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Comparison of Offshore Foundations Performance under Combined Horizontal-Vertical loading in the Niger Delta of Nigeria

S.B. AKPILA

Department of Civil Engineering, Rivers State University of Science and Technology, P.M.B 5080, Port Harcourt, Nigeria

ABSTRACT

The performance of both square and circular foundation on clay in the offshore Niger Delta has been attempted based on wave load simulation. Horizontal forces were evaluated from the impact of varying wave heights on circular piles while the empirical methods of Skempton, Brinch Hansen and Vesic were used to evaluate vertical loads. Sliding failure of square footing begins when the ratio of vertical load to area and undrained shear strength, V/As_u*, assumes negative values (i.e. at* $H/As_u > 3.427$*) while for circular footing, it occurs when mean value of the ratio of horizontal force to footing area and undrained shear strength,* H/As_u*, is greater than 0.0816. For square footing stability against sliding , the vertical load should be at least twice the anticipated horizontal load, while for circular footing, the vertical load should be at least 75 times the horizontal load anticipated when the ratio of foundation depth to breadth is lesser than one,* $D_f/B<1.0$*, and 70 times for* $D_f/B>1.0$*. For square foundation with* $D_f/B>1.0$*, higher horizontal force of about 10.5 times greater than those for* $D_f/B<1.0$ *are required to initiate sliding.*

Keywords: Empirical, sliding, stability, shear strength.

INTRODUCTION

The oil exploration and exploitation activities are increasingly drifting into the Niger Delta offshore environment. These operational facilities are supported by offshore foundations severely impacted upon by gravity and environmental loads. Gravity loads are due to the self weight of the structure while environmental loads are wave induced, giving rise to vertical, horizontal and moment loading. These loads are subsequently transferred to the foundation and are assessed as either single loading; vertical, horizontal or moment but generally, offshore structures are being impacted upon by varying degree of combined loading. Varying magnitudes of foundation displacement are induced by these forces; lateral (u_h), rotational (θ_m) and vertical (u_v) displacement. Horizontal forces are evaluated for varying pile diameters and wave heights using Morrison equation, adopting the linear wave theory of Airy [1], while concentric vertical loads are evaluated using the widely used methods [2,3,4]. Studies on foundation subjected to combined loading have been reported by many scholars [5, 6, 7, 8, 9].

The increasing level of exploration and production activities in the Niger Delta offshore environment calls for further understanding of offshore foundations performance to gravity and environmental loading. Evaluation of these displacements is very important in assessing the overall stability of the structure. Consequently, this paper attempts to make a comparison on the performance of square and circular foundations subjected to combined horizontal-vertical load induced forces and displacement in the Niger Delta.

MATERIALS AND METHODS

Wave Characteristics

The wave characteristics; wave height, wave period were deduced from relevant meteorological and oceanographic studies [10, 11, 12], while wave celerity, c, and wave length, L, were evaluated for conditions of shallow water waves [13].

Hydrodynamic Coefficients

Inertia coefficients, $C_{m,}$ and drag coefficient, $C_{d,}$ are reported to generally lie in the range of 0.8 to 2.0 [14] and there values are usually obtained from standard charts. However, Akpila and Ejezie [15] have reported that these coefficients have C_m of 1.5 and C_d of 0.7 in the offshore Niger Delta. The dimensionless parameters for maximum drag force, $K_{Dm,}$ inertia force, K_{im}, maximum drag moment, $S_{Dm,}$ and maximum inertia moment, $S_{im,}$ were evaluated from standard charts.

Hydrodynamic Forces

The total instantaneous hydrodynamic force, F, on a submerged structure per elemental length, ds of the cylinder can be is obtained from the expression;

$$F = \frac{C_d}{2}\rho_w D^2 + C_m \rho_w \left(\frac{\pi D^2}{4}\right)\frac{2\pi^2 H}{T^2}\left[\frac{\cosh k(d+z)}{\sinh kd}\right]\sin(kx - \omega t) \qquad (1)$$

While the maximum horizontal force is obtained by summing both the drag force and inertia force as follows:

$$F = \frac{C_d}{2}\gamma_w D H^2 K_{Dm} + C_m \gamma_w \pi \frac{D^2}{4} H K_{im} \qquad (2)$$

where F is horizontal force, γ_w is unit weight of water, D is pile diameter, ρ_w *is* density of water and H is wave height.

Concentric vertical loads

The renowned methods of Skempton [2], Brinch Hanson [3] and Vesic [4] were adopted for cases with the ratio of foundation depth to breadth, $D_f/B \leq 1.0$ and $D_f/B \geq 1.0$.

