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Analysis techniques of mat foundation: A comparative study

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ABSTRACT: The analysis and design of mat foundations are yet to be established to a standard level. All the techniques such as Conventional method, Approximate flexible method and discrete element methods developed so far are based on several assumptions and idealizations of mat on soil, and a detailed comparative study of the performance of these analysis techniques is yet to be performed. The present paper studies the deflection and moment at various locations of mat foundations calculated using computerised discrete element techniques, ACI approximate flexible method and Conventional method. Effect of parameters such as modulus of subgrade reaction depicting underlying soil type, mat stiffness, Poisson's ratio of concrete, column spacing, vertical and lateral loads, etc. have been thoroughly investigated. On the basis of this study, attempts have been made to put forward explanations to the observed behaviour of mat and performance of analysis techniques.

1 INTRODUCTION

The present study forms part of a comprehensive research programme (Hossain, 1993) aimed at the comparative study of different mat analysis techniques. Although the present paper compares moments and deflections at selected locations for a specific combination of input parameters, the performance of the analysis methods as portrayed in the discussion is applicable, qualitatively, to general situations.

2 THE ANALYSIS METHODS

Mats can be analysed using Conventional method, ACI approximate flexible (ACIA) method, finite difference (FD) method, and finite grid method with and without soil spring zoning (FGZ and FG). All but the conventional method utilise, in the analysis procedure, modulus of subgrade reaction, which is in turn related to the soil pressure and its deformational characteristics. Whereas detailed description of mat analysis techniques is available elsewhere in Bowles (1974, 1986, 1988), ACI 436 (1966) and Shukla (1984), a brief account is presented here.

In the conventional method of design, the mat is assumed to be infinitely rigid with a linearly varying pressure distribution under the mat. The mat is divided in both directions into strips loaded by column loads and supported by soil pressure. Each strip is then assumed to act as an independent beam subjected to the contact pressure and column load.

The ACIA method is a more general approach in which the mat is assumed flexible and plate action is considered. The method is based on theories of plate resting on Winkler's medium. The effect of a concentrated load on plate damps out quite rapidly and as a result there is a circular zone of influence for each column. To find the effect of column loads at any point, the radial moment, tangential moment, shear and deflection, due to each column load, whose influence zone extends beyond that point, are determined. After converting radial and tangential moments to rectangular co-ordinates, the effect of all the column loads within the zone of influence are superimposed to find the total moment, shear and deflection at any point of the mat. In the event that the zone of influence falls beyond the mat boundary, end conditioning forces are applied.

The FD method uses the fourth order differential equation for thin plates. To solve this equation for a mat-soil system, the mat is divided into grids and for each point of intersection, this equation is transposed into a finite difference equation. Once all the difference equations for all the intersection points are found, the deflections at all points can be determined by solving these simultaneous equations.

The FG method uses the techniques of finite element. The entire mat is divided into beam-column elements by suitable gridding. Stiffness matrix for each element with two soil springs at the ends is built and at the same time a global matrix for the whole mat on soil is developed. When the global stiffness and the load matrix are known, the node deflection matrix can be readily obtained. Consequently, the member forces and nodal displacements can be found.

Whereas, in the FG method, the soil springs remain uncoupled i.e. deformation of one spring is not affected by others, the soil spring zoning technique allows FGZ method to cater for the coupling action of springs by employing softer springs towards the centre. This invariably mimics mat-soil system more rationally.

3 THE COMPUTER PROGRAMS

The program for FD method has been suitably adopted for microcomputers from Bowles (1974). The program for FG and FGZ methods is taken from Bowles (1988) after modification. A data generation program is also employed for this program. A computer program is developed for the ACIA method (ACI 436, 1966). Conventional method is not considered for developing program since it is suitable and convenient for hand calculation.

4 ANALYSIS SCHEME

The analysis scheme is divided into two parts. Firstly, a trial mat is selected to be analysed by different methods and the results obtained are compared. Secondly, several parameters are selected to determine their effects on moments and deflections at a selected point on the mat.

