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SEISMIC RESPONSE OF BARRAGE RAFT FLOOR UNDER HETEROGENEOUS SOIL MEDIUM

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ABSTRACT

Seismic analyses of a barrage raft floor resting on homogeneous and heterogeneous subsoil condition were carried out by means of finite element modeling and analysis. Three dimensional models considering soil-raft-structure system were developed for both circumstances. The soil continuum, cut-off, pier, beam and abutment were modeled using eight noded brick element whereas raft floor was modeled using four noded plate bending element. The relevant amount of soil around and bottom of the barrage raft foundation has been modeled to find the effect of homogeneous and heterogeneous soil media on the seismic behavior of barrage raft floor. The seismic analysis was performed using the site dependent response spectra by giving excitation across the flow and the finite element analyses takes into account adequately all factors that control significantly the response of the soil-raft-structure system. Influence of homogeneous and heterogeneous soil media was considered on the barrage raft floor under seismic condition at the upstream, ogee and downstream sections. Significant variations in dynamic behaviour of barrage raft floor were found and it has also been observed that stresses are significantly higher under heterogeneous soil medium compared to homogeneous soil medium.

INTRODUCTION

A barrage is a diversion headwork, which is employed to divert inflows into the canal from a river. In a barrage the crest is kept at low level and the gates alone affect heading up of water. During the floods, the gates are raised to pass the high flood flow. When the flood recedes, the gates are lowered and the flow is obstructed, thus maintaining the required pond level at the upstream of the barrage for feeding the main canal under gravity.

Barrages are usually made of masonry, plain cement concrete or reinforced concrete, depending on the nature of foundation encountered, availability of construction material, dewatering problems, economy of construction, etc. A barrage can have gravity or a raft floor. In recent years, the hydraulic and structural engineers are seized upon the important task of evolving safe and economic design criteria for the barrage raft due to several advantages such as less excavation and dewatering, lesser construction time, superior flexural behaviour etc. The finite element analyses of barrages have been carried out by Sarkar (2001) and Sasidhar (2002). A comparative analysis of a barrage raft floor has also been carried by Venkatesh et al (2004), Pandey et al (2005) on homogeneous foundation media. In the present study three-dimensional finite element method has been used for carrying out the response spectrum analysis (Clough et al 1993) when barrage raft floor resting on homogeneous and heterogeneous soil medium. In this method barrage considering soil-raft-structure system have been modelled through an assemblage of finite elements.

FINITE ELEMENT METHOD

The finite element method is a numerical procedure for analyzing structures and continua. It is a powerful tool in structural analysis of simple to complicated geometries. In the recent years with the advent of compact and powerful computers, the analyses performed by finite element method have become more acceptable. The basic steps involved in the finite element method are as mentioned below.

I. Discretization of the continuum.
II. Calculation of the element stiffness matrices.
III. Assembling the element stiffness matrices.

IV. Calculation of the element load vectors.
V. Assembling the element load vectors.
VI. Imposition of boundary conditions.
VII. Imposition of external forces.
VIII. Calculation of the displacement vectors.
IX. Calculation of the strains and stress field.

A detailed discussion on the finite element method is beyond the scope of this paper but well documented in standard literature (Desai and Abel, 2000; Krishnamurthy, 2002; Cook et al., 1989**;** Bathe, 1982; Zienkiewicz, 1977).

IDEALIZATION OF BARRAGE BAYS

The present section as shown in Fig. 1 deals with barrage raft floor of bays 1-2, which has been separated by expansion joints from rest of the bays. Plan of bays 1-2 with three sections of the barrage raft floor in transverse direction (across the flow) i.e. upstream section (A-A), ogee section (B-B) and downstream section (C-C) at different distances from upstream edge have been chosen for the comparison under dynamic loadings. The barrage raft floor with cut-off along with abutment wall, single pier and double pier of bays 1 and 2 are completely resting on alluvial soil. The abutment wall has been provided to retain the abutment soil up to its full height.

