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Dynamic Analysis for Gravity Platform Foundations

Analyse Dynamique pour les Fondations des Plate-Formes

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SYNOPSIS This paper describes the foundation analysis of a typical prototype gravity platform, for which the wave action is considered as a time dependent load. Wave records for North Sea storms are shown to possess predominant periods in the range of 5 to 25 seconds. The possibility exists, therefore, that a large gravity platform resting on a relatively flexible foundation could respond dynamically to such periodic forces and produce large dynamic foundation stresses and displacements. These stresses could be far larger than those predicted by static calculations. This possibility is investigated for the considered structure, with particular attention being given to the effect of energy being radiated away from the oscillating structure.

A finite element analysis is used for the foundation, structure and water. The energy radiation effect through the foundation is modelled on the finite element boundary by the inclusion of special damping terms. The results indicate that a static analysis is realistic in this particular case. However, this conclusion is not a general one, and it is explained that structural and foundation conditions, other than those considered in this paper, could give rise to large dynamic effects.

INTRODUCTION

The present trend in the search for oil in the North Sea is making it necessary for wells to be drilled in regions where ever increasing depths of water are encountered. This has produced a need for large drilling platforms, and the gravity type has become a popular solution. It is believed that the enlargement of platforms has increased the tendency of the foundation-platform systems, together with the associated surround water, to respond dynamically to wave loading. If the natural period of oscillation of a system is small compared with the period of wave loading, as could be the case for stiff foundation conditions, or a small platform, then the problem may be solved by a simple static analysis. However, as the natural period of the platform system increases, due to an increase in platform size for example, the greater becomes the necessity to consider the loads as truly dynamic in nature. Under an applied time varying load, the dynamic foundation-platform system experiences larger foundation stresses and displacements than under the corresponding static load due to inertia effects. This paper seeks to explore the possibility that the system may respond to realistic wave loading in a dynamic manner, thus rendering the static foundation analysis of limited value. Here, foundation and structural conditions applicable to a typical prototype situation are investigated. However, before the foundation-structure-fluid system is considered in detail, it is necessary to consider the dynamic nature of the wave loading.

WAVE LOADING

Naturally occurring waves are not of sinusoidal form, in general, and must therefore by analysed to determine their frequency characteristics. One well-known method is to determine the energy content for particular wave records and to plot this as a function of frequency or period, see for example Cartwright and Longuet-Higgins (1956). This energy spectrum can then be used to establish the force levels acting on particular structures as described, for example, by Moan et al (1975).

As an alternative to the above energy spectrum, Dungar, Eldred and Severn (1976) consider a method which entails the analysis of particular wave records, in a similar manner to earthquake records. Forty North Sea wave height-time records, taken in storm conditions by the Famita vessel, were analysed, and the wave height was related to corresponding structural loading in terms of both drag forces and inertia forces. For each record, the response of a single degree of freedom structure, with a particular resonant period, T_r, and critical damping coefficient, c, was calculated and compared with the response for a static force corresponding with the maximum wave height of the record. This ratio of the maximum dynamic response to the static response under the same loading amplitude, termed the load dynamic magnification factor, L.D.M.F., was plotted as a function of T_r and c. Figure 1 shows these curves, for the case of inertia loading, within a range of damping coefficients 2 to 40%. L.D.M.F. of unity is obtained if the loading is applied slowly, as indicated in figure 1, for resonant periods of the structure below 5 seconds. However, structures with resonant periods between 5 and 25 seconds have a tendency to respond to North Sea waves with an L.D.M.F. greater than unity; the maximum L.D.M.F. being for a resonant period of approximately 12 seconds. The following sections will discuss the details involved in establishing a value for the resonant period, and will give likely D.M.F. values for realistic prototype conditions.

