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APPROACHES OF ANALYSIS OF OGEE SHAPED BARRAGE RAFT FLOOR ON VARYING FOUNDATION MEDIA

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ABSTRACT

The analysis of ogee shaped barrage raft floor is a challenging task for the designers because of varying heterogeneous strata disposition, worst combination of loading conditions and functional requirements. A typical Indian barrage bay 3 and 4 has been chosen for analytical comparison between conventional and numerical approach. The behavior of ogee shaped barrage raft floor under representative load cases highlighted that conventional analytical approach i.e. Hetenyi's method may prove to be inadequate for varying foundation media, which has been recommended by Indian standard code. Unlike the analytical approach, the numerical approach of analysis especially the finite element method with the help of digital computers is capable of accounting for the variation in foundation media, which is a pointer to the advantage of numerical modeling approach of analysis of a typical barrage structure especially the ogee shaped barrage raft floor. The conventional and numerical approaches have been compared to show the limitations of conventional approach and their implication on design estimates.

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 ogee shaped barrage raft floor due to several advantages such as less excavation and dewatering, lesser construction time, superior flexural behavior etc.

A number of analytical methods are available for the design of ogee shaped raft floors, viz., conventional method (Bowles, 1982), Baker's method (Baker, 1948), Hetenyi's method (Hetenyi, 1964) and numerical methods (Desai et al 2000). Out of the above Hetenyi,s method (Design and construction features of barrages in India, 1981) is widely adopted for analysis and design of barrages raft floor in India as this method has also been recommended by Indian standard code (IS:11130-1984). 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) and Pandey et al (2005) on homogeneous foundation media. There is paucity of literature with regard to analysis and design of ogee shaped barrage raft floor. However, this paper is an attempt to indicate that codal recommendation (IS 11130-1984) with regard to adoption of Hetenyi's method of analysis needs to be viewed with caution in comparison of finite element method.

OVERVIEW OF METHODS ADOPTED FOR ANALYSIS OF OGEE SHAPED BARRAGE RAFT FLOOR

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. Finite element program "ANSYS" has been employed in the present study. 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).

Hetenyi's method

Hetenyi proposed the method of beams on elastic foundation (Hetenyi, 1964) with the following basic assumptions:

(i) The reaction forces of the foundation are proportional at every point to the deflection of the beam at the point. The pressure at a point in the foundation is independent of the pressure or deflections produced elsewhere in the foundation.
(ii) The foundation deforms only along the portion directly under loading.

The reaction forces are assumed to be acting vertically upwards opposing the deflection of the beam. When deflection is directed downwards there will be compression in the supporting medium but on the other hand where the deflection is upwards, tension will be produced. The supporting medium is assumed to take up such tensile forces.

Hetenyi proposed rigidity criteria in terms of λL, where λ is known as the characteristic of the system, which takes into account the width, length and elastic properties of the media. The term λL is given by

$$\lambda L = \sqrt[4]{\frac{K_0 B L^4}{4EI}} \qquad (1)$$

Where, K_0 = Coefficient of subgrade reaction of soil
B = Width of footing
L = Length of footing
E = Modulus of elasticity of the footing material
I = Moment of inertia of footing

The beams are classified into three groups based on the value of the parameter λL, as given below.

Group I: short beam: $\lambda L<\pi/4$
Group II: beams of medium length: $\pi/4<\lambda L<\pi$
Group III: long beams: $\lambda L>\pi$

For beams belonging to Group I, the bending deformations can be neglected in comparison to the deformation produced in the foundation. Hence, these beams can be assumed to be rigid and can be analysed by conventional method. Group II consists of beams in which force acting at one end of the beams has a finite and significant effect at the other end. Thus in beams of this category the end conditioning forces on the two ends have a significant counter-effect on each other. Group III consists of beams in which the counter-effect of end-conditioning forces on each other is a diminishing one. When investigating one end of the beam we can assume that the other end is infinitely far away. Forces applied at one end will have a negligible effect at the other. Based on above criteria Hetenyi formulated the various expressions to find deflections, moments and shear forces for different category (Hetenyi, 1964).

