete is not fully set depends only on the capacity of the liner which penetrates upto the top of the rock layer. The ultimate resistance, p_u is calculated using clause 2.6.7b of API RP 2A (1989) of the American Petroleum Institute. As per the above clause:

$$P_u = 3C + \gamma + \frac{JXC}{D} \quad (1)$$

C = Undrained shear strength of undisturbed sample (Taken as 5 KN/m^2 based on soil investigation)

γ = effective unit weight of cohesive layer (Taken as 4.3 KN/m^2 based on soil investigation)

J = dimensionless empirical const. (0.5 as per API)

X = depth below sea bed in m = 3.65 m

D = pile diameter = 1.0 m

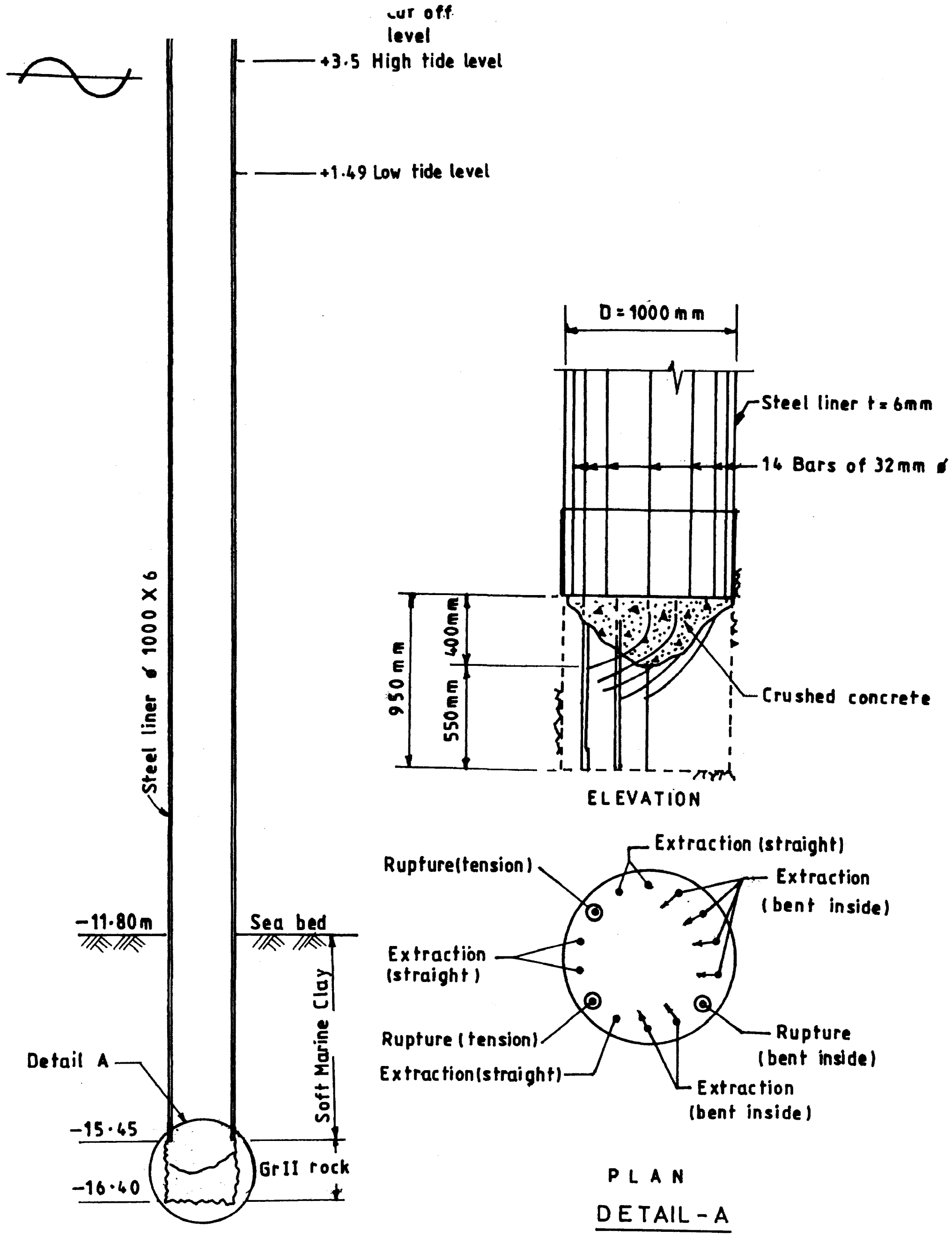
p_u at sea bed level = 15 KN/m^2

p_u at bottom of liner = 39 KN/m^2

M_u, moment of resistance offered to liner = 155 KN.m

ESTIMATION OF STRUCTURAL CAPACITY OF PILES

Concrete of grade M25 is used for the piles. The structural capacity of the pile at 1, 7, 14 and 28 days after the concrete has been poured is calculated, based on the bond stress that is developed during the different stages of setting of concrete.



