Vertical vibration of suction caissons in floating structures offshore Niger Delta

La vibration verticale des ‘caissons de succion’ en structures flottantes au large de ‘Niger Delta’

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ABSTRACT

The vertical vibration and dynamic stability of suction caissons used as anchors for deepwater floating structures are investigated using the “Lumped Parameter System” of foundation vibration analyses. Load conditions corresponding to variable wave steepness are examined, while geotechnical characteristics typical of the Niger Delta offshore are considered for different caisson geometry (size). The *Diffraction theory,* which is normally applicable for computation of wave forces on large floating structures, is used here to determine the forces. Results obtained from analyses show that with increasing mass of caisson the amplitude of vibration decreases while the induced dynamic force on the surrounding soil increases. Beyond a certain magnitude of caisson mass however, it is observed that there is no further significant decrease in the amplitude of vibration. Another important observation is that there is appreciable reduction in the amplitude of vibration when several smaller units of suction caissons are used instead of a single massive unit. Amplitudes of vibration of groups of 2, 4, 6, 10 and 20 caissons units are respectively observed to be of the order of 67, 41, 32, 23 and 23% of the amplitudes of vibration of the corresponding single massive units. Beyond a certain maximum equivalent number of caissons, there is no further reduction in the amplitudes of vibration of the units.

RÉSUMÉ

La vibration verticale et la stabilité dynamique des "caissons de succion" utilisée comme les ancres pour les structures flottantes des eaux profondes sont étudiées à l’aide du système d’analyse de vibration de fondation basé sur "des paramètres regroupé". Les conditions de chargement correspondant à des escarpements variables de vagues sont examinées, pendant que les caractéristiques géotechniques typiques d’off-shore du "Niger Delta" sont considérées pour les géométries (dimensions) différentes des caissons. La théorie de Diffraction qui est normalement appliquée pour le calcul des forces de vagues sur les grandes structures flottantes est employée ici pour déterminer les forces. Les résultats obtenus à partir de ces analyses indiquent qu’avec l’augmentation de la masse de caisson, l’amplitude de vibration baisse tandis que la force dynamique provoquée sur le sol environnant augmente. Au-delà d’une certaine magnitude de masse de caisson, par ailleurs, il est noté que l’amplitude de vibration ne baisse plus de manière significative. Une autre observation constitue une réduction considérable de l’amplitude de vibration causée par l’utilisation de plusieurs unités plus petites de succion de caissons au lieu d’une seule unité de masse. On observe que les amplitudes de vibration relevant des groupes d’unités de caissons de 2,4,6,10, et 20 sont respectivement de l’ordre de 67,41,32,23 et 23% d’amplitudes de vibration correspondant aux unités massives simples. Au-delà d’un certain nombre équivalent maximum de caissons, il n’y a plus de réduction d’amplitudes de vibration des unités.

Keywords : Suction caisson ; Floating structures ; Deep water ; Vertical vibration ; Amplitude; Dynamic force

1 INTRODUCTION

The recent upsurge in the activities of the oil and gas industry in Nigeria has led to siting of production facilities in the deep water environments off the Niger Delta coastline. Deep sea oil and gas exploitation operations require stable platforms, which are the most important of the production facilities. Wind induced wave forces present themselves as a major challenge to operations in the deep water environments. The interaction of foundation elements with seabed materials provides the necessary resistance against deformation of underlying soils and movement of surface facilities. It is therefore necessary to understand the true nature of deep water sub-bottom materials and their interaction with anchoring systems to provide stability for floating structures subjected to wave-induced dynamic loading.

2 NATURE OF DEEP WATER SEDIMENTS

Deep water soils are saturated and highly porous. The water content is generally high but, with time, appreciable consolidation takes place. The condition of the seabed at Nkossa oil and gas field in the Gulf of Guinea adjourning the Niger Delta Offshore is described in Colliat et al (1998). For water depths between 150 and 250m several borings revealed the existence of soft, normally consolidated clays. Jeanjean et al (1998) also gives details of geotechnical investigations conducted at the Marlin site in the Gulf of Mexico which yielded similar soil parameters for design of suction caissons. In general, deep sea sediments are normally consolidated and highly compressible clays with low strength. Figure 2.1 shows the Niger Delta offshore in south-east Nigeria, while Table 2.1 gives a summary of typical soil properties of the area.