IDEALIZATION OF BARRAGE BAYS 3-4 WITH OGEE SHAPED RAFT FLOOR

Typical barrage bays 3-4, have been selected for this study. The ogee shaped barrage raft floor of bays 3-4 is separated by expansion joints from rest of the bays. The plan of bays 3-4 (Fig. 1) 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 has been chosen for the comparison under representative loading condition. The ogee shaped barrage raft floor with cut-off of bays 3-4 are completely resting on alluvial soil with single and double pier but suddenly at the edge of bay 4 towards bay 5 there is discontinuity in foundation soil media due to presence of hard rock as shown in typical transverse section of the bays 3-4 (Fig. 2). The longitudinal section with variation in the height of pier from upstream (25 m) to downstream (3.5 m) along with ogee shaped raft floor and cut-offs are as shown in Fig. 3.

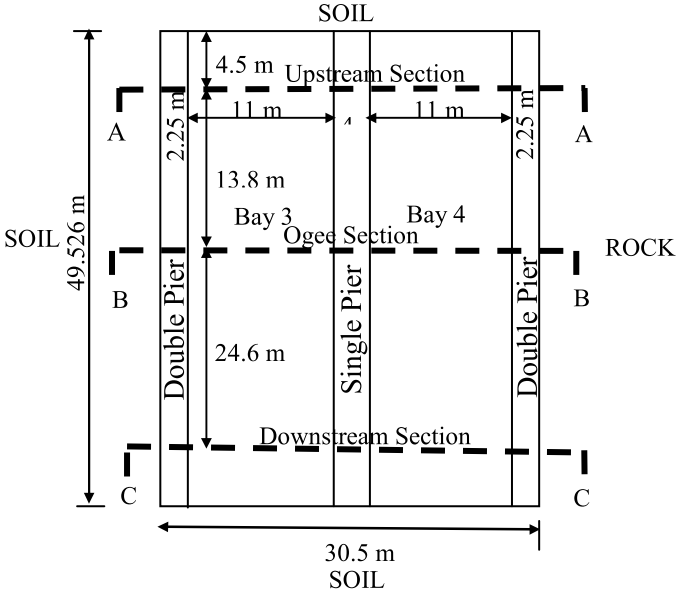

Fig. 1. Plan of barrage bays 3-4

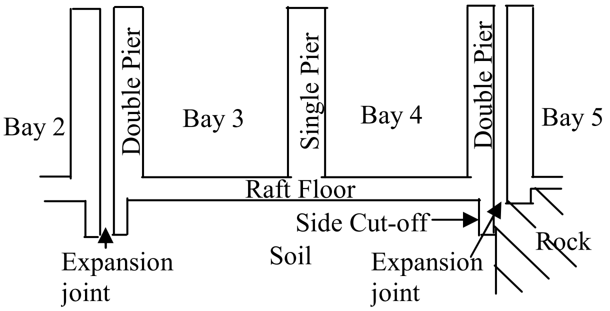

Fig. 2. Transverse section of barrage bays 3-4

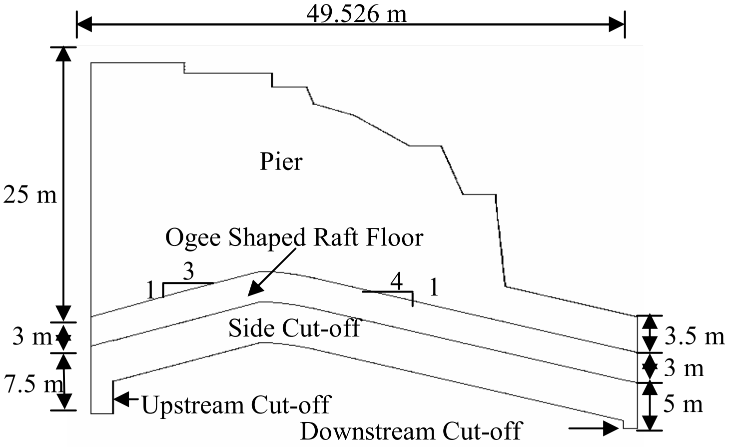

Fig. 3. Longitudinal section along the pier, raft floor and cut-off of the barrage bay