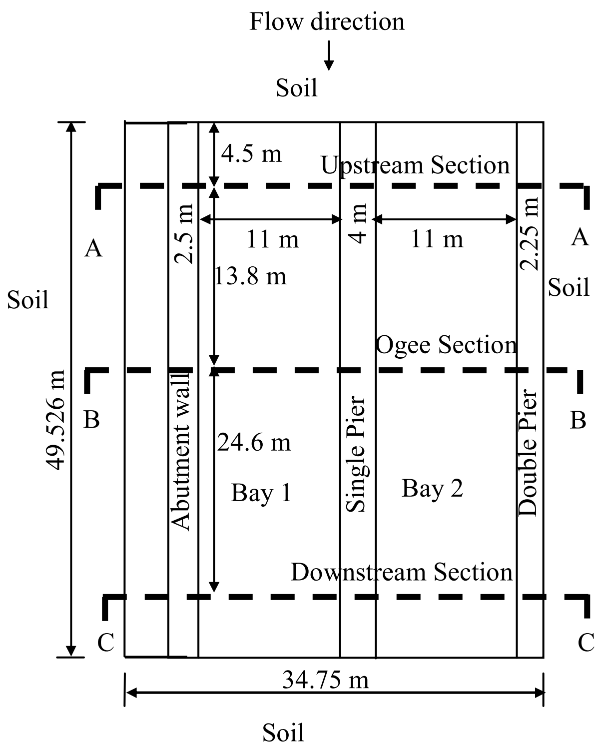

Fig. 1. Plan showing various comparative sections of bays 1-2

An attempt has been made to predict dynamic stresses of barrage raft floor resting on homogeneous and heterogeneous (non-homogeneous) soil medium.

<u>Homogeneity and Heterogeneity Considerations</u>

The analysis of barrage raft floor resting on cohesionless soils, whose elastic modulus or shear modulus increases with the confining pressure, is more complex as modulus of elasticity and Poisson's ratio vary with the confining pressure. This non-homogeneity of soil in the form of increasing stiffness with depth has a significant effect on the stress of the raft floor under dynamic loading.

Terzaghi (1943) suggested an approximate solution, in which variation of elastic modulus with respect to depth is considered linear, and is given by

$$E_s = E_0 + mZ \tag{1}$$

where E_0 and m are constant and E_s is the value of modulus of elasticity at a depth Z. Brown and Gibson (1972) developed a solution for the surface settlement of a deep elastic stratum whose modulus has increased linearly with depth. Carrier and Christian (1973) examined the settlement of a rigid circular raft resting on similar medium. Burland and Wroth (1974) highlighted the need for providing charts which take into account the non-homogeneity of soil as an aid to the designers since non-homogeneity in the form of increasing stiffness with depth has a marked influence on the surface settlements. Hain et al. (1976) have modeled the soil as an isotropic elastic continuum similar to Terzaghi's (1943) approximate solution, in which the modulus increases linearly with depth as-

$$E_s = E_0 + E_n.Z \tag{2}$$

where,

E_s = elastic modulus of the soil at any depth Z
E_0 = elastic modulus at the surface
E_n = rate of increase of the modulus with depth

In the present study the Poisson's ratio is independent of depth and non-homogeneity of soil has been considered in terms of first order material non-linearity, since soil is a highly non-linear material under applied loads. On the application of loads, the shear modulus and elastic modulus of soil increase with the depth and these increments have been assumed parabolic in nature. The variation in shear modulus of soil has been calculated using the following correlation (Arya et al, 1979)

$$G_1 = G_2 \left(\frac{\sigma_{oct1}}{\sigma_{oct2}} \right)^{0.5} \tag{3}$$

where,
G_1= shear modulus at mid depth of top layer
G_2 = shear modulus at mid depth of second layer below the first layer
σ_{oct1} = octahedral stresses in first layer of soil (mean stresses)
σ_{oct2} = octahedral stresses in second layer of soil (mean stresses)

The entire soil medium has been divided into four equal horizontal layers, each with a thickness of 20.0m. The variation in elastic modulus within the layers has also been considered. The first layer (up to 20.0m) below the raft floor has been divided into five parts whereas second, third and fourth layers have been divided in four, three and two parts respectively. Therefore, the total numbers of soil layers in all are fourteen and are shown in Fig. 2.