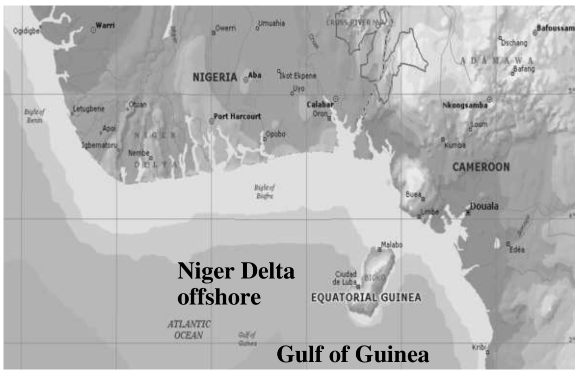

Figure 2.1: Niger Delta Offshore

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Table 2.1: Summary of Soil Properties at Marlin Site

Bore hole	Depth, m	Water content, %	Submerged unit weight kN/m^3	Plasticity index, %
BH 1	0 – 3.6	90 – 150	2.8 – 3.9	65 – 100
BH 2	0 – 2.4	90 – 150	2.8 – 3.9	65 – 100
BH 3	0 – 3.0	90 – 150	2.8 – 3.9	65 – 100
BH 4	0 – 2.4	90 – 150	2.8 – 3.9	65 – 100
BH 1	3.6 – 11.0	90 – 60	3.9 – 6.3	40 – 60
BH 2	2.4 – 11.0	90 – 60	3.9 – 6.8	35 – 60
BH 3	3.0 – 12.8	90 – 60	3.9 – 6.3	35 – 60
BH 4	2.4 – 11.8	90 – 60	3.9 – 6.8	35 – 60
BH 1	11.0 – 21.0	50 – 60	6.0 – 7.0	33 – 38
BH 2	11.0 – 19.5	50 – 65	6.0 – 7.0	30 – 40
BH 3	12.8 – 22.9	40 – 50	-	30 – 40
BH 4	11.0 – 22.9	50 – 65	6.0 – 6.8	32 – 42

Source: JeanJean et al, (1998)

3 SUCTION CAISSONS

Suction caissons are steel cylinders with thin walls, closed at the top (as shown schematically in Fig. 3.1) and driven into the sea bed initially by self-weight. Subsequent penetration is aided by suction pressure created in the interior of the caisson by water pumps. The geometry of suction caisson used in any particular situation is determined by the soil conditions on site. In general, larger penetration depth to diameter ratio is required in soft clay for sufficient holding capacity to be mobilised since side friction only improves with depth in such materials (Sukumaran, 2004).

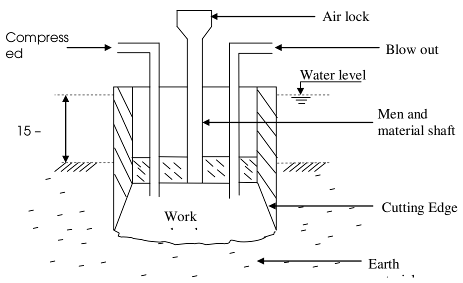

Figure 3.1: Pneumatic caisson

4 DATA GATHERING AND ANALYSIS

4.1 *Index properties of deep water soil*

Soil properties, such as void ratio and dynamic shear modulus can be obtained if the specific gravity of solid particles is known. The specific gravity of the particles for organic clay can be obtained from Table 4.1.

Table 4.1: Values of Specific Gravity for Soils

Soil type	Specific gravity, G_s
Gravel	2.65 – 2.68
Sand	2.65 – 2.68
Silt, inorganic	2.62 – 2.68
Clay, organic	2.58 – 2.65
Clay, inorganic	2.68 – 2.75

Source: Bowles, (1997)

Another very important input parameter for computing the dynamic quantities necessary for vibration analysis is the Poisson's ratio. Typical values are presented in Table 4.2

Table 4.2: Poisson's ratio for different soils.

Soil type	μ
Most clay soils	0.4 – 0.5
Saturated clay soils	0.45 – 0.5
Cohesionless medium & dense	0.3 – 0.4
Cohesionless loose & medium	0.2 – 0.35

Source: Bowles (1997)

It is often common to use a Poisson's ratio of 0.5 in analysis for saturated clays. This represents condition of no volume change which is typical for rapid loading condition of fine-grained saturated soils.