ALL LEVELS ARE IN m

FIG. 1. DETAILS OF DAMAGED PILE

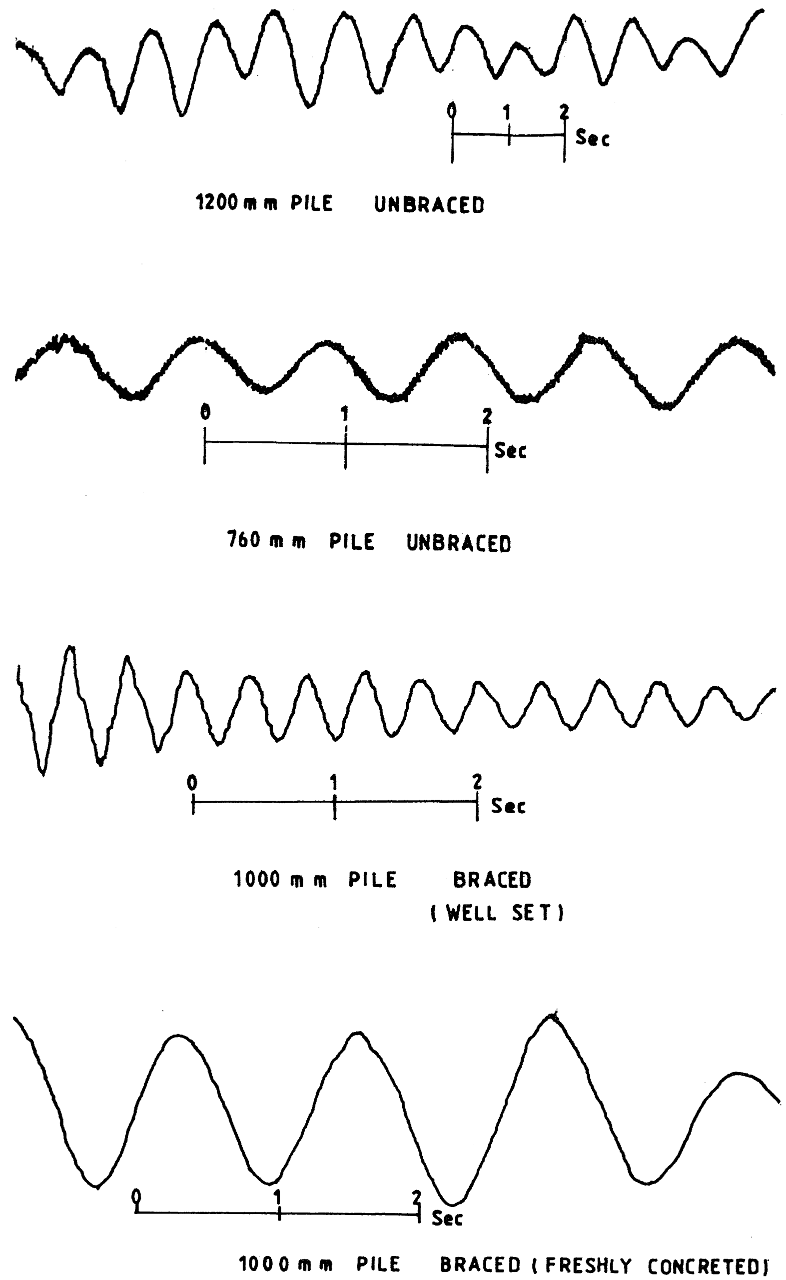


FIG. 2. TYPICAL RECORDS OF FREQUENCY RESPONSE

The bond stress is calculated using

$$f_{bond} = \frac{0.6\ f_t^{2/3}}{\gamma_e} \qquad (2)$$

where γ_e - coefficient = 1.3

f_t, the strength of concrete at any stage t, (as per clause 5.2.1 of SP24, 1983) in days is given by the equation.

$$f_t = \frac{t}{a+bt} f_{28} \text{ where} \qquad (3)$$

a = 4.7 & } empirical constants
b = 0.833 }
f_{28} = cube strength at 28 days
= 25N/mm^2 for M25

The tensile stress, S, that can be mobilised by the bar is calculated using

$$S = f_{bond}\ \Pi\ \phi\ L \qquad (4)$$

Where ϕ - diameter of bar and
L - bond length of the bar

In this analysis, the length of the bar in the rock layer, i.e. 1 m is taken as bond length, assuming point of fixity at the top of rock level. The point of fixity which is assumed at the top of rock level when the concrete is fresh will gradually go down as the concrete sets, further reducing the bond length. The adequate bond length of 32 mm bars is 1030 mm in compression and 1290 mm in tension, as per Indian Codal Provisions. Adequate bond length could have been provided by bending the reinforcement of the piles radially at the bottom, as per the usual practice.

σ_s, stress in steel = S/A, where A is area of cross section of 32 mm bar. Knowing S & f_t the ultimate moment capacity M_u is worked out and the results are given in Table 2.

TABLE 2 STRUCTURAL CAPACITY OF 1000mm PILE

t (days)	f_t (N/mm^2)	f_{bond} (N/mm^2)	S (KN)	σ_s (N/mm^2)	M_u (KNm)
1	4.5	0.6	57.30	71.2	153
7	16.7	1.35	135.71	168.7	348
14	21.3	1.59	159.84	198.7	428
28	25.0	1.82	182.96	227.4	500

MEASUREMENT OF FREQUENCY RESPONSE

