EFFECT OF INTRA PLANAR DIFFERENTIAL SETTLEMENT ANALYSIS OF BOILER SUPPORTING STRUCTURE - A CASE STUDY

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ABSTRACT

In boiler supporting structure, heavy loads are transferred to the ground through several columns embedded in reinforced concrete foundation. The foundation gets settled due to various factors such as loads acting on the structure, calamity, consolidation, nature of soil, fluctuations in ground water table etc. Due to this settlement, there occurs phenomenal changes in the geometry of the structure and hence, the force transfer mechanism within the structure cannot be predicted. This paper presents the effect of differential settlement on the foundation loading for a typical boiler supporting structure using STAAD - III. It is observed that there is significant effect on the vertical loading of the foundation due to the differential settlement that is obtained from a total of three hundred and seventy five trials. It is suggested to incorporate the increased variation of load caused due to settlement in the design itself such that the superstructure/foundation corresponding to that settlement is tolerated. It is concluded that if the foundation is designed for 10% extra load, it can withstand a differential settlement of 6mm safely. This extra load is the typical value obtained for this structure from varied set of combination of settlements and hence not applicable in general for any structure and any loading.

Keywords: *Boiler Supporting Structure, Differential Settlement, Load Combinations, Load Factor, Permissible Settlement*

INTRODUCTION

In large power plants, steam generating equipment (i.e., high pressure boilers) and its auxiliaries utilise to a very great extent the application of steel structures and it forms a vital component throughout its life time for stability, safety and reliability of equipment. The boiler supporting skeletal structure is made of steel and the foundations are of reinforced concrete. This supporting structure consists of complicated arrangement consisting of columns, beams and vertical bracings in both longitudinal and transverse directions along with horizontal floors and bracing system at different levels. All the structural members acts in a composite form/integrated form to resist all induced forces on the structure. Thus, it primarily does the function of supporting the weights/forces due to all the boiler equipments and other platforms/floors both vertically as well as horisontally and safely transfers the loads to the foundation and at the same time keeping the boiler in safe working condition to meet the required power output.

The foundation plays a major role in the transfer of various loads acting on the structure to the ground. They are acting as the medium between the superstructure and soil over which the structure is constructed. Generally, the foundation design of any structure for smooth transfer of loads is done considering the various properties of soil along with the loads to be transferred through it. It is also done by considering the permissible settlements that can undergo during its service conditions based on the type and importance of structure. Therefore, there is need for the foundations to be designed even accounting the settlements that can prevail in the site such that the structure is safe and stable enough to perform its function properly in spite of any differential settlement.

In this paper, the foundation of a typical boiler supporting structure is to be designed with a load factor obtained based on the trials performed by the settlement of column or combination of columns that lie in a single frame. The evaluation of load factor for the design is quite essential, as the supporting structure has to safely withstand the settlement that prevail in the site at a later stage. These industrial structures are of much importance due to the cost involved in construction and from its functional operation. Due to these reasons, the foundation has to be designed carefully. Thus, varied magnitudes of settlement of column(s) or combination of columns are considered and the corresponding vertical loads acting on the foundation are evaluated. This unique way of determination differs from regular approach of Geotechnical engineering.

SOIL STRUCTURE INTERACTION

Differential settlement [1] is a matter of serious concern in the case of framed structures as even small amounts of differential settlement can cause a substantial amount of redistribution of loads in column elements, while drastically affecting moments and shears in beam elements. These can be of such magnitudes as may render designs that ignore it, totally unsafe. Such redistribution however, has a wholesome influence on differential settlements themselves, and it is this aspect that needs an analysis.

The rigidity of superstructure has greater influence on the differential settlement of foundations. If the superstructure is perfectly flexible, and therefore statically determinate, settlements and differential settlements will take place unhindered. While on the other extreme, if the superstructure is perfectly rigid, settlements can occur but differential settlements cannot, since the superstructure can partake only of rigid body movements. And in the case of intermediate rigidity, differential settlement causes a redistribution of forces in the superstructure that causes a restraint on differential settlement. Therefore, interaction emerges with the net effect of which is that, the differential settlements are very much evened out, there by relieving the structure of much of the harmful consequences of unrestrained settlements [2].