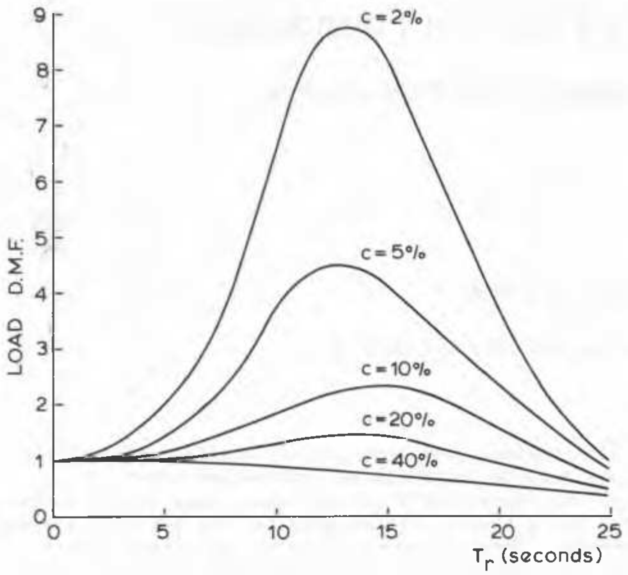


Fig. 1 Dynamic magnification factors for North Sea storm waves

THE GROUND RESONANT PERIOD

It is apparent from the above discussion that a knowledge of the resonant period of the structural system is essential before the system is classified as a 'dynamic system' or a 'static system'. However, the term 'resonant period' for a structure such as a gravity platform resting on a semi-infinite foundation, must be used with care. A resonant condition cannot be achieved without a reflecting boundary. Consequently, the example of an infinitely rigid structure resting on a semi-infinite elastic homogeneous half space does not possess a resonant period. Much of the energy is transmitted to the foundation and is radiated away from the source in the form of compression waves, shear waves and Rayleigh waves. When the response of this system to a given applied sinusoidal force is plotted as a function of the forcing period, T, there exists, however, a value of T which corresponds to the maximum response conditions. This may be termed the ground resonant period, T_g, which will be related to T_r in a later section.

Three previous methods of analysis that have been used to estimate the value of the ground resonant period are given in Dungar and Eldred (1977). The main criticism raised is the assumption of a finite boundary to the foundation mesh. This assumption is acceptable for static analyses, where displacements become very small at a finite distance from the position of the applied load. However, for dynamic analyses, such artificial boundaries reflect energy in a similar manner to the real boundaries previously described; and consequently the resonant period is dependent upon the assumed foundation mesh size.

THE EFFECT OF VARIOUS FOUNDATION CONDITIONS

In practice, foundation conditions will vary both in elastic properties, and in the layering of strata. Each foundation will create a different dynamic response for the same gravity platform; and so each foundation-platform system should be investigated carefully. The presence of weak or hard layers provides reflecting surfaces for energy transmitted from the structure. This will create a semi-resonant condition, which will retain energy in the region of the structure; and consequently will give greater dynamic stresses and displacements than for a homogeneous foundation. Another likely situation for this retention of energy is for the foundation elastic modulus to vary with depth. Several such situations have been investigated by Dungar and Eldred (1977) for an idealised gravity platform for the condition of wave loading. Several general conclusions can be drawn from this paper.

The first semi-resonant mode of vibration of a homogeneous, elastic, semi-infinite foundation supporting an idealised platform is a combination of the swaying and sliding of the structure. A very stiff structure of height 120m and diameter 120m was considered, resting on a foundation of 3×10^5 kN/m^2 elastic modulus. Results for this system gave a maximum T_g of about 5 seconds, which is at the minimum period of interest for North Sea storm waves. Increasing the size of structure, however, increases this resonant period, and also increases the maximum structural D.M.F. (ratio of dynamic displacements to static displacements under sinusoidal loading). This trend can also be seen when the stiffness of the foundation decreases.

Varying the soil conditions by introducing stiff horizontal bands of soil, or by increasing the modulus of the soil with depth again increases the maximum structural D.M.F. This is most marked when an infinitely stiff horizontal boundary is introduced, thus causing complete reflection of the energy. However, this stiffening of the soil has the effect of lowering the ground resonant period. In some cases, the foundation-structure system is then taken out of the region of possible dynamic magnification altogether. However, the possibility does exist of a foundation-structure system with realistic prototype properties responding dynamically within the range of periods of 5 to 25 seconds; and more importantly, in the range of 10 to 15 seconds as shown in Figure 1. A soft foundation with stiff horizontal layers, supporting a large structure could respond with a period well within this critical range.

METHOD OF ANALYSIS

In this study, the approach used is based upon the finite element method, but includes a representation for the energy which is radiated away from the structure and associated foundation. Finite elements are also used for the fluid region.