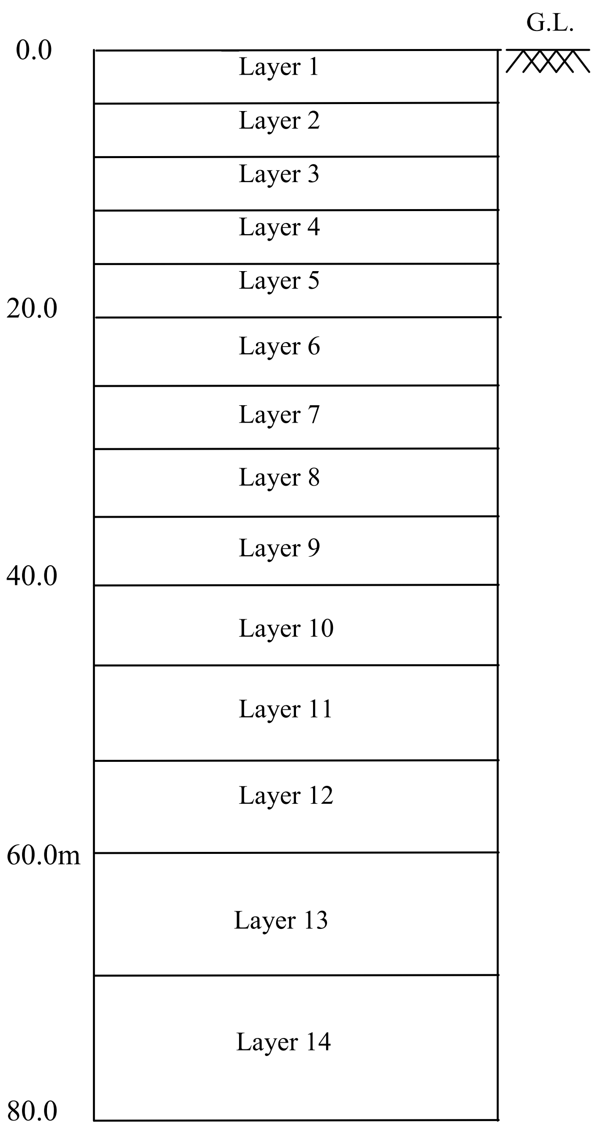

Fig. 2. Variation of soil layer with depth for non-homogeneous soil medium

The parabolic variation of modulus of elasticity of soil with respect to depth has been obtained for non-homogeous soil medium (Fig. 3) where as modulus of elasticity and Poisson's ration of homogeneous soil medium were 1 x 10^5 kN/m^2 and 0.3.

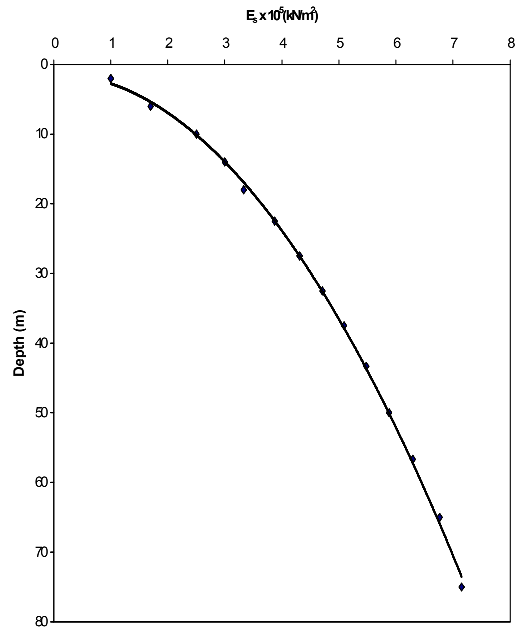

Fig. 3. Parabolic variation of modulus of elasticity (E_s) with depth for non-homogeneous soil medium

PHYSICAL MODELLING

Eight noded isoparametric brick elements have been used for the three-dimensional modeling of soil media (King, 1977). The cut-off, pier, abutment wall and beam have been also modeled using eight noded isoparametric brick elements. The four noded three-dimensional isoparametric shell elements have been used for barrage raft floor modeling to simulate the behaviour of barrage raft floor as plate bending element (King, 1977). In this model the depth of the soil media considered is 80m from the crest level. The extent of surrounding soil up to 35m on both sides of the transverse section of the raft and 50m on both in upstream and downstream side equivalent to the length of the raft floor along the flow has been considered.