APPROACHES AND CONDITION OF ANALYSES

Finite element approach

Three-dimensional eight noded isoparametric brick elements have been used for the modeling of soil and rock media (King, 1977). The cut-off, pier, abutment wall and beam have also been modeled using eight noded isoparametric brick elements. The element is defined by eight nodes having three degrees of freedom at each node, translations in the nodal x, y, and z directions. The four noded three-dimensional isoparametric shell elements have been used for barrage raft floor modeling to simulate the behaviour of ogee shaped barrage raft floor as plate bending element (King, 1977), having six degrees of freedom per node capable of taking loads normal to the plane. In this model the depth of the soil and rock media considered is 80m from the crest level. The extent of surrounding soil and rock 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 moments at the same section under study in the two consecutive models converged under gravity load. The material properties of various components of barrage as well as for soil and rock media are as given in Table1. The adopted model with finite element mesh consisting of the pier and beam structure with the supporting ogee shaped raft floor is shown in Fig. 4**.** The finite element mesh for the entire structure-raft-foundation soil and rock system has been presented in Fig. 5. The dark grey portion in the figure resembles the rock portion. The total number of elements used for the adopted finite element model is 18744, which resulted in 21204 nodes in the model.

The boundary condition imposed on the finite element models consist of restraining the limiting boundary of the foundation soil and rock in such manner that displacement normal to the boundary surface are restrained i.e. the base of the foundation media at the depth of 80 m is restrained against vertical displacement and at the ends along and across the direction of flow, foundation media is restrained against the horizontal displacement.

The finite element investigations are based on linear elastic model for representative load cases so as to compare with Hetenyi's method. The self-weight of the soil and rock media has not been considered as it has been assumed that entire soil and rock media is already settled by its own weight. It has also been assumed that within the entire soil & rock media, elastic modulus and Poisson's ratio remain the same as well as soil and rock junction has been assumed to be in contact with each other.

Table 1. Material Properties used in Bays 3-4 Model

Components	Modulus of Elasticity (E) (kN/m^2)	Unit Weight (γ) (kN/m^3)	Poisson's Ratio (μ)
Pier/Abutment	2.5×10^7	25	0.15
Raft Floor	2.5×10^7	25	0.16
Cut-off	2.4×10^7	25	0.18
Foundation soil	1×10^5	20	0.3
Foundation rock	1×10^7	26	0.25

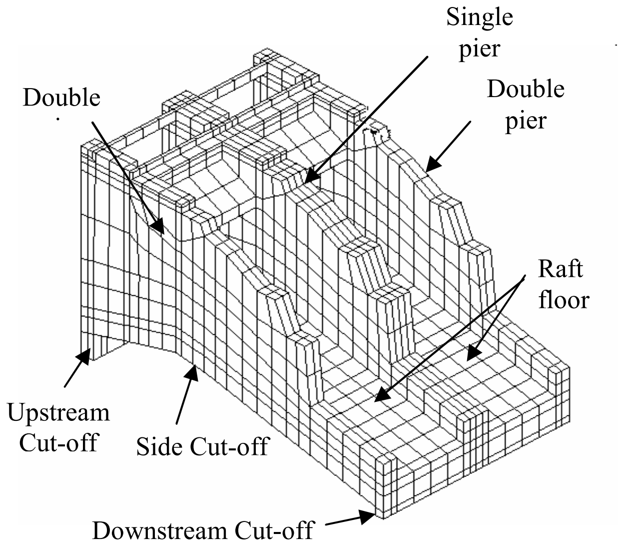

Fig. 4. 3D-finite element discretization of the pier and raft floor with cut-off of the bays 3-4