4.2 *Dynamic soil parameters*

Computations are made to obtain combined weight of suction caisson and soil plug which forms the mass of the vibrating foundations. Parameters such as dynamic shear modulus, spring constant and modified spring constant which take into account the embedment depth of caisson are also computed for different sizes of caisson. Details of these are presented in Tables 4.3-4.5.

Table 4.3: Computed Dynamic Shear Modulus on Deep Water Soil

Depth (m) (below seabed)	Water content % (upper limit)	Effective unit weight kN/m^3 (mean value)	Void ratio	Dynamic shear modulus (kPa) (computed)
0 – 3.6	150	3.4	3.975	2,294.2
3.6 – 12.8	90	3.9	2.385	2,265.3
12.8 – 12.9	65	6.4	1.723	4,832.4
22.9 – 39.6	80	5.6	2.120	10,757.3

Table 4.4: Computed Weights and Combined Weights of Caisson and Soil Plug (H_c: D = 2:1)

S/No	Caisson height H_c,(m)	Caisson Diameter D (m)	Weight of Caisson, kN	Weight of Soil Plug, kN	Combine Weight kN
1	8.0	4.0	173.01	340.95	513.96
2	9.0	4.5	219.13	481.28	700.41
3	10.0	5.0	270.69	655.64	926.33
4	11.0	5.5	327.70	874.09	1201.79
5	12.0	6.0	390.14	1136.37	1526.51
6	13.0	6.5	458.03	1695.18	2117.21
7	14.0	7.0	531.37	2074.34	2605.71
8	30.0	15.0	2445.9	26819.7	29265.6

Table 4.5: Computed Dynamic Parameters

H_c (m)	D (m)	Combined mass (kg) x10^3	Dynamic shear modulus G, kPa	Spring constant K_z, (KN/m)	Modified spring constant $K_{(z)d}$ kN/m
8.0	4.0	52.39	2294.2	36707.2	66073.0
9.0	4.5	71.40	2294.2	41295.6	74332.1
10.0	5.0	94.93	2294.2	45884	82591.2
11.0	5.5	122.51	2294.2	50472.4	90850.3
12.0	6.0	155.61	2294.2	55060.8	99109.4
13.0	6.5	215.82	2265.3	58897.8	106016.0
14.0	7.0	265.62	2265.3	63428.4	114171.1
30.0	15.0	2983.24	2265.3		

4.3 *Deepwater wave characteristics*

Deepwater waves are known for long swells with long wavelengths and long periods. According to AP1 (2000) which is concerned with the analysis and design of fixed offshore production platforms in the Gulf of Mexico, deepwater waves exhibit amplitude ranges between 18.3 and 24.4m, and steepness ranges between 1/11 and 1/15. Steepness is given by:

$$S = \frac{H}{gT^2} \tag{4.1}$$

where H is wave height (double amplitude), g is acceleration due to gravity, and T is apparent wave period. Certain deep water sites are known for incessant occurrence of intense hurricanes than others. Designs have therefore focussed on events (storms) of higher return periods.

Table 4.6 presents computed circular frequencies of waves based on wave steepness and amplitude.

Table 4.6: Computed Deepwater Wave Frequencies

Steepness (S)	Amplitude, H (m)	Circular frequency ω, (rad/s)
1/11	18.3	1.387
	24.4	1.201
1/12	18.3	1.328
	24.4	1.150
1/13	18.3	1.276
	24.4	1.105
1/14	18.3	1.229
	24.4	1.065
1/15	18.3	1.188
	24.4	1.029

4.4 *Computation of wave forces*

The Diffraction Theory has been used for computation of wave forces since most floating production systems are very large in dimension compared to incident waves. According to the theory, the expressions for wave forces are developed based on the assumptions that flow is oscillatory, incompressible and irrotational so that the fluid velocity may be represented as the gradient of a scalar potential, ϕ which is the sum of incident and scattered potentials and satisfies the Laplace Equation, given in rectangular Cartesian coordinate system as:

$$\nabla^2\phi = \frac{\partial^2\phi}{\partial x^2} + \frac{\partial^2\phi}{\partial y^2} + \frac{\partial^2\phi}{\partial z^2} = 0 \tag{4.2}$$

With proper definition of all the boundary conditions and substitution for the value of ϕ in the general Laplace equation, dynamic fluid pressures corresponding to the first and second-order wave theories are obtained which can be translated into wave forces on floating structures.