Several iterations were made for refining the mesh of the models from coarser to finer till the values of stresses at the same section under study in the two consecutive models converged. The discretized adopted model consists of pier, abutment, beam structure with the supporting raft floor and cut-offs are shown in Fig. 4, while the complete discretised model with soil has been shown in Fig. 5. The material properties of other components except foundation soil are as shown in Table 1.

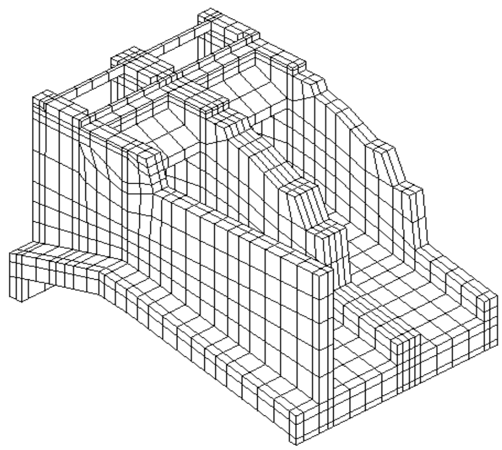

Fig. 4. 3D-Finite element discretization of the pier, abutment and raft system with cut-off of bays 1-2

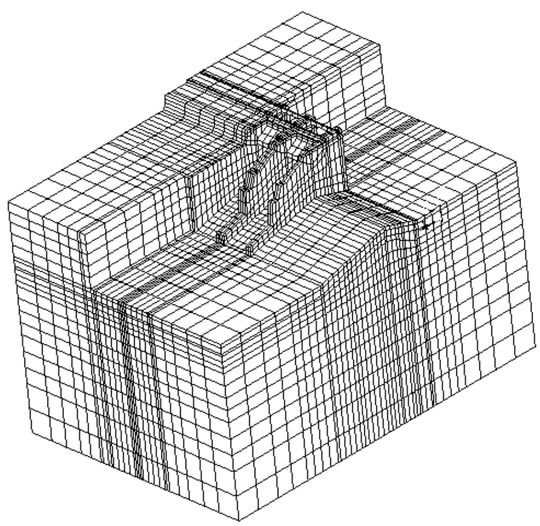

Fig. 5. 3D-Finite element model of bays 1-2 with pier, raft and foundation soil

Table 1. Material properties used in bays 1-2 model

Components	Modulus of Elasticity (E) (kN/m^2)	Unit Weight (γ) (kN/m^3)	Poisson's Ratio (μ)
Pier/Abutment	2.5 x 10^7	25	0.15
Raft Floor	2.5 x 10^7	25	0.16
Cut-off	2.4 x 10^7	25	0.18

The boundary conditions imposed on the finite element model are such that the base of the foundation soil media at the depth of 80 m is restrained against vertical displacement and the horizontal ends of foundation soil media along and across the direction of flow are restrained against the horizontal displacement.

SEISMIC ANALYSIS

To study the dynamic behaviour of raft floor resting on homogeneous and non-homogeneous soil, the choice of analytical method requires careful consideration. Generally, for large or complex structures equivalent static force analysis for seismic conditions are often deemed to be not accurate enough and many authorities demand dynamic analyses for certain types and size of structure. Various methods of differing complexity have been developed for the dynamic seismic analysis of structures They all have in common the solution of the equations of motion as well as the usual statically relationships of forces and displacements at equilibrium. The technique used in the present study is response spectra method.

Response Spectrum Method

Response spectrum method is the representation of the maximum response of an idealized single degree of freedom system having a specified period and damping during the earthquake. The maximum response is plotted against the undamped natural period for various damping values, and can be expressed in terms of maximum acceleration, maximum velocity or maximum displacement.