The axisymmetrical elements used to represent the structure and foundation are of triangular cross section, with the stresses and strain taken as harmonic functions of the polar coordinate, θ, as described for static analysis, by Wilson (1965). Application to dynamic analysis has also been discussed in detail by Dungar (1972). This axisymmetric geometry reduces the degree of numerical complexity and size compared with an equivalent full three-dimensional analysis. This assumption is not a severe restriction, as the foundation is nearly truly axisymmetric. The only asymmetric part is the structure, but this can be idealised to retain the same size, mass and stiffness. This tends only to affect the stresses and displacements within the structure itself, giving a good estimate for the large dynamic stresses within the foundation.

The foundation properties, as well as some properties within the structure, are elastic only over a limited range of stress. Only elastic properties are used for the present study. The present method, however, will show the general trends for a particular structure, and demonstrate whether or not there is a dynamic problem.

In order to avoid the problem of reflecting foundation boundaries, the foundation mesh is given finite boundaries, to which damping terms are added to absorb the radiated energy. This method is based on that of Lysmer and Kuhlemeyer (1969), and is discussed in detail, together with a presentation of solutions in comparison with existing closed form solutions, by Dungar and Eldred (1977).

The fluid region is also represented by axisymmetrical finite elements. Here the effect of compressibility of the fluid, surface waves and viscosity are neglected to enable the calculation to be made for fluid add-mass. The problem reduces to the solution of the Laplace equation and details of the finite element methods for effecting this solution, with appropriate boundary conditions, are described in Zienkiewicz (1971) and Dungar and Jackson (1975).

Dungar and Eldred (1977) have described the method of solving to obtain the dynamic displacements. When these are plotted against the sinusoidal frequency, a value of maximum structural D.M.F. for the particular foundation-structure system, along with its associated value of T_g, can be obtained.

When the first mode of vibration is considered alone, this plot resembles that for a single degree of freedom system. This enables Figure 1 to be used by assuming that over a limited range of sinusoidal forcing frequencies, the foundation-structure system can indeed be simplified to a single degree of freedom system, i.e. $T_g = T_r$. Similarly, the system damping can be obtained by approximating the maximum structural D.M.F. to 1/2c. From these values of T_r and c, the load D.M.F. for North Sea storms can be estimated from Fig. 1.

DISCUSSION OF RESULTS

A series of finite element meshes were generated and used for a particular gravity structure, such that it could be analysed for a range of frequencies. Particular attention was given to the size of element, and to the distance to the mesh boundary, as suggested by Dungar and Eldred (1977). The loading was applied in two parts; the first part comprised a moment component only, so that only swaying forces were present; and the second part comprised vertical and horizontal components, so that only a sliding force was applied and no moment was applied to the base. When these two parts were added, the total gave the maximum prototype loading to be expected in the North Sea.

The foundation was modelled as a layered system, with the elastic modulus increasing in three steps from 3×10^4 kN/m^2 at the sea bed, to 4×10^5 kN/m^2 at 125m below the sea bed. This created three horizontal reflecting surfaces. The structure was 190m high, with a base diameter of 140m and a mass of 1.1×10^9 kg.

Figures 2, 3 and 4 give the results for the applied moment, the applied horizontal force and the combined force respectively. The results are plotted in the form of structural D.M.F. against the frequency, ω, for three degrees of freedom as follows:

(i) refers to the horizontal motion of the sea bed at the edge of the structure

(ii) refers to the vertical motion of the sea bed at the edge of the structure

(iii) refers to the horizontal motion of the centre of the top of the structure.

Figure 2 has no graph for (i) and Figure 3 has no graph for (ii) as the static displacements were very small in these cases.