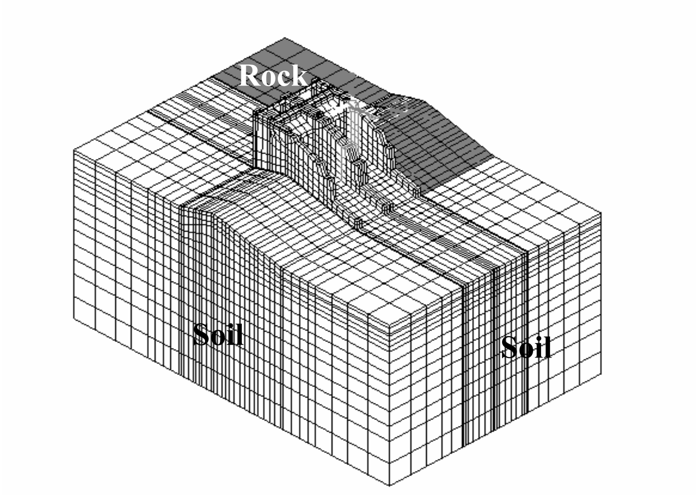

Fig. 5. 3D-Finite element discretization of the pier, raft, soil and rock system of bays 3-4

Hetenyi's approach

Hetenyi's method of beams on elastic foundation uses the rigidity criterion, which is determined by considering the width, length, thickness, modulus of elasticity of raft floor and subgrade modulus of foundation soil. The subgrade modulus of foundation soil (K_0) has been has been obtained from the equation based on theory of elasticity (Bowles, 1982) which is co-related with modulus of elasticity of foundation soil as shown below.

$$K_0 = \frac{E_s}{I_f(1-\mu^2)B} \qquad (2)$$

where, E_s = Modulus of elasticity of foundation soil
μ = Poisson's Ratio
B = Width of the footing
I_f = Influence factor

Using the above correlation coefficient of subgrade modulus of foundation soil has been obtained for bays 3-4 raft floor as $K_0 = 1.465 \times 10^5$ kN/m^3. The following parameters have been used for determining the rigidity criteria (λL) for bays 3-4 raft floor are

Unit width of raft floor = W = 1m
Length of raft floor = L = 30.5 m
Thickness of raft = D = 3 m
Modulus of elasticity of the raft material *(E_r)*
$E_r = 2.5 \times 10^7$ kN/m^2
Moment of inertia of raft *(I)*
$I = 1/12 \times 1 \times 3^3 = 2.25$ m^4

The subgrade modulus of bays 3-4 has been computed for the assumed plate width 0.75m for comparison. The barrage raft floor has been analysed by Hetenyi's method using the principle of reciprocity and superposition for the representative load cases. The representative loading adopted for the comparative analysis so that they can be simulated in both the methods of analysis. The analyses of barrage raft floor by finite element and Hetenyi's method have been compared for the following representative load cases, usually adopted in design.

1. Gravity load (Empty Condition)
2. Differential hydrostatic pressure and Gravity load (Flow Condition)
   (a) Case I - Bay 3 is closed and Bay 4 is opened
   (b) Case II - Bay 4 is opened and Bay 3 is closed
3. Earthquake and Gravity load i.e. Equivalent static load (Empty Condition)

COMPARATIVE ANALYSIS OF OGEE SHAPED BARRAGE RAFT FLOOR OF BAYS 3-4

The bending moments and deformations as per Hetenyi's and finite element method, for different load cases at upstream (A-A), ogee (B-B) and downstream (C-C) sections have been compared as mentioned below.

Influence of gravity load case

The comparative bending moments have been represented in Figs. 6 to 8 for upstream, ogee and downstream sections of bays 3-4. The comparison of moments obtained by Hetenyi's method and FEM analysis indicate the significant qualitative difference. It can be observed that the Hetenyi's method provides a similar pattern of moments with differences in magnitude in presented sections, in contrast to moments obtained from FEM analysis. Similar to the preceding case the moments obtained from FEM analysis are lacking in positive moments except towards the end of bay 4 where both the methods yield positive moments. The significant variation in the moments from negative to positive in the vicinity of bay 4 obtained by FEM analysis is due to the presence of rock strata at the edge of bay 4 which cannot be accounted in Hetenyi's method. The observations lead to a significant shortcoming of Hetenyi's method inasmuch as it cannot consider continuity and variation of foundation media beyond the raft section. **Fig.**

The compared deformations shown in Figs. 9 to 11 indicate a large difference between Hetenyi's method and FEM analysis. Differential settlement has been observed in case of FEM analysis due to the variation of foundation media. In contrast, Hetenyi's method cannot account for the effect of variation in foundation media, which can lead to a gross approximation of the actual behaviour of foundation media.