The response spectrum technique is a simplified technique in which time period of the modes of vibration are determined and the maximum response magnitudes corresponding to each mode are evaluated with reference to a response spectrum. Modal combination rules are then used for superposition of the responses in the various modes. The resultant moments and forces in the structure correspond to the envelopes of maximum values, rather than a set of simultaneously existing values (Chopra, 2003; Clough et al, 1993).

The response spectrum method is based on appropriate response spectra from which either the accelerations or displacements corresponding to each mode of vibration, of interest, may be extracted. Site dependent spectra have been used in the seismic response of the raft floor. The site dependent spectra are based on the geological and seismotectonic set up of the area and includes the seismic history of the region. The site dependent spectra embody the seismic environment and local geotechnical features of site as well as the importance and risk factor related to the structure. Therefore, site dependent spectra are specifically recommended for important structures for appropriate assessment of design parameters.

Complete quadratic method (CQC) has been adopted in the present study. These methods generate coefficients for the combination of mode shapes. This combination is done by a generalization of the method of the square root of the sum of the squares which has the form

$$R_a = \left(\sum_{i=1}^{N} \sum_{j=1}^{N} \varepsilon_{ij} R_i \, R_j \right)^{\frac{1}{2}} \qquad (4)$$

where,

R_a = total modal response
N = total number of expanded modes
ε_{ij} = coupling coefficient
$R_i = A_i \psi_i$ = modal response in the ith mode
$R_j = A_j \psi_j$ = modal response in the jth mode
A_i = mode coefficient for the ith mode
A_j = mode coefficient for the jth mode
ψ_i = the ith mode shape
ψ_j = the jth mode shape

In CQC method the equation (4) reduced to

$$R_a = \left(\sum_{i=1}^{N} \sum_{j=1}^{N} k\varepsilon_{ij} R_i \, R_j \right)^{\frac{1}{2}} \qquad (5)$$

where,

k = 1 if i = j
k = 2 if $i \neq j$

The design basis earthquake (DBE) site dependent smoothened spectra for 5% damping for seismic response of barrage raft floor has been considered for study and is shown in Fig. 6.

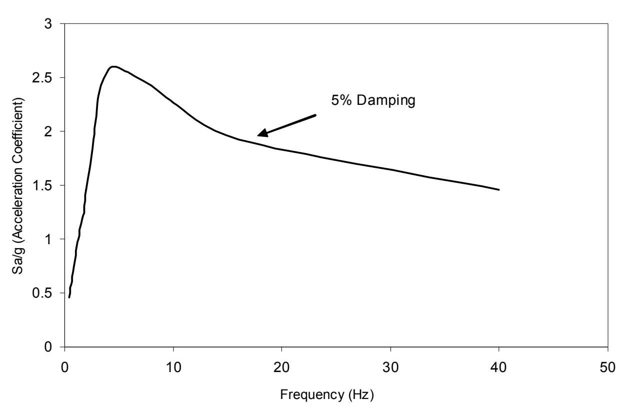

Fig. 6. Site dependent response spectra

SEIESMIC RESPOSE OF RAFT FLOOR

The stresses as per finite element method for dry condition when raft floor resting on homogeneous and heterogeneous soil media at upstream (A-A), ogee (B-B) and downstream (C-C) sections have been compared.

<u>Influence at upstream section</u>

The effect of soil homogeneity and non-homogeneity has been presented in Fig. 7 for upstream section. It is evident from the figure that stresses in homogeneous soil are quite different from those in non-homogeneous soil.

<u>Influence at ogee section</u>

The influence of soil homogeneity and non-homogeneity at ogee section represents the similar trends as observed in case of upstream section (Fig. 8). The difference in stresses is with respect to magnitude of stresses has been found as stresses are higher compared to upstream section due to its geometric and spatial variations.

<u>Influence at downstream section</u>

The trend of compared stresses at downstream section is different from upstream and ogee sections and it can be observed from the shown Fig. 9. The change in trend may be due to presence of abutment wall as stresses are more towards bay 1 compared to bay 2.