Once the pressures on the surface of the body are known, the force in a particular direction is obtained from the integration of the component of the pressure in that direction over the submerged surface. The amplitude of wave forces to be computed are those exerted on two-dimensional floating structures such as pipelines, barges, ships, and horizontal structures. The maximum vertical force F_y is given by:

$$\overline{F}_y = \frac{F_y(\max)}{\rho g a H / 2} \tag{4.3}$$

where $\overline{F}_y$ is force coefficient.

Chakrabarti (2003) gives plots of the force coefficient, $\overline{F}_y$ as a function of diffraction parameter, ka, values of which are substituted into equation 4.3 to compute the wave force on the floating structure. Table 4.7 tabulates computed wave forces on a two dimensional half-submerged floating structure with cross sectional radius, a = 10m.

The forces are calculated for various possible wave steepness and amplitudes corresponding to that obtained in deep waters. Column 5 is computed using L = $1.56T^2$ (m), L is wavelength and T is period for deepwater waves.

Table 4.7: Computed Wave Forces On Half-Submerged Cylinder, (d/a = 4.0), d = Water Depth

Wave Steepness (S)	Amplitude, H (m)	ω, (rad/s)	Diffraction parameter, Ka = 2πa/l	$\overline{F}_y$	F_y (kN)
1/11	18.3	1.387	1.96	0.44	395.0
	24.4	1.201	1.47	0.60	718.1
1/12	18.3	1.328	1.80	0.48	430.9
	24.4	1.150	1.35	0.68	813.8
1/13	18.3	1.276	1.66	0.58	520.6
	24.4	1.105	1.24	0.70	837.8
1/14	18.3	1.229	1.54	0.59	529.6
	24.4	1.065	1.15	0.77	921.6
1/15	18.3	1.188	1.44	0.65	583.4

a - cross sectional radius of two dimensional floating structures and H - double amplitude of water wave.

5 DYNAMIC STABILITY ANALYSIS

5.1 *Mass-spring-dashpot model for suction caissons*

Figure 5.1 represents a floating system on water surface which is anchored to the seabed by means of suction caissons through connecting mooring lines. The entire structural arrangement is subjected to water wave forces causing up– and downward movement of the floating facility which in turn induce vibratory motions in the anchor. Depending on the point of attachment and inclination of the mooring line to the horizontal, the induced vibratory motion is either vertical or horizontal or both or rotational.

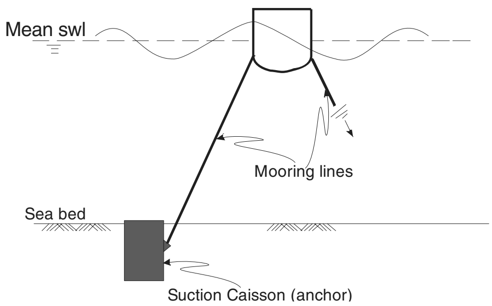

Figure 5.1: Suction Caisson as Anchor for Deepwater Floating Structures

5.2 *Amplitudes of vibration and dynamic forces*

The vertical vibration amplitude of suction caissons is determined using the well-known relation:

$$A_z = \frac{F_z / K_z}{\sqrt{\left[1-\left(\omega^2 / \omega_n^2\right)\right]^2 + 4D_z^2\left(\omega^2 / \omega_n^2\right)}} \tag{5.1}$$

The maximum dynamic force on the surrounding soil is calculated from:

$$F_{dynamic} = A_z \sqrt{\left[K_z^2 + (C_z \omega)^2\right]}, \quad (5.2)$$

where: $\omega_n = \sqrt{\frac{K_z}{m}}$ = natural circular frequency.

Figure 5.2 presents the relationship between computed amplitudes and size (mass) of caissons for vertical oscillation and for different wave steepness. Also shown is Figure 5.3 which presents the relationship between computed mass of caisson and and induced force on surrounding soils. Figure 5.4 shows equivalent number of suctions that can be considered instead of using a single massive one. It reveals the percentage reduction in the vibration amplitude which can be achieved if several smaller units of caissons are used rather than a single massive caisson.

