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INVESTIGATIONS ON SOIL-RAFT-SUPERSTRUCTURE INTERACTION

ETUDES DES INTERACTIONS SOL-RADIER-SUPERSTRUCTURE

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SYNOPSIS: Finite element analysis was carried out to study soil-raft-superstructure interaction Under static loads. Analysis was performed by idealizing soil as Winkler's springs and also as three dimensional prismatic elements. In the interaction analysis, soil, raft and superstructure were considered as a single compatible unit. In the non-interaction analysis, the structure, separated from the raft and soil, was assumed to be supported on an unyielding base. Laboratory tests were performed on syndanyo models representing rafts of different thicknesses on a prepared cohesionless soil bed. Plate load test was conducted to determine the modulus of subgrade reaction and modulus of elasticity of the soil. The elastic properties of the syndanyo sheets were also determined experimentally. The displacements and moments obtained by the finite element method, using 3D prismatic soil elements, were found to agree quite well with the results obtained from the syndanyo model tests.

INTRODUCTION

The role of a typical raft foundation is to transmit the load coming from the superstructure to the soil beneath without causing distress to any of the components of the superstructure or foundation. Generally, the raft is analyzed by the conventional method in which it is assumed to be rigid, resulting in uniform or linearly varying contact pressure distribution, depending on whether the raft supports symmetric or eccentric loads. However, the actual contact pressure distribution is the result of the foundation-soil interaction, which can be determined only by an interaction analysis involving the elastic properties of both the foundation and soil. Thus, soil-structure interaction is an important aspect in the process of predicting overall structural response.

Many soil-structure interaction studies have been reported where the soil medium is represented by a bed of Winkler's springs. (Lee and Harrison, 1970., Hain and Lee, 1974 and others). Cheung and Zienkiewicz (1965) developed stiffness matrix for an isotropic, homogeneous, elastic half space by integrating Boussinesq's solution for point load over the loaded area. Fraser and Wardle (1974) extended this approach to develop the stiffness matrix for a layered continuum. The element developed by Fraser and Wardle (1974) is called surface element or layered continuum element. Investigations on soil-raft superstructure interaction was earlier reported by Srinivasaraghvan (1980) using surface elements to model soil behaviour. With the refinement and advances in finite element method and the availability of large capacity high speed digital computers, three dimensional prismatic finite elements can be used to represent the behaviour of soil and also for discretising the soil medium. In this work an attempt has been made to study the soil-raft-superstructure system as a single compatible unit by representing the soil by three dimensional prismatic elements. The same problem was studied using Winkler's hypothesis also, for purposes of comparison.

SCOPE OF THIS INVESTIGATION

The finite element analysis carried out pertains to a) soil idealized as Winkler's springs and b) soil idealized as three dimensional prismatic elements. Both non-interaction and interaction analysis have been carried out. In the non-interaction analysis, the forces and moments obtained from the analysis of superstructure alone, by assuming it to be supported on an unyielding base, are applied on the raft-soil system and analysed. In the interaction analysis, the three phase system namely, soil-raft-superstructure is analysed as a single compatible unit.

This is followed by a detailed parametric study to find out the influence of various parameters on the forces and moments in the raft and the superstructure and to evolve guidelines for the design of multistoreyed snf multibay rafted structures. For instance one, three and five floors have been considered for the superstucture. The thickness of the raft has been varied from 0.3 to 0.9 m. The modulus of elasticity of the soil ranges from 10 to 30,000 kN/m^2. (kPa).

Experimental investigations have also been carried out for different thicknesses of the raft. Three Syndanyo models were tested. The results of the experimental investigations have been compared with theoretically predicted values.

PROBLEM DETAILS

A two bay by two bay space frame supported by a raft resting on the soil is considered for analysis. The length of the beam is 6 m and the height between the floors is assumed as 3.6 m. The size of beams is 40 cm x 60 cm and that of columns is 40 cm x 40 cm. Three types of superstructure arrangement are considered and the load distribution in them is as shown in Fig. 1. The loading in all the beams is applied as uniformly distributed load, w and the raft is loaded uniformly with an intensity of 40 kN/m^2 . Only symmetric vertical loading is considered. Horizontal loading due to wind and other causes is neglected. Since the object of this investigation is to find out the influence of each of the components of the system, namely, soil, raft and superstructure, the average contact pressure under the raft is maintained at 115 kN/m^2 for each of the superstructure arrangements shown in Fig. 1. This amounts to keeping the total load on the raft constant for different superstructure arrangements.