Influence of differential hydrostatic pressure and gravity load case

The bending moments as per Hetenyi's method and FEM analysis for differential hydrostatic pressure for case I and II with gravity load at upstream sections are shown in Figs. 12 and 13. It can be observed from the figures that, the moments obtained by Hetenyi's method and finite element analysis at the upstream section exhibit changes in the moments due to differential head condition but the behaviour is consistent with previous observations.

The deformations shown in Figs. 14 and 15 for upstream section replicate the consistent trend as presented in gravity load case.

Influence of earthquake and gravity load case

In this case the earthquake load has been considered using the seismic coefficient method (IS 1893-1984). The compared distribution of bending moments by Hetenyi's method and FEM analysis are as presented in Figs. 16 and 17 for empty condition with earthquake direction (←) at upstream and ogee section. Significant differences in the magnitude of bending moments have been observed between Hetenyi's method and FEM analysis. Once again the FEM analysis is lacking in positive moments, in general, compared to Hetenyi's method except towards the end of bay 4 the where two methods yield opposing moments.

The deformation behaviour replicates that of the preceding section, which is presented in Figs. 18 and 19 for upstream and ogee section.

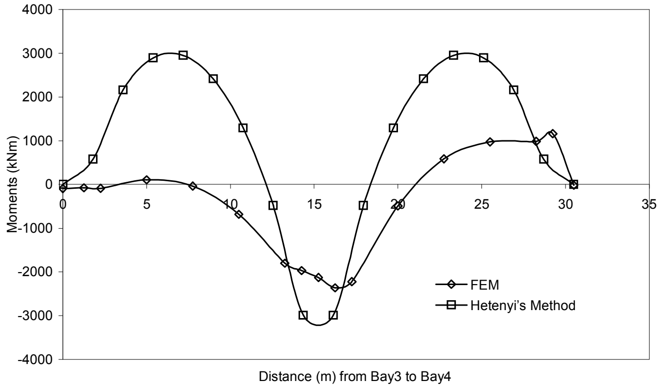

Fig. 6. Comparative moments at upstream section for gravity load

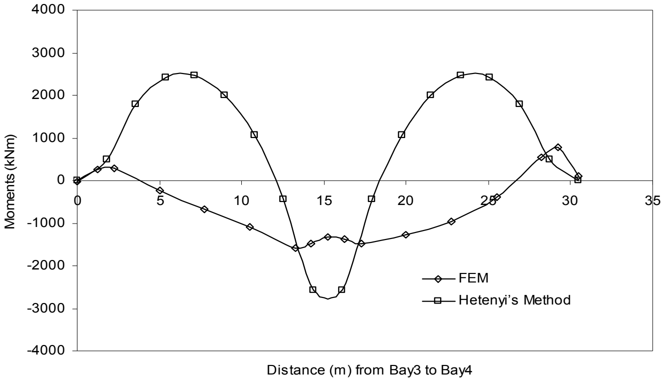

Fig. 7. Comparative moments at ogee section for gravity load

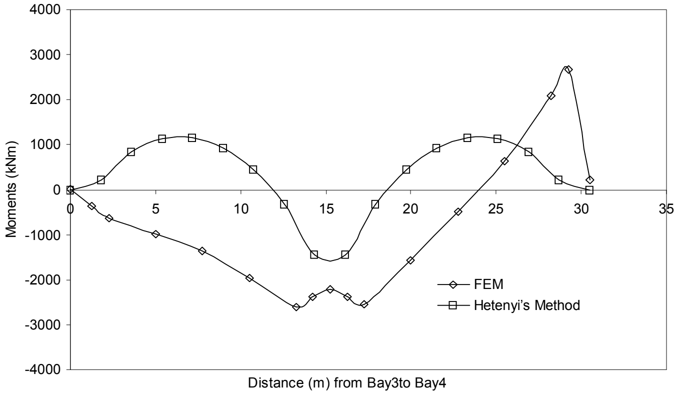

Fig. 8. Comparative moments at downstream section for gravity load

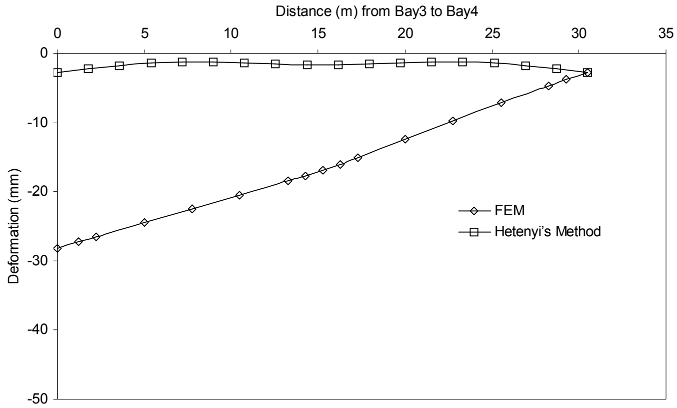

Fig. 9. Comparative deformation at upstream section for gravity load

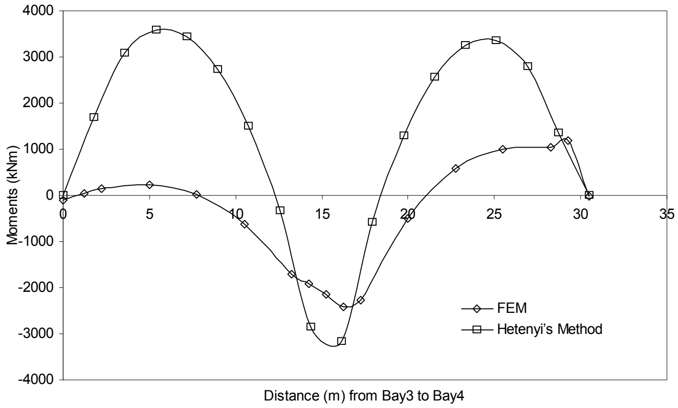

Fig. 12. Comparative moments at upstream section for gravity load and differential head when bay 3 is closed and bay 4 is open

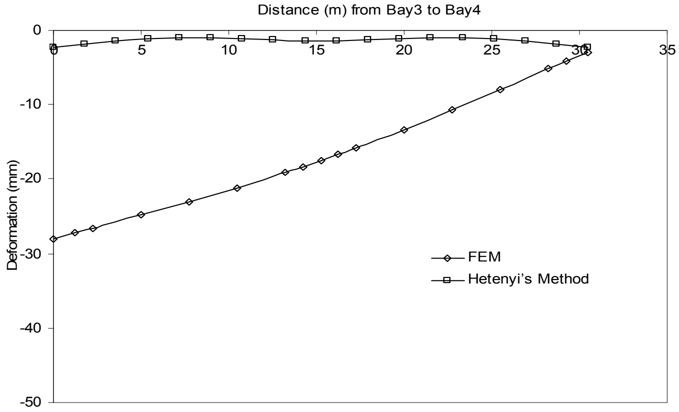

Fig. 10. Comparative deformation at ogee section for gravity load

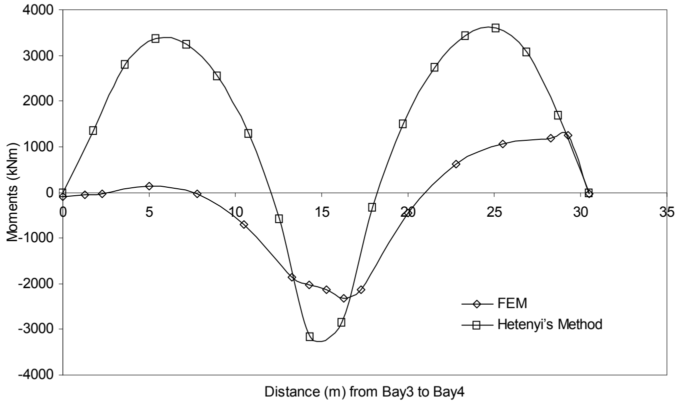

Fig. 13. Comparative moments at upstream section for gravity load and differential head when bay 3 is open and bay 4 is closed