The integrity of the piles located near the fallen and tilted piles is assessed by measuring the natural frequency of these piles. The natural frequency of freshly concreted and well set piles has also been measured.

The measurements are carried out on 2 numbers of 1200 mm, 2 numbers of 1000 mm and one number of 760 mm diameter piles. The measurement on 1000 mm pile is carried out one hour after the concrete is poured while the measurement on other piles are carried out 28 days after concreting. The 760 mm pile is braced at the top. One 1200 mm pile is not braced at the top, while the other 1200 mm pile is braced in the direction parallel to the berth. The 1000 mm pile is braced in two directions, parallel and perpendicular to the berth.

The measurement is carried out using an accelrometer fixed to the free end of the piles. The sensing axis of the accelerometer is kept parallel to the berth. The pile is given a push in the direction of sensing axis of the accelemeter which set the pile in free vibration with its natural frequency. A measuring amplifier and strip chart recorder, kept in a boat nearby is used to amplify and record the signal. The experiment is repeated and the average is taken as the natural frequency of the pile in the direction parallel to the face of the berth. The natural frequency perpendicular to the face of the berth is also measured. The typical record for well set 760, 1000 and 1200 mm pile and freshly concreted 1000 mm pile is given in Fig.2. The frequency response indicates that the amplitude of vibration is sufficient to be picked by the accelerometer and the signal is undisturbed due to low noise level in the area. The results are summarised in Table 3.