A building supported on mat is selected to carry out the comparative study. Figure 1 shows the plan of the mat with design load on each column. The mat is 21942 mm by 18285 mm in plan dimensions. The building is 7 storied having each storey 3658 mm high. The mat is 762 mm thick which is safe against punching due to column loads used in this study.

Dead and live loads are determined on the basis of a flat plate having 229 mm thickness and a live load of 3.83 kN/m^2. As the full live load on all the spans is never applied in reality, a reduction in factored live load as per Winter (1981) is used. It has been found that for the 7 storied building, the loads due to wind is very small compared to dead and live loads and combination of dead and live load governs.

The most important soil property required in the analysis is the modulus of subgrade reaction (k_s). A value of 15709 kN/m^3 is taken for soil having allowable bearing capacity q_a = 144 kN/m^2 which is reasonable for Dhaka city. This value contains a safety factor of 3. The other soil parameter required is the maximum linear soil deflection which is assumed to be 19 mm according to Bowles (1988).

The cylinder strength, unit weight and Poisson's ratio of concrete are taken as 20.7 MPa, 23.6 kN/m^3 and 0.15, respectively.

The objective of the parametric study is to observe the effect of several parameters involved in the behaviour of the mat-soil system. The parameters selected are modulus of subgrade reaction, mat stiffness, Poisson's ratio, vertical and lateral load, number and spacing of columns. To observe the effect of one of these parameters, the parameter is varied over a reasonable range keeping all other parameters to values of the idealised mat problem employed in the comparative study.

5 RESULTS OF THE COMPARATIVE STUDY

The analysis of the mat-soil system by FG, FGZ and FD methods was preceded by a mesh sensitivity analysis. The exercise was needed to ensure that the mesh/element size was small enough to produce realistic results. It has been observed (Hossain 1993) that a mesh of 1219 mm grid is adequate for the present mat from the point of accuracy as well as economy in terms of computer resources.

The moment diagram along column line C is shown in Figure 2. The highest moment at column C3 is due to FGZ method and the value is 478.2 kN-m/m. The FG, FD and ACIA methods give moments which are 4.9%, 13.7% and 23.1% less than the moment obtained by FGZ method, respectively.

At column point C2, the highest moment obtained by FGZ method is 448.7 kNm/m. Moments derived from FG, FD, ACIA and Conventional methods are less than FGZ by 4.3%, 13.4%, 23.4% and 90.7%.