DIFFERENTIAL SETTLEMENT

The foundation of different elements of a structure may have unequal settlements and the difference between such elements will cause differential settlement. The differential settlement shall be obtained by taking the difference of maximum and minimum settlements. Some of the causes of the differential settlement are as follows;

a) Geological and physical non-uniformity (or) anomalies in type, structure, thickness, and density of the soil medium (pockets of sand in clay, clay lenses in sand, wedge like soil strata, that is, lenses in soil), an admixture of organic matter, peat, mud, etc.,
b) Non-uniform pressure distribution from foundation to the soil due to the non-uniform loading and incomplete loading of the foundation,
c) Varying water regime at the construction site,
d) Over stressing of soil at adjacent site by heavy structures built next to light ones.
e) Overlap of stress distribution in soil from adjoining structures,
f) Unequal expansion of the soil due to excavation for footing,
g) Non-uniform development of extrusion settlements,
h) Non-uniform structural disruptions (or) disturbance of soil due to freezing and thawing, swelling, softening and drying of soils.

The permissible values of differential settlement in isolated footing for steel structures as specified by IS: 1904[8] are maximum settlement of 50 mm and differential settlement of 0.0033L in sand, hard and plastic clays with 'L' is the spacing between the footings.

LITERATURE SURVEY

The settlement analysis of building frames is carried out by Meyerhof [3]. It explains about the settlement moments and forces in simple rigid frames. Apart from it, the study also estimates the differential settlement for calculating secondary stresses that take into account the properties of soil and foundation and the load and rigidity of the frame. A rigorous method based on representative settlement-pressure is used to examine the critical loading conditions in building frames. It is concluded that due to differential settlement, load is transferred from internal to external footings and, when neglected, gives rise to serious errors of computation. The approximate formulae developed for settlement moments and forces give satisfactory results from which representative safe bearing pressures can be estimated.

Another analytical method based on the same assumptions of Meyerhof's [3] but with a somewhat simpler approach has been independently proposed by Chamecki. In this method, the reactions at the foundations are calculated assuming no settlement but allowing for frame stiffness. From these reactions, the settlements are back calculated treating the structure as perfectly flexible. It is followed by determination of the coefficient of load transference, which depend on frame stiffness and using these coefficients estimate the transfer of loads between the columns, because of settlement that is obtained above. With the new foundation loads, the revised settlements are determined. This method is one of the successive approximation and can be continued as long as it is necessary to obtain the desired standard of accuracy. However, this method does not discuss stresses induced in the frame by these settlements. This method seems to be the more promising but the acid test, as far as the practicing engineer is concerned to compare calculations with measurement.

A detailed study of the relation between maximum settlement of the buildings with the influence of building width and height along field data on allowable maximum settlement and maximum differential settlement are proposed by Grant et al [4]. Further extending to structure foundation analysis, the effect of increasing relative flexibility of foundation in column loads by Winkler model, linear elastic model and their effects on maximum positive and negative bending moments are discussed by Lee and Brown [5].

OBJECTIVES AND SIGNIFICANCE

This paper presents a study on the effect of the settlement of column or combination of columns on the vertical load acting on the footing. The objectives are summarised as follows:

1. To validate the settlement moments and forces in simple rigid frames obtained using STAAD – III with the published literature.
2. To determine the change in the vertical load of the foundation due to settlement.
3. To establish the worst affected footing caused due to any of the combinations of settlement within the individual frame.
4. To evaluate the vertical load variation on the footing that gets drastically affected.
5. To propose load factor for the design of the footing in counter acting the settlement effect.
6. To ensure overall safety and stability of the entire structure in spite of settlement.

SETTLEMENT MOMENTS AND FORCES IN RIGID FRAMES

A straight horizontal member AB of length (L) is subjected to clockwise bending moments M_{AB} and M_{BA}, joint rotations θ_A and θ_B and Δ, all taken positive are shown in Figure 1, and then it can be shown that

$$M_{AB} = 2EK(2\theta_A + \theta_B - 3R)$$

$$M_{BA} = 2EK(2\theta_B + \theta_A - 3R)$$

where 'E' is the modulus of elasticity of member, 'K' is the stiffness of the member (= I/L), 'I' is moment of inertia and 'R' is deflection ratio (Δ/L).