TABLE 3 NATURAL FREQUENCY OF PILES

Sl. No.	Particulars of the pile	Period in secs. Parallel to the berth	Period in secs. Perpendicular to the berth	Frequency (Average) in H_z Parallel to the berth	Frequency (Average) in H_z Perpendicular to the berth
1	1200 mm diameter pile (braced parallel to the berth)	0.47 0.47 0.51 0.52	0.66 0.65 0.69	2.03	1.49
2.	1200 mm diameter pile (unbraced)	0.85 0.82 0.80	0.85 0.77 0.77	1.22	1.25
3.	760 mm diameter pile (unbraced)	1.075 1.0 1.08	0.97 0.93 0.93 0.93 0.96	0.95	1.06
4.	1000 mm diameter pile (braced in two directions)	0.37 0.38 0.38	0.416 0.416 0.44	2.65	2.36
5.	1000 mm diameter pile (freshly concreted and braced in two directions)	1.025 1.075 0.985 1.73	1.4 1.56 1.32	0.97	0.67

The analysis of results indicates the following:

1. The frequency of 1200 mm pile braced in the direction parallel to the berth is 2.03 Hz parallel to the berth and 1.4 Hz perpendicular to the berth and gives an indication of increased stiffness in the direction of bracing.

2. The frequency of 1000 mm pile is more than the frequency of 1200 mm pile. This is due to the fact that the 1000 mm pile is braced at the top, in two directions.

3. The results obtained for a freshly concreted pile reveals certain interesting facts. The frequencies measured parallel and perpendicular to the berth are 0.67 and 0.97 Hz respectively. The differences in these values are due to the bracings of different cross section. Even if an average value is taken, the frequency is 0.82 Hz compared to the 2.5 Hz for a similar pile where concrete had developed its full strength. In other words, till concrete in pile develops full strength, there is a duration when the frequency of the pile is one third of what it should be later. Extending this argument to other piles, the frequency soon after concreting would have been 0.4 Hz for 1200 mm pile and 0.33 Hz for 760 mm pile.

4) Dynamic amplification factor(DAF) of a structural system depends on the ratio of frequency of the forcing function ($\bar{w}$) to the natural frequency (w) of the system and damping. Since very low damping is expected on such structures. (2 to 4 percent only).

$$DAF = \frac{1}{(1-r)^2} \quad \text{where } r = \frac{\bar{w}}{w} \qquad (5)$$

The wave frequency at the location is in the range of 0.5 Hz to 0.1 Hz. Consequently there are occasions when the fundamental frequency of the pile is well within the range of frequency of wave before the concrete is set resulting in large deformation to the pile.

5) The measured acceleration level(more than 30 mm/sec) corresponds to a deflection of nearly 20 mm. During the measurement the sea was comparatively calm and the tidal level was well below the horizontal bracings interconnecting the piles. At high tide the bracings can be below water. This means, that at times the horizontal bracings will be in the splash zone when the wave loading impacts will be of high magnitude increasing the amplitude of vibration of the pile further.

FINITE ELEMENT ANALYSIS FOR NATURAL FREQUENCY

A finite element analysis of the 760 mm pile is carried out using structural analysis program, SAPIV developed by Bathe etal. (1973). The pile is discretised using 27 beam elements and the soil below the dredge line is idealised using spring element (Fig.3). Vesic's (1961)theory is used to determine spring constant. The first five frequencies of the pile are 1.01, 6.4, 18.15, 35.8 and 40.09 Hz respectively. The natural frequency of 1.01 H_z compares well with the measured value of 1 H_z.