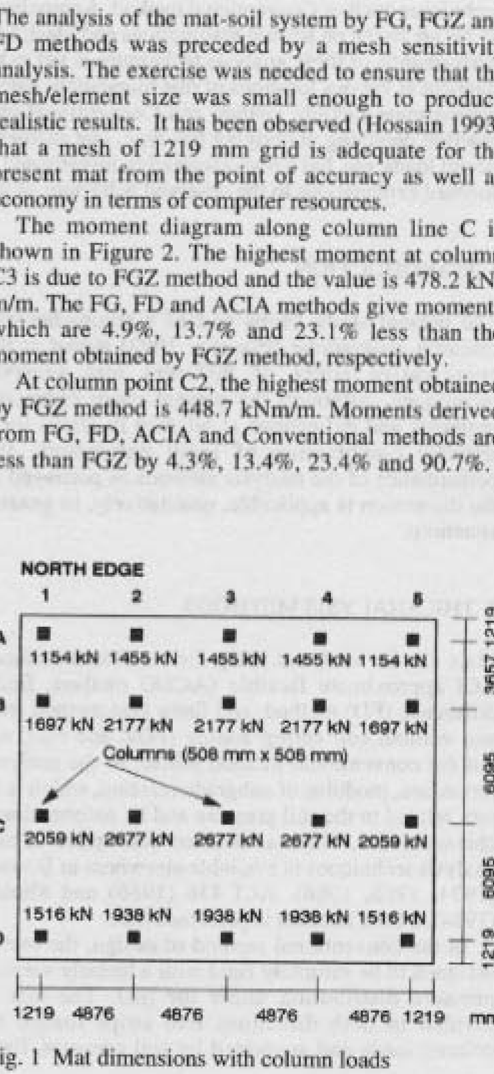

Fig. 1 Mat dimensions with column loads

It is found from the moment diagrams that FGZ method yields higher positive moments at column points than other methods. But at mid point between columns, the negative moments obtained by FG method are higher than those obtained by FGZ method. This implies that soil spring zoning accumulates positive moments at column points by reducing negative moments at points between columns. It introduces softer soil springs towards the centre of the mat and the stiffness contributed by the springs are, thus, reduced. But results show that the stiffness reduction of springs are more pronounced at points between columns than at columns. The reduction of stiffness at column points being lesser, they take higher share in contrast to middle points.

Deflections obtained by different methods along column lines A and C are presented in Figure 3. It appears that the slope of the curve, which is the curvature, becomes flatter for finite grid method with zoning than the same without zoning at points between the columns. On the other hand, at column points, this curvature is higher for FGZ method. As moment is directly proportional to curvature, it is not surprising that FGZ method yields higher moments at column points and lesser at points between columns compared to the same method using no soil spring zoning. It is also evident that the effect of zoning is more pronounced at interior columns than exteriors and it is due to the fact that zoning makes softer spring towards the centre from all directions.

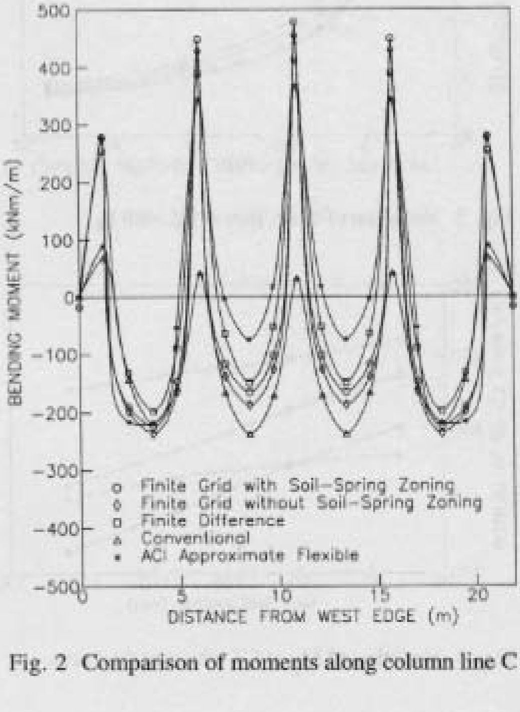

Fig. 2 Comparison of moments along column line C

The FD method yields moments at columns about 8 to 18% less than FGZ method, higher variation being found towards the centre due to softer soil springs (Hossain, 1993). As for negative moments between column points, FD produces 48% less to 17% higher moments than FGZ method. If FD method is compared to FG method, it creates positive moments at column points 7 to 17% less than the moments found by the latter method. The FD method yields less negative moments between column points than moments obtained by FG method. The ACIA method gives better results at column points away from edges and at these points moments are about 15 to 30% less than the same obtained by FGZ method. The poor performance of ACIA method near edges are due to the concentrated effect of the end conditioning forces.

Deflection curves show that FG and FD methods give almost equal deflection at all the points; both these methods consider uniform soil springs under the mat. The results of FGZ method clearly indicate the effect of zoning. In this method, the deflections of interior points are much higher than the deflections obtained from FG and FD methods. At column line A, the deflections at the edges are lower for FGZ method in comparison to its without zoning counterpart. This may be visualised as the uplift of a corner of plate which is deflected in a dish shape. At column line A and C, the edge deflections of mat from FG and FD methods are higher than the centre deflections.

The ACIA method yields very high deflections at edges along all the column lines due to the concentrated effect of end conditioning forces. At exterior column line A the deflection of interior columns are quite small compared to other methods. For interior column lines, the deflections of points away from edge are more or less comparable to FG, FGZ and FD methods.