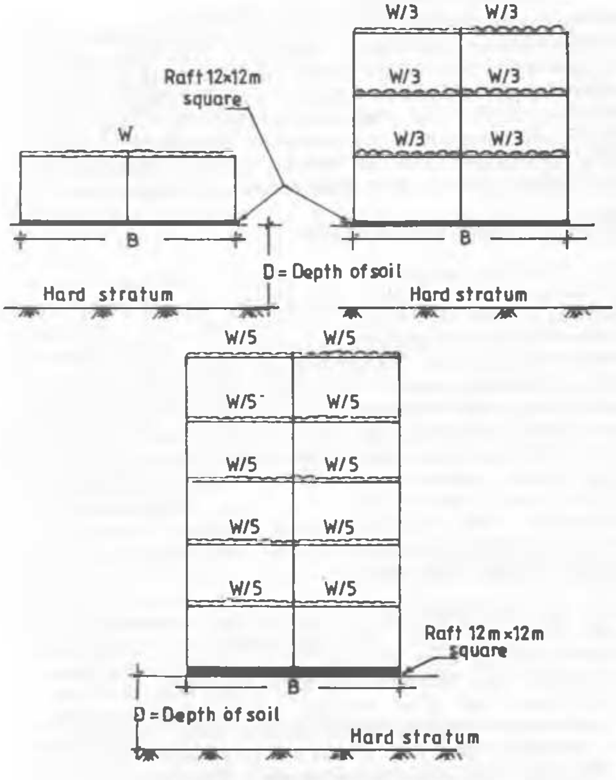

FIG.1. LOAD DISTRIBUTION FOR DIFFERENT SUPERSTRUCTURE ARRANGEMENT

ANALYSIS WITH SOIL AS WINKLER'S SPRINGS

Using the symmetry of the problem only one quarter of the model was analysed. The beams and columns of the superstructure are idealized using three dimensional beam elements and raft is idealized using thin plate bending elements. The soil is modelled according to Winkler's hypothesis which considers that the soil medium as made up of closely spaced linear elastic, identical and independent springs. In the analysis, such a medium is idealized as a single spring under each nodal point and is modelled using boundary element. The response of the soil depends upon a single parameter of the soil, namely, the modulus of subgrade reaction, K. The value of K of the soil medium depends not only on the material of the soil but also on the foundation dimensions. Both non-interaction and interaction analysis have been carried out. A convergence study has been carried out to arrive at the appropriate fineness of the finite element mesh required Influence of various parameters such as raft rigidity and the superstructure rigidity on the behaviour of the three phase system, namely, soil-raft-superstructure, has been studied by varying either the raft thickness or the number of floors keeping the other parameters constant. The results of the above analyses reveal the state of stress in the raft and the distribution of forces and moments in the superstructure.

ANALYSIS WITH SOIL AS 3D BRICK ELEMENTS

Here again only one quarter of the model was analysed taking advantage of the symmetry of the problem. Beams and columns are idealized using three dimensional beam elements and the raft is descretised using thin plate bending elements. The soil is considered as homogeneous, isotropic, with a finite depth below the foundation. The depth of the soil strata between the raft and the rigid boundary has been varied from 1.0 to 3.0 times the width of the raft. The soil is modelled by 3D brick elements. Properties of the soil is defined by two parameters namely, the modulus of elasticity of the soil, E_s and the Poisson's ratio, μ_s . Both non-interaction and interction analysis have been carried out. A convergence study has been carried out to arrive at the appropriate fineness of the finite element mesh required. A parametric study has been carried out. The results of this study are described in greater detail by Sivaraman (1988) In view of the limitations of space, the important conclusions of the study alone are presented in this paper. The parameters studied are depth of soil layer below the foundation, modulus of elasticity of the soil, raft rigidity and the superstructure rigidity.

EXPERIMENTAL INVESTIGATIONS

Experimental study has been carried out to compare the observed values with the theoretically predicted results. The planning and execution of the experimental programme have been described in greater detail with appropriate illustrations by Sivaraman (1988). However, the salient features of the experimental investigation are briefly presented below.

The dimensions of the model were arrived on the basis of the thickness of the available syndanyo sheets. Three different thicknesses of syndanyo sheets were used namely, 6.5 mm, and 12.2 mm and 19.2 mm. The beams and columns of the superstructure resting on the raft, were made out from 19.2 mm thick sheet. The size of the square raft used was 240 mm x 240 mm. Syndanyo was chosen as the material for the model (for both the raft and the frame) because of the following reasons: 1) linear elastic behaviour under working loads. 2) ease of model making. 3) elastic modulus and Poisson's ratio are comparable to that of concrete. 4) immediate transfer of load. 5) creep effects are negligible.

The superstructure consisting of columns and beams was fixed to the raft using araldite. The surface of the model was cleaned with the zero degree sand paper and then wiped with a dry cloth before pasting the strain gauges. Quick setting cyanoacrylate adhesive was used for fixing strain gauges to the model. The terminals from the strain gauges were connected to a P.C.B chip fixed to the model and from there to the measuring bridge using 50 core ribbon wires. In order to reduce the interference of the ribbon wire at the contact surface between the model and the soil, insulated copper wires of gauge S.W.G 28 were used at the bottom of the raft. A dummy strain gauge fixed to a syndanyo specimen was connected to the bridge for temperature compensation. The syndanyo specimen with the dummy strain gauge pasted on it was placed on the soil in the tank. Rosettes (90 degrees) were fixed at the centre of the plate elements on both the top and bottom face in order to compare the experimental results with those obtained from theoretical analyses. The strain gauge used in this study had a resistance of 120.5 ± 0.5 ohms with a gauge factor of 2.02 ± 2 % and a gauge length of 5 mm.