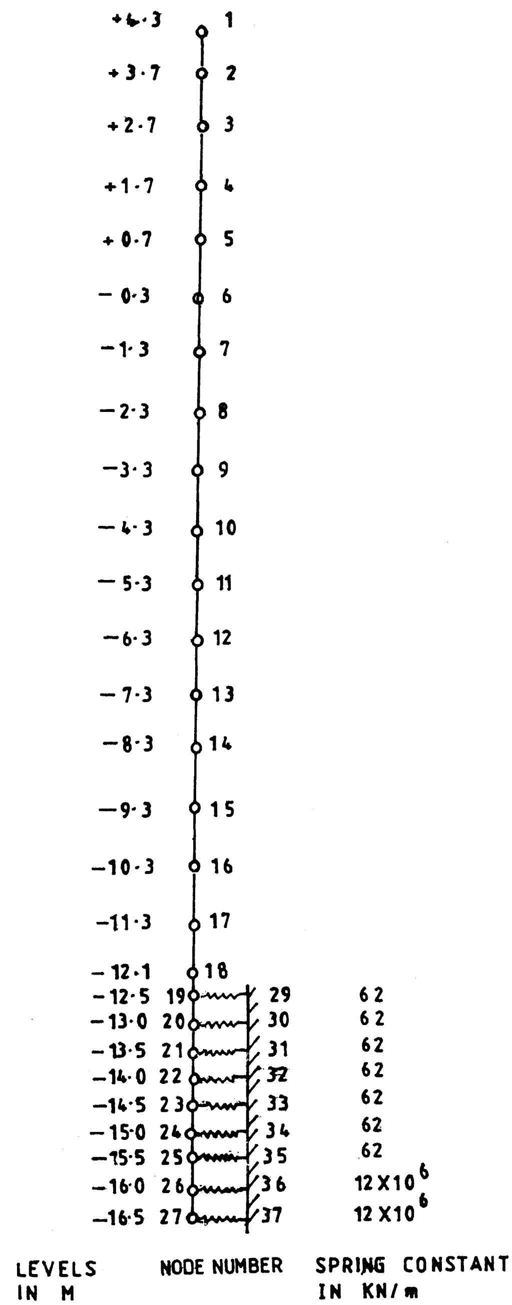


FIG.3. DISCRETISATION OF 760 mm PILE.

SUMMARY AND CONCLUSION

The lateral capacity of the pile when the concrete is not fully set depends only on the capacity of the liner which penetrate upto the top of the rock layer. The moment of resistance offered to liner by the soil for the fallen pile is 155 KNm. The equivalent lateral forces at +3m level of the pile is 8.4 KN. This is comparable to the wave and current forces that have to be considered due to wave height in the range of 1.8 to 2.2m, wave period in the range of 3 to 6 seconds and current velocity in the range of 0.55 to 1.65 m per second. The presence of the pontoon working near the pile would also have increased the wave height locally. The structural capacity of the piles after 1, 7, 14 and 28 days of concreting is 153, 348, 428 and 500 KNm respectively.

The embedment length of steel liner is found to be the critical parameter till the concrete attains strength. At the location of the failed piles the thickness of soil overburden is small. This in turn resulted in a liner embedment not fully adequate to take care of the lateral forces during the setting period of the concrete resulting in a weakened zone of concrete at the bottom.

The vibration response of freshly concreted piles and well set piles and piles braced in one and two directions at the top are measured. The measurement indicates that the natural frequency of freshly concreted pile is only about 1/3 of the well set piles and is close to the wave frequency. The natural frequency of the pile in the braced direction is more than that in the unbraced direction.

REASONS FOR THE FAILURE

1) Because of the inadequate support in the liner at the bottom right from the very beginning, the pile is subjected to the order of lateral forces which are affecting some form or the other the setting process of the concrete itself at the critical point, that is directly below the liner. To some extent this must have weakened the concrete as well as the bond between the reinforcement and concrete. With this inherent weakness, the wave activity combined with the current on the day of failure have caused sufficient lateral forces resulting in the failure.

2) The fact that similar thing did not happen for the piles in the neighbourhood, is explained from the fact that the soft marine clay layer in the other regions was much thicker. With the result, the liner itself was able to take care of lateral forces during the process of setting of concrete in the piles. Once the concrete sets, the frequency of the pile increase and the pile is much stronger and can readily withstand the lateral forces.

RECOMMENDATIONS

1) The construction of bored concrete piles in open sea needs lot of care. It should be ensured that the liners have adequate embedment into the soil so that in the prevailing wave andcurrent conditions, no stresses are transferred to the fresh concrete below the liner. Equally desirable is to brace the piles suitably. The support for the new piles should come from points which are sufficiently strong and not from liners or piles which are freshly cast.

2) The bracing should always be above the high water level so as to avoid not only current forces but also wave forces to the extent possible.

3) The bracing in two different directions is preferable to take care of the random nature of the load.

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