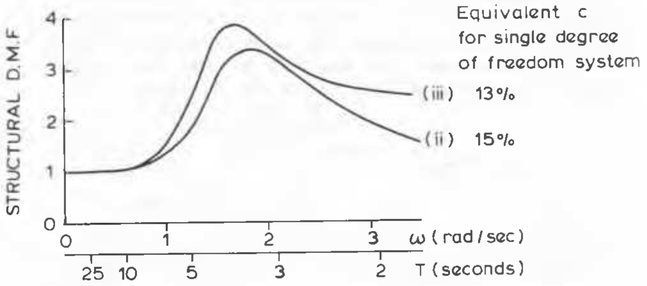


Fig. 2 Magnification factors for rocking load case

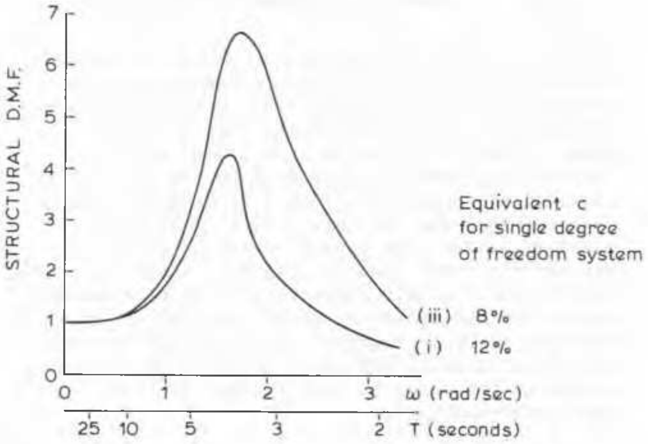


Fig. 3 Magnification factors for horizontal load case

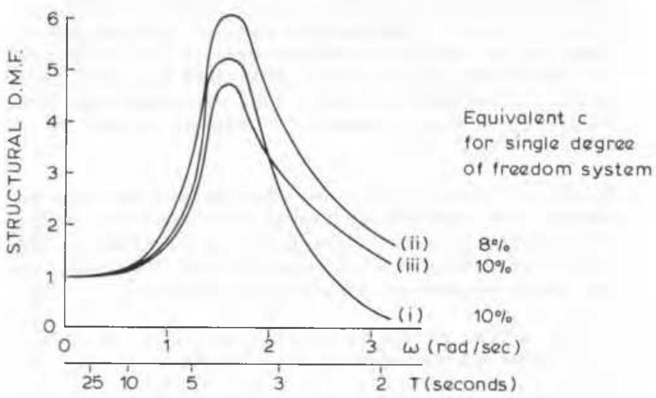
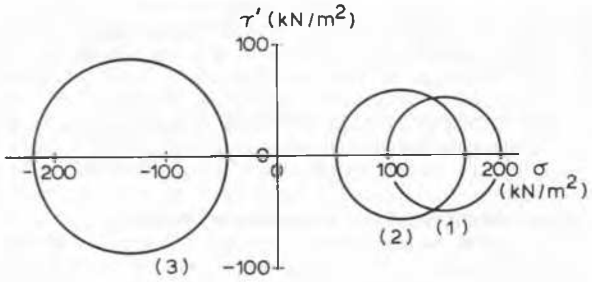


Fig. 4 Magnification factors for total load case

Typical foundation stress results for a point under the edge of the structure are given in Figure 5 in the form of Mohr's circles. The point considered is on the plane of symmetry, where no lateral displacements are caused. The results compared are for self weight of the structure only (1), 'static' application of wave loading (2) and 'dynamic' application of wave loading for an oscillation of period T_g (3). In cases (2) and (3) the maximum stress circle incurred within the cycle is shown.



Compressive stresses are plotted as positive.

Fig. 5 Foundation stresses under structure

As can be seen, the response to purely sinusoidal loading is large over a limited frequency range, giving dynamic displacements up to 6 times static, and dynamic stresses which take the soil into a state of tension. However, when the value T_g (approx. 3.6 secs) is looked up on Figure 1, it is seen to lie outside the region of response. Thus it seems that for this particular foundation-platform system, the ground resonant period lies outside the range normally found in North Sea storm conditions. In this case then it can be concluded that no dynamic problem exists, and that this platform could be designed by static methods for this particular foundation. However, this may not always be the case, so each system should be analysed dynamically.

CONCLUSIONS

(1) A gravity structure with a relatively flexible foundation must be idealised so that the effects of radiated energy are included in the solution. It is not sufficient to terminate the boundary of solution with conditions of fixed displacements, unless there are justifiable reasons such as the occurrence of rigid bed rock at a known depth.

(2) The geotechnical details, below any particular gravity platform, are of prime importance when assessing the response of the platform. Both the ground resonant period, T_g, and the peak structural D.M.F., for sinusoidal oscillation are influenced by the presence of layered soil below the platform.

(3) The response of this particular complete platform-foundation-fluid system, under the action of North Sea storm waves, could be analysed statically. However, there is evidence that it is not necessarily safe to analyse all such systems by simple static means.

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