6 RESULTS OF THE PARAMETRIC STUDY

6.1 *Effect of modulus of subgrade reaction*

The values of modulus of subgrade reaction selected for the study are 7854, 15709, 31418 and 47126 kN/m^3. These values represent loose to medium dense sand and clayey soil having ultimate bearing capacity 96 to 383 kN/m^2.

Moments M_y (moment about east-west line) at C3 are presented in Figure 4. The FGZ, FG, FD and ACIA methods show 6%, 13%, 13.6% increase and 6.7% decrease in moment for an increase in k_s from 7854 to 47126 kN/m^3.

For column point C3, deflections are presented in Figure 5. For a modulus of 47126 kN/m^3, FGZ, FG, FD and ACIA methods yield deflections 80.0%, 79.6%, 78.6% and 77.4% less than the same for a modulus of 7854 kN/m³.

6.2 *Effect of stiffness of mat*

To find the effect of stiffness of mat on the behaviour of mat foundation, thickness is varied from 762 to 1219 mm keeping all other geometric and material properties unchanged. All these thicknesses are safe from punching point of view.

Moments M_y at C3 are presented in Figure 6. At this point, all the methods yield lesser moments for higher thickness and the decrease is substantial. At column C3, moments obtained by FGZ, FG, FD and ACIA methods are 6.8%, 15.8%, 19.2% and 7.3% lesser for the mat with 1219 mm thickness compared to results for 762 mm thick mat.

Deflections at column point C3 are presented in Figure 7. At C3 the FGZ, FG, FD and ACIA methods yield deflections 5.3%, 2.7%, 4.3% and 35.7% less for 1219 mm thick mat than the same for 762 mm thick mat.

6.3 *Effect of Poisson's ratio of concrete*

To find the effect of Poisson's ratio (μ) of concrete on moment, μ is varied from 0.15 to 0.25. The value of μ increases with age.

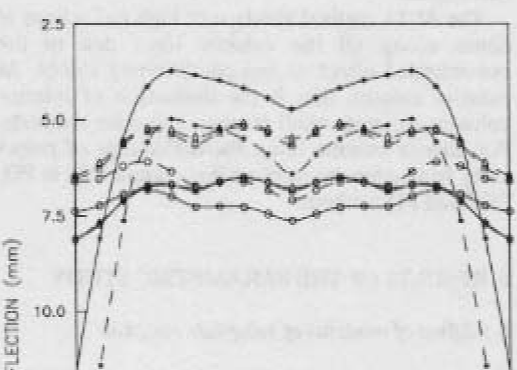

Fig. 3 Comparison of deflections along lines A, C

Shukla (1984) stated that higher μ gives higher moments. From this study it has been found that this is true for ACIA method because higher μ value results in higher moment coefficients. It has been also found valid for FD method. But in case of FG and FGZ methods, where beam-column elements are used, μ is only used to calculate shear modulus of concrete, which is very slightly affected by μ.