In general for all the sections stresses predicted for raft floor resting on homogeneous soil have been found to be lower as compared to non-homogeneous soil. This behavior is due to over all increase in stiffness of soil medium in case of heterogeneous soil media.

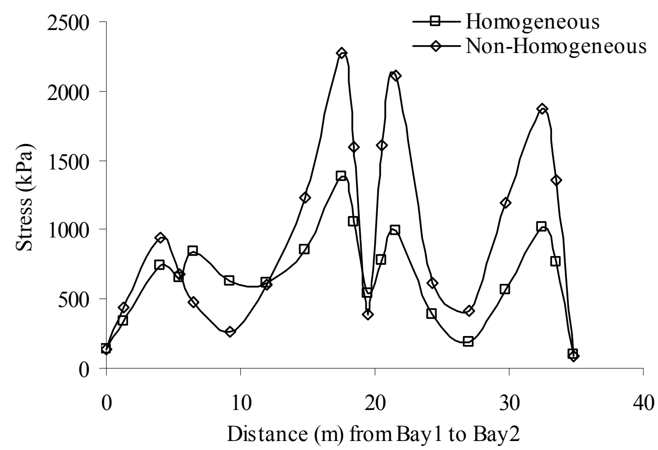

Fig. 7. Comparative stress at upstream section (A-A)

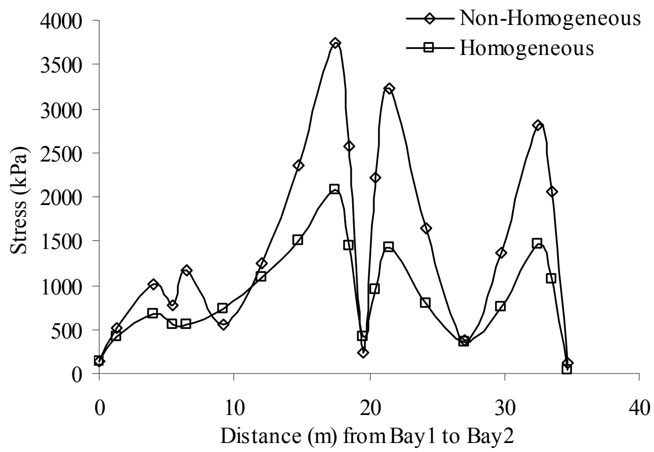

Fig. 8. Comparative stress at ogee section (B-B)

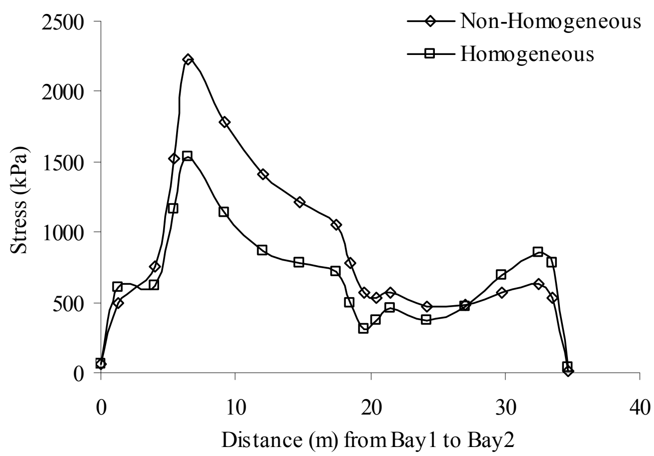

Fig. 9. Comparative stress at downstream section (C-C)

CONCLUSIONS

Based on the foregoing studies the following points may be concluded:

i) The stresses evaluated on raft floor from seismic analysis indicated the differences on account of homogeneous and heterogeneous soil considerations.

ii) The stress magnitude at every sections were different from each other and stresses trends were significantly different for downstream section compared to upstream and ogee section.

iii) The heterogeneous soil model yielded higher stresses compared to the homogeneous condition. This can be attributed to the increase in stiffness of foundation media on account of the non-homogeneity.

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