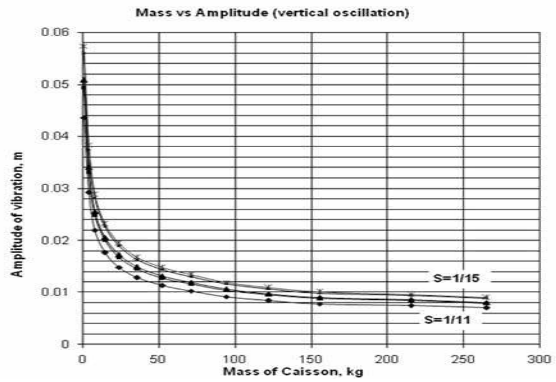

Figure 5.2: Mass vs. Amplitude of Vibration

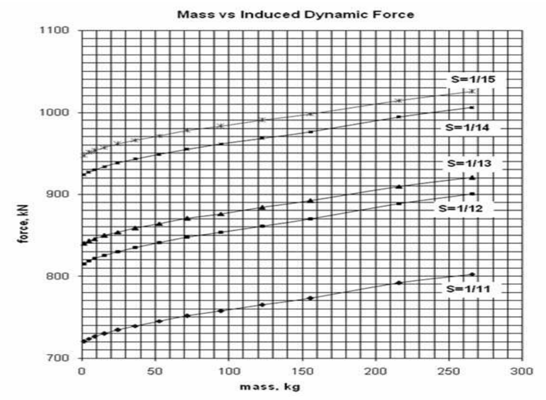

Figure 5.3: Mass vs. Induced Dynamic Force

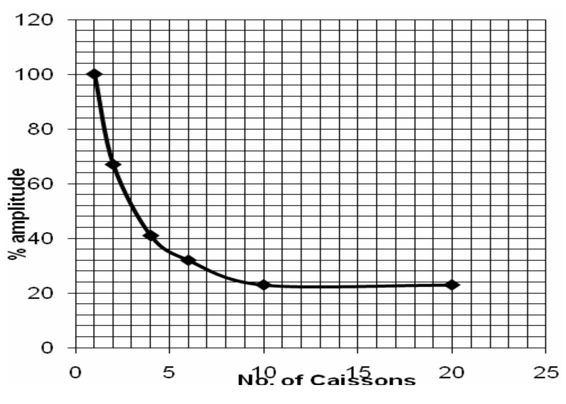

Figure 5.4: Number of Caissons vs. Amplitude of Vibration (%)

6 DISCUSSION OF RESULTS

From the results of analyses, it is observed that the amplitude of vibration decreases whereas induced dynamic force on the surrounding soils increases with increasing caisson mass. Beyond a certain value of caisson mass however this trend in the variation of amplitude of vibration ceases. No significant decrease in the amplitude of vibration is observed any longer. From the point of view of economy this observation is important because it establishes the maximum size of caisson to be used in any particular situation. It is also observed that for a given mass of caisson both the amplitude of vibration and induced forces on the surrounding soils increase with decreasing wave steepness.

Furthermore, a reduction in the amplitude of vibration is realized when several smaller units of suction caissons are used as a group instead of a single massive unit. Amplitudes of vibration of groups of 2, 4, 6, 10 and 20 caissons are observed to be of the order of 67, 41, 32, 23 and 23% respectively of the amplitudes of vibration of the corresponding single massive units. This is translated into a reduction of amplitude of the order, 23, 59, 68, 77 and 77% respectively for each member caisson in the groups of 2, 4, 6, 10 and 20. The results also reveal that beyond a certain maximum equivalent number of caissons, there is no further reduction in the amplitude of the vibratory units. At this maximum the combined mass of the smaller units is somewhat less than the mass of the single massive unit. Adopting the maximum equivalent number of caissons in designs therefore, increases the margin of safety and achieves cost reduction as less material would be used.

7 CONCLUSION

Dynamic stability of suction caisson can be assessed using the "Lumped Parameter System" approach which models the foundation system as a mass-spring-dashpot system. This involves computing dynamic soil parameters such as dynamic shear modulus, spring constant for soil, damping ratio, and natural frequency of soil-foundation system. Information regarding sinusoidal wave loading of floating structures is also required. Accurate determination of the maximum constant force amplitude of sinusoidal wave forces is necessary considering its effect on the amplitude of vibration. The determination of the maximum force amplitude depends on the wave characteristics and the size of the floating structure in question. A careful analysis of the foundation system using the mentioned parameters and method will yield results which can be compared with recommended standards. Rather than using a single massive unit of suction caisson several smaller units can be considered. This will reduce the total load that would be borne by the single massive caisson and hence, the amplitudes of vibration.

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