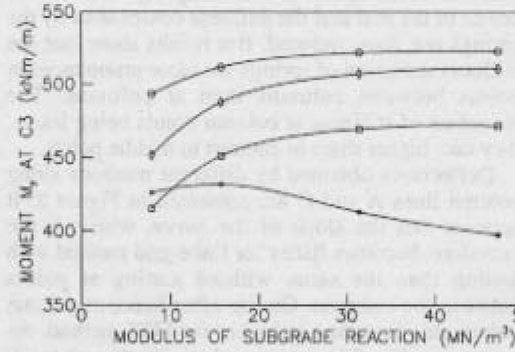

Fig. 4 Variation of M_y at C3 with k_s

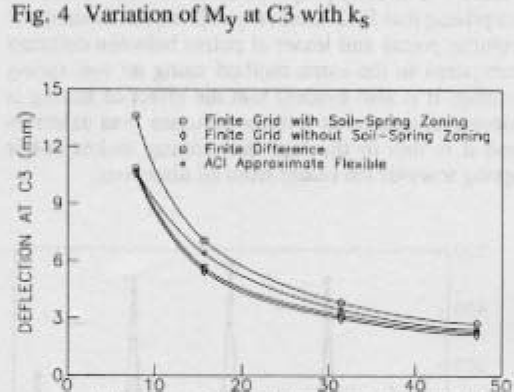

Fig. 5 Variation of deflection at C3 with k_s

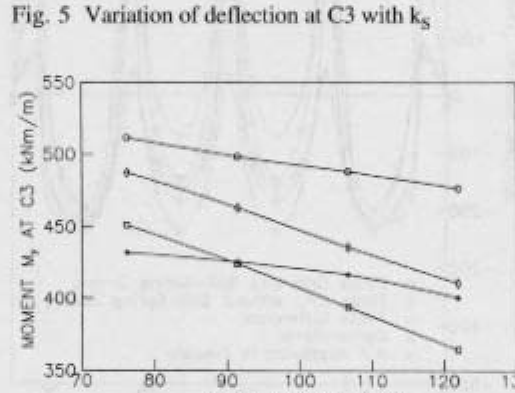

Fig. 6 Variation of M_y at C3 with mat thickness

6.4 *Effect of load*

To determine the effect of vertical and horizontal loads and their combination, a 14 storied building is considered having the same plan as used in the comparative study. The dead load and live load on each column is calculated and the design vertical load is found to be nearly equal to twice the load for a 7 storied building. Only FGZ method is employed in the analysis. A wind load equivalent to 53.6 m/s has been considered. Although loads in the leeward columns have been increased following Mician (1985), reductions in the windward columns have not been done as per ACI 318-89 (1989).

Bending moments along column line 3 are presented in Figure 8. Southward wind has no effect at A3, but with the increase in distance towards south, increased negative moments are found between columns. At column B3 and C3, column moments are reduced due to southward wind, but at D3 it is increased. North wind has similar effects on the reverse directions but here both A3 and B3 moments are increased.

The deflections along column line 3 are shown in Figure 9. Northward wind causes the north side of mat to deflect more and, as a result, the south side is slightly uplifted.

6.5 *Effect of number and spacing of column*

To find the effect of column numbers, the same mat-soil system with 7 stories as used in the comparative study is taken. Keeping the plan area and the load same, the 8 columns along column lines 2 and 4 are dropped.

Bending moments along column line 3 with and without columns in lines 2 and 4 are shown in Figure 10. By dropping column lines 2 and 4, contributing area of column line 3 is doubled and thus, load is also doubled. It has been found that all the moments are doubled for dropping these columns. Thus, the summation of all column moments in north-south direction remains the same. In a more detailed study (Hossain, 1993), summation of bending moments along east-west direction was also found to remain unchanged with or without columns in line B.