The syndanyo superstructure-raft model was placed centrally on the prepared sand bed after levelling the surface. Four dial gauges were used to measure the vertical displacements. Electrical strain gauge terminals were soldered to switching unit which was connected to strain measuring unit. A small initial load of 40 kg was applied to ensure proper seating of the model on the sand bed. This seating load was maintained for 5 minutes and then released. The load was applied as a central concentrated load using a hydraulic jack, through a well oiled steel ball placed at the centre of the model. The load was measured using a 5 T proving ring. The load was applied in stages and after every loading 15 minutes were allowed before the dial gauge and strain gauge readings were noted. Experiments were conducted in the night between 8 p.m and 2 a.m to reduce the effect due to temperature variation to a minimum.

From the experimental investigations carried out, the surface displacements of the syndanyo model were calculated from the displacement dial gauge readings. The bending moments Mxx and Myy were computed from the strains measured using the appropriate relations between B.M. and the strains. Three different models with different raft thicknesses were prepared and tested. The results obtained from the tests are compared with the theoretical results.

CONCLUSIONS

1. When the superstructure rigidity is taken into account in the analysis, the differential settlement in the raft is reduced. The effect of superstructure rigidity in reducing the differential settlement between the centre and the corner of the raft is more pronounced with thinner rafts than with thicker ones (Table 1).

2. The Winkler analysis yields higher absolute settlement and lower differential settlement in the raft when compared to the corresponding values obtained by analysis using 3D brick elements.

3. Contact pressure under the raft is significantly reduced when the superstructure rigidity is considered in the analysis.

4. Inclusion of superstructure rigidity in the analysis results in reduced bending moments in the raft, whereas increasing the raft thickness to achieve lesser differential settlement may increase the bending moments in the raft. Hence, an optimal design can be obtained by using thinner rafts and including the superstructure rigidity in the analysis. This calls for a full interaction analysis (Table 2).

5. The results of small scale tests conducted with syndanyo models on a prepared sand bed, shows a satisfactory agreement between theoretical and experimental values. However, the settlement in the raft predicted by 3D brick model agrees better with the experimentally observed values, than the settlement predicted by Winkler's model. The maximum difference between the measured and computed values of differential settlement between the centre and the corner of the raft is 28 % (Table 3).

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Table : 1 Differential Settlement between Centre and Corner of the Raft
Es = 10,000 kN/m^2 , μs = 0.4 D = 2B

	Settlement (mm) at the centre for raft thickness			Settlement (mm) at the corner for raft thickness			Diff. Settlement (mm) between the centre and corner of the raft of thickness		
case	0.3 m	0.45 m	0.6 m	0.3 m	0.45 m	0.6 m	0.3 m	0.45 m	0.6 m
One	102.99	87.87	80.29	56.44	56.38	58.23	46.54	31.48	22.06
Three	93.22	82.88	77.47	62.10	60.07	60.53	31.11	22.81	16.93
Five	88.39	79.94	75.59	64.85	62.14	62.00	23.54	17.80	13.58

Table : 2 Percentage Reduction in Bending Moment (Mxx) of the Interaction Analysis over the Non-Interaction Analysis. Es = 10,000 kN/m^2 ; μ_s 0.4; D = 2B

Number of Floors	Raft thickness (m)	Non - Interaction		Interaction		6% Reduction in Mxx	
		Centre	Corner	Centre	Corner	Centre	Corner
One	0.3	-150.0	64.36	-137.5	51.51	08.30	19.97
Three	0.3	-136.6	44.83	-104.8	33.95	23.30	24.27
Five	0.3	-126.9	44.19	- 88.9	29.86	29.93	32.43
One	o.45	-246.7	67.43	-228.3	77.37	07.46	-14.70
Three	0.45	-226.7	46.96	-182.1	61.10	19.67	-30.17
Five	0.45	-209.5	47.76	-155.1	58.90	25.97	-23.32
One	0.60	-337.6	53.81	-313.5	69.81	7.14	-29.70
Three	0.60	-311.7	34.0	-257.7	59.09	17.32	-73.80
Five	0.60	-287.0	36.54	-220.9	60.06	23.30	-66.00

Table 3: Comparison of Experimental and Theoretical Raft Settlements (t = 6.5 mm)

Type of Analysis	Load (N)	Raft Settlement in mm			% Difference of Settlement w.r.t. experimental value		
		Centre	Corner	Mid edge	Centre	Corner	Mid edge
Experimental		0.385	0.315	0.280			
Winkler	2108	0.603	0.423	0.454	56.00	34.30	62.00
3D Brick		0.467	0.253	0.301	21.00	-19.70	7.50
Experimental		0.915	0.615	0.590			
Winkler	4216	1.207	0.845	0.908	31.90	37.40	53.90
3D Brick		0.934	0.507	0.602	2.08	-17.60	2.03
Experimental		1.409	0.930	0.906			
Winkler	6356	1.819	1.274	1.368	29.00	47.10	50.30
3D Brick		1.408	0.764	0.907	00.00	-17.90	00.00