Vertical and Horizontal Load (M = 0)

The expression for a rectangular foundation subjected to combined vertical- horizontal load [4] is given as;

$$\frac{V_u}{A} = (2+\pi)s_u\left(1 + \frac{B'/L'}{2+\pi}\right)\left(1 - \frac{\frac{2+B'/L'}{1+B'/L'}H}{(2+\pi)s_u B'L'}\right) \qquad (3)$$

where B' and L' are the dimensions of the fictitious effective area A' of the foundation, s_u is undrained shear strength of soil, V_u is maximum vertical load and H is wave height. For the case of $B'=L'$ Equation (3) becomes;

$$\frac{V_u}{As_u} = 1.2\left[(2+\pi) - \frac{3H}{2As_u}\right] \qquad (4)$$

For circular footing, the following expression is adopted [16];

$$\frac{V}{As_u} = 1.2\left(1 + \pi + \sqrt{1 - \left(\frac{H}{As_u}\right)^2} - \sin^{-1}\frac{H}{As_u}\right) \qquad (5)$$

and the maximum horizontal load (H_o) is given by;

$$H_o = As_u = \left(\frac{1}{2+\pi}\right)V_o \qquad (6)$$

where sliding failure is incipient at $V/V_o \leq 0.5$. A recent study on the performance of foundations under vertical load induced displacement in the offshore Niger Delta of Nigeria has been reported [17].

RESULTS AND DISCUSSION

Wave Characteristics

A maximum directional wave height, H_{max} of approximately 7.0 m, mean wave period of 17 sec and average wind speed of 14.1m/s were obtained.

Hydrodynamic Coefficients

Hydrodynamic coefficients, $C_{d,}$ and $C_{m,}$ assumed a constant value of 0.7 and 1.5. The dimensionless parameters of inertia and drag forces (K_{im} and K_{Dm}) had constant values for a given wave height on pile diameter range of 1.0 – 2.0m. Generally, for a given wave height, K_{im} assumes lower values compared to K_{Dm} and a similar trend is also observed between S_{im} and $S_{Dm.}$

Square and Circular footing with $D_f/B<1.0$ (H-V, M=0)

An undrained shear strength of subsea soil is generally evaluated as 2.0kN/m^2 and the magnitude of horizontal force varies from 23kN to 938kN while foundation area used varies from 98-314m^2. Typical failure envelopes depicted on dimensionless plots of V/As_u and H/As_u (Figures 1 to 4) revealed that for a square footing, a V/As_u of 6.168 occurred at H/As_u equal to 0. Subsequently, V/As_u values decreased with increase in H/As_u and at V/As_u equal to 0.0, the value of H/As_u is 3.427. When H/As_u exceeded 3.427, negative values of V/As_u occurred for footing area less than 113m^2 indicating sliding failure. Consequently, for failure against sliding the vertical load is observed to be at least twice the anticipated horizontal load.

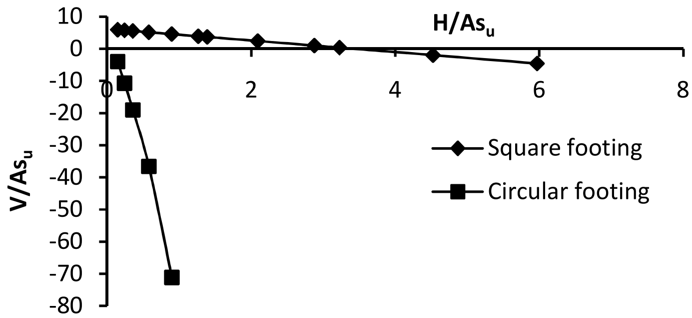

Figure 1: Square and Circular footing ($D_f/B<1.0$ and Area = 78mm^2)

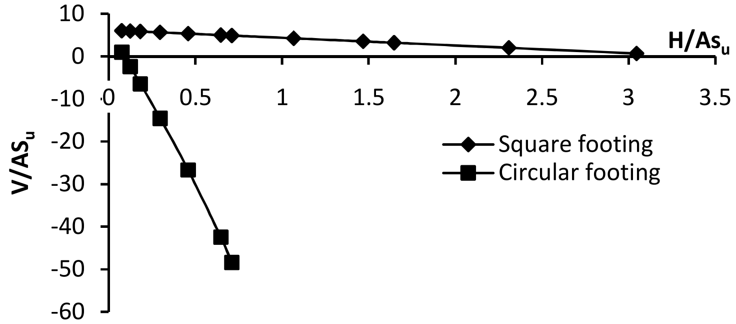

Figure 2: Square and Circular footing ($D_f/B<1.0$ and Area = 154mm^2)