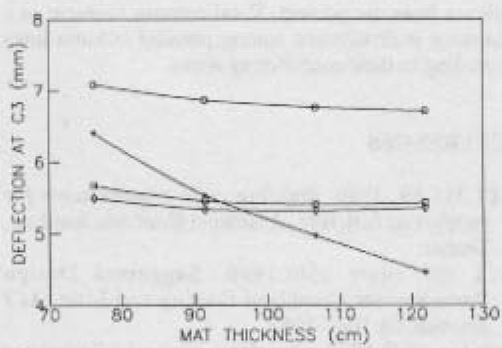

Fig. 7 Variation of deflection at C3 with mat thickness

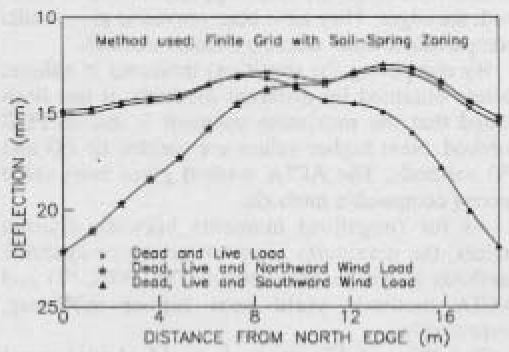

Fig. 9 Variation of deflection along column line 3 with different load cases

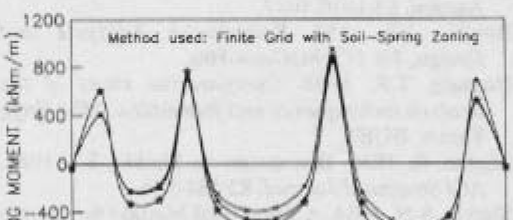

Fig. 8 Variation of moment along column line 3 with different load cases

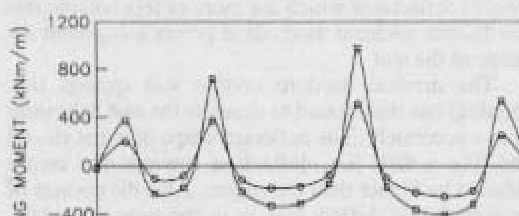

Fig. 10 Variation of bending moment along column line 3 with and without columns in lines 2 and 4

7 CONCLUSIONS

Conventional method of analysis has found to be inadequate to give realistic results in the analysis of mat foundations. There are two reasons; firstly in this method the mat is analysed strip by strip with uniform soil pressure acting under the strip which causes large moments between columns and small moments at column points. Secondly, the high moments at column points are flattened when the total moment in a strip is divided over the whole width.

The ACIA method is based on functions derived for infinite plates. Although end conditioning forces are applied to simulate a finite mat, they are applied in strips and cause concentrated effects at the edges. But this method yields results more or less comparable to discrete element methods at points far from the edges.

The FD method is based on the basic differential equation of plates resting on Winkler's medium and has been proven to yield results comparable to other refined discrete element approaches.

The FG and FGZ methods utilise the techniques of finite element. These methods employ beam column elements having only bending, torsion and shear at both the edges. They have been proven to give results comparable to other discrete element methods.

By comparing the (positive) moments at column points obtained by different methods, it has been found that the maximum moment is due to FGZ method. Next higher values are yielded by FG and FD methods. The ACIA method gives least value among comparable methods.

As for (negative) moments between column points, the maximum moment among comparable methods is due to FG method. The FGZ, FD and ACIA methods yield next higher moments, respectively.

The FG and FD methods yield almost equal deflections at all the points. But with soil spring zoning, the deflections towards the centre of the mat are found to be much higher. The ACIA method yields deflections which are more or less comparable to discrete element methods at points away from the edge of the mat.

The method used to couple soil springs (i.e. zoning) has been found to simulate the mat behaviour more accurately. The deflected shape of a mat should be like a dish (i.e. deflection towards the centre should be higher than the edges). Also the corners of a mat should deflect less as in the case of a plate. These behaviours are found when soil spring zoning is employed.

The effect of modulus of subgrade reaction on deflection of mat is much pronounced than its effect on moment. In all the methods, mat deflections decrease almost exponentially with an increase in modulus of soil. An increase in moment has been observed with an increase in soil modulus.

Increase in mat thickness increases flexural rigidity and as the mat becomes stiffer, the load transferred from column to soil is more uniformly distributed around column and, thus column moment is reduced. The FD and FG methods show this reduction at all the column points. All the methods yield lower deflections at all the points with increase in mat thickness, as it should.

With the increase in Poisson's ratio of concrete, moments increase in all the methods. However, this increase is more pronounced in FD method and almost negligible in FG and FGZ methods. Poisson's ratio has almost no effect on deflection of mat irrespective of the method used.

With the increase in column loads on one side of the centroid of the mat, as in the case of wind load, little change has been observed in moments on the other side. But there is substantial increase in moments and deflections on the side where loads are increased. A slight uplift on the other side of increased load has been observed.

Spans remaining unchanged in a direction of mat, the summation of column moments in that direction remains unchanged no matter how many parallel column lines are present. Total column moment in a direction is distributed among parallel column lines according to their contributing areas.

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