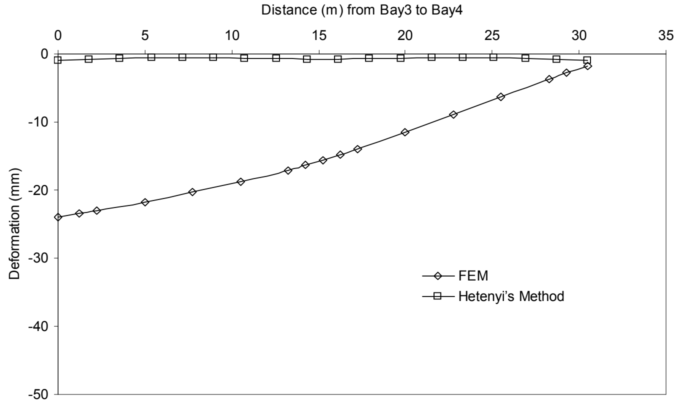

Fig. 11. Comparative deformation at downstream section for gravity load

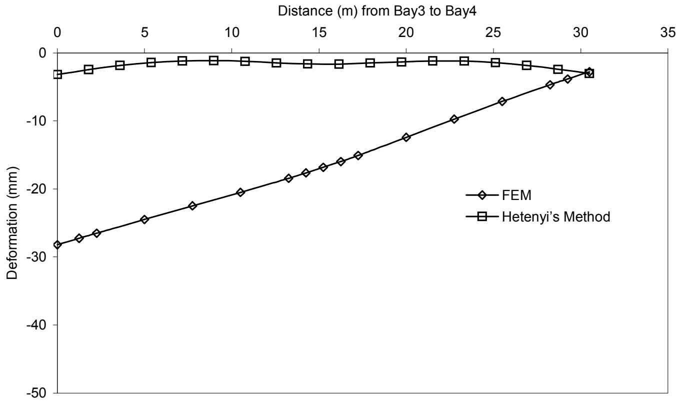

Fig. 14. Comparative deformation at upstream section for gravity load and differential head when bay 3 is closed and bay 4 is open

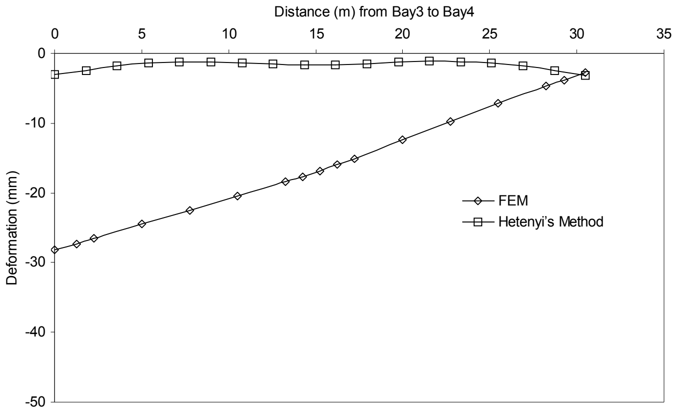

Fig. 15. Comparative deformation at upstream section for gravity load and differential head when bay 3 is closed and bay 4 is open