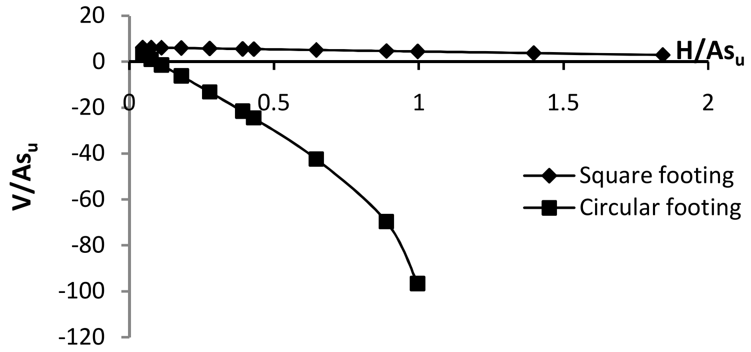

Figure 3: Square and Circular footing ($D_f/B<1.0$ and Area = 254mm^2)

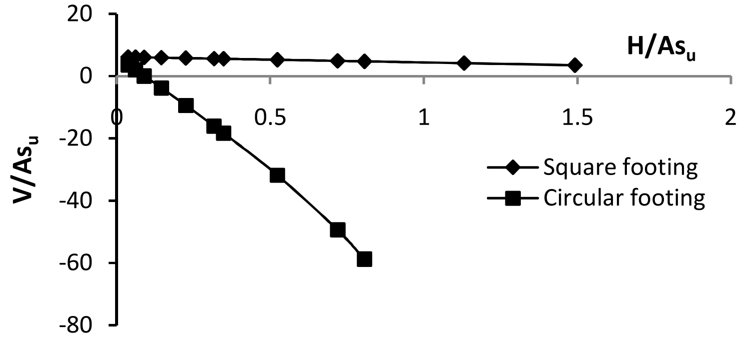

Figure 4: Square and Circular footing ($D_f/B<1.0$ and Area = 314mm^2)

For circular footings, the maximum vertical load ranged between 3.252As_u to 8.963As_u with a mean value of 6.107As_u, for zero horizontal loading (H/As_u=0). At V/As_u equal to zero, horizontal load assumed a value of H/As_u ranging from 0.0634 to 0.097, gave a mean value of H/As_u equal to 0.0816. Generally, sliding failure of circular footing occurs when mean values of H/As_u exceeds 0.0816. Under combined loading, the bearing capacity factor decreased in value, hence, reducing the bearing capacity of footing. The mean factor 6.107 is synonymous with the dimensionless bearing capacity factor N_c with respect to cohesion and the value is higher than 5.70 presented by Terzaghi [18] and 5.14 given by Vesic [4].

Square and circular Footing with D_f/B >1.0 (H-V, M=0)

The undrained shear strength of subsea soil is generally evaluated as 21kN/m^2. Typical failure envelopes depicted on dimensionless plots of V/As_u and H/As_u (Figures 5 to 8) revealed that and for a square footing, a maximum vertical load of 6.168As_u occurred at H/As_u equal to zero as in the case of D_f/B <1.0. Subsequently, V/As_u values decreases with increase in H/As_u. However, within the range of horizontal forces used in this study, the value of V/As_u did not assume negative value. Higher horizontal force of about 10.5 times greater than those for D_f/B<1.0 are required to initiate sliding for square footing with D_f/B >1.0.

For circular footing, the maximum vertical load ranged from 6.062As_u to 6.280As_u giving a mean maximum vertical load of 6.182As_u which occurred at H/As_u equal to zero. At V/As_u equal to zero, the horizontal load assumed a mean value, H, of 0.089As_u and subsequently, negative values of V/As_u occurred when H/As_u exceeds 0.089; indicating sliding failure. Besides, bearing capacity failure due to vertical loading occurred when V exceeded 6.182As_u. Hence, under combined loading (H-V), the vertical load on a circular footing is observed to be at least 70% in excess of the horizontal load anticipated to check the occurrence of bearing capacity failure by sliding.

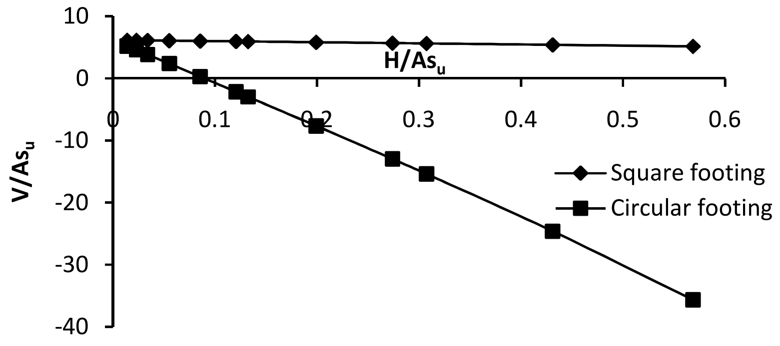

Figure 5: Square and Circular footing (D_f/B>1.0 and Area = 78mm^2)

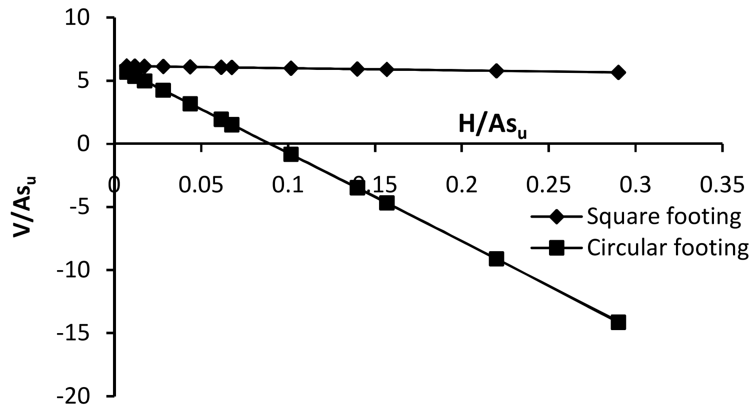

Figure 6: Square and Circular footing (D_f/B>1.0 and Area = 154mm^2)

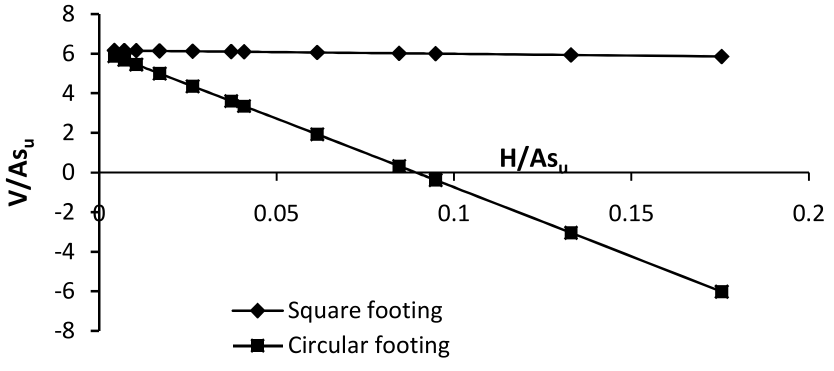

Figure 7: Square and Circular footing (D_f/B>1.0 and Area = 254mm^2)

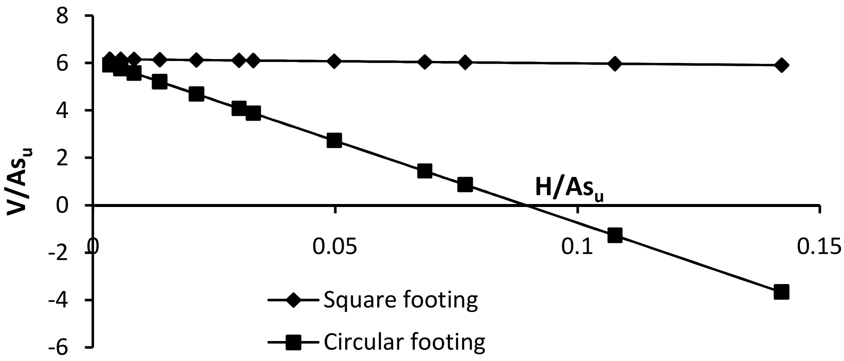

Figure 8: Square and Circular footing (D_f/B>1.0 and Area = 314mm^2)

CONCLUSION

Based on this study, the following conclusions can be drawn;

1) Sliding failure of square footing begins when V/As$_u$ assumes negative values (i.e. at H/As$_u$ > 3.427) and when mean value of H/As$_u$ exceeds 0.0816 for circular footing.
2) For square footing stability against sliding , the vertical load should be at least twice the anticipated horizontal load, while for circular footing, the vertical load should be at least 75 times the horizontal load anticipated for D_f/B<1.0 and 70 times for D_f/B>1.0.
3) For square foundation with D_f/B>1.0, higher horizontal force of about 10.5 times greater than those for D_f /B<1.0 are required to initiate sliding.
4) The generated models can be used for preliminary design of horizontal load induced displacement of offshore foundation in the Niger Delta.

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