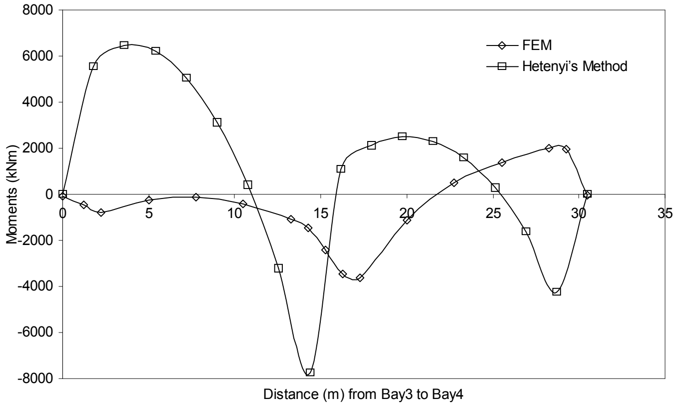

Fig. 16. Comparative moments at upstream section for gravity and earthquake load

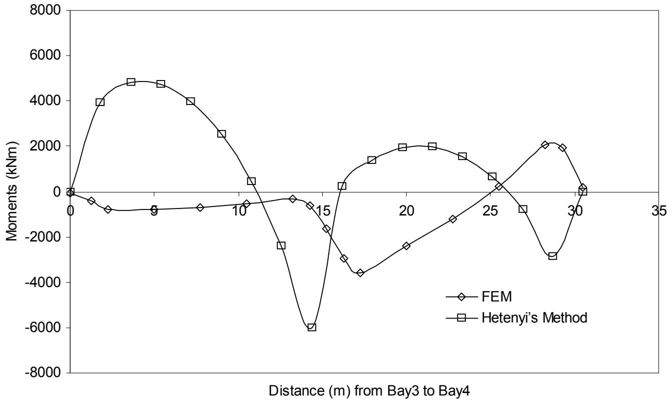

Fig. 17. Comparative moments at ogee section for gravity and earthquake load

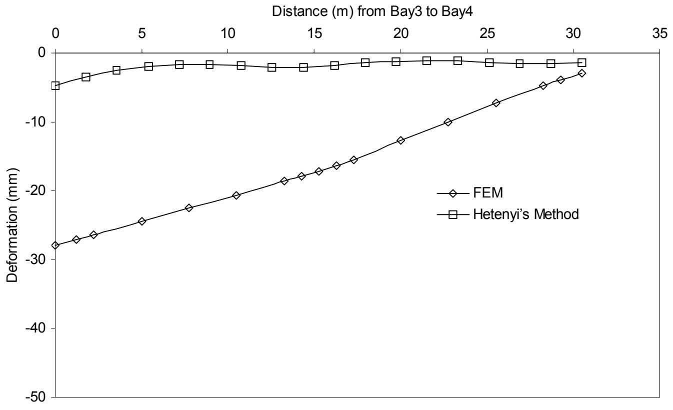

Fig. 18. Comparative deformation at upstream section for gravity load and earthquake load

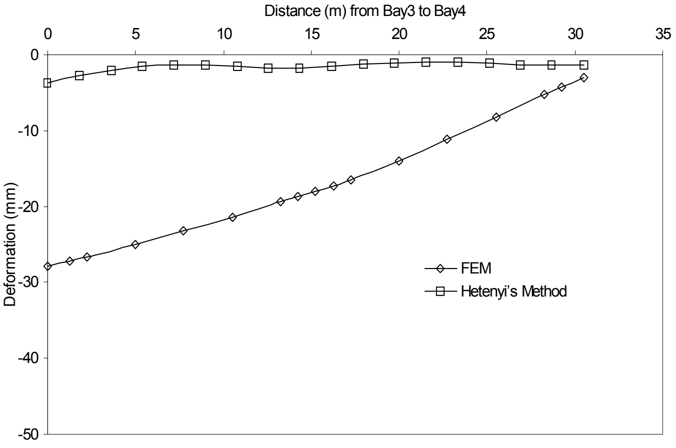

Fig. 19. Comparative deformation at ogee section for gravity load and earthquake load

CONCLUSIONS

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

i) The moments as evaluated from Hetenyi's method and the FEM analysis indicate major differences on account of limitations of the former method of analysis. The differences extend beyond the differences of magnitude to encompass even opposing nature of moments as evaluated by both analytical techniques.

ii) The deformations as evaluated by Hetenyi's method are considerably lower than those computed by FEM for the entire set of representative load cases, at all sections considered.

iii) The variations in foundation media cannot be considered in case of Hetenyi's method. This may have significant bearing on design parameters estimated by Hetenyi' s method in heterogeneous foundation media.

iv) Hetenyi's analysis is unable to account for the geometrical disposition of the ogee shaped raft floor and spatial variation of stiffness.

v) In the light of the above comparative study Hetenyi's method may be used to arrive at preliminary design estimate rather than final design parameters.

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