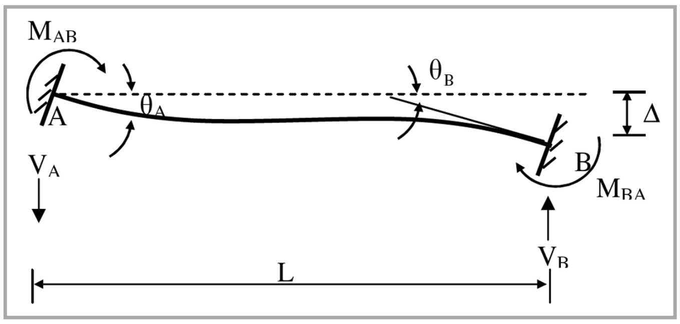

Figure 1: Beam with support settlement

The horizontal reactions 'H' acting towards the center line of the frame and vertical reactions 'V' acting upwards is taken as positive.

$$V_A = -\frac{(M_{AB} + M_{BA})}{L}$$

$$V_B = -\frac{(M_{AB} + M_{BA})}{L}$$

The application of these expressions to settlement problems is illustrated by Meyerhof for a single storey, three-bay frame, subjected to a differential settlement 'Δ' between its middle and outer footings. Figure 2 shows the description of the typical rigid framed structure. The height of all the columns is 'h'. The length of the end beams is L_1 while the mid beam is L_2. The moment of inertia of columns AE and DH is I_1 while BF and CG is I_2. The moment of inertia of beams EF and GH is I_3 while FG is I_4. The mid columns settle by an equal amount of settlement 'Δ'. The general expressions for settlement moments and forces are determined as follows.

$$K_1 = \frac{I_1}{h} \tag{1}$$

$$K_2 = \frac{I_2}{h} \tag{2}$$

$$K_3 = \frac{I_3}{L_1} \tag{3}$$

$$K_4 = \frac{I_4}{L_2} \tag{4}$$

$$K_E = K_1 + K_3 \tag{5}$$

$$K_F = K_2 + K_3 + K_4 \tag{6}$$

$$N_O = 2K_E(2K_F - K_4) - K_3^2 \tag{7}$$

$$N_1 = K_E + K_1 \tag{8}$$

$$R = \left(\frac{\Delta}{L_1}\right) \tag{9}$$

$$M_{Ef} = -\left(\frac{12EK_1K_3(K_F+K_2)R}{N_O}\right) \tag{10}$$

$$M_{EA} = +\left(\frac{12EK_1K_3(K_F+K_2)R}{N_O}\right) \tag{11}$$

$$M_{FB} = +\left(\frac{12EK_2K_3N_1R}{N_O}\right) \tag{12}$$

$$M_{GC} = -\left(\frac{12EK_2K_3N_1R}{N_O}\right) \tag{13}$$

$$M_{FG} = +\left(\frac{6EK_3K_4N_1R}{N_O}\right) \tag{14}$$

$$M_{GF} = -\left(\frac{6EK_3K_4N_1R}{N_O}\right) \tag{15}$$

$$M_{AE} = +\frac{M_{EA}}{2} \tag{16}$$

$$M_{DH} = -\frac{M_{EA}}{2} \tag{17}$$

$$M_{BF} = +\frac{M_{FB}}{2} \tag{18}$$

$$M_{CG} = -\frac{M_{FB}}{2} \tag{19}$$

$$M_{FE} = -(M_{FB} + M_{FG}) \tag{20}$$

$$M_{GH} = +(M_{FB} + M_{FG}) \tag{21}$$

$$M_{HD} = -(M_{EA}) \tag{22}$$

$$M_{HG} = -(M_{EA}) \tag{23}$$

$$H_A \text{ and } H_D = \frac{3M_{EA}}{2h} \tag{24}$$

$$H_B \text{ and } H_C = \frac{3M_{FB}}{2h} \tag{25}$$

$$V_A \text{ and } V_D = -\left(\frac{M_{EF}+M_{FE}}{L_1}\right) \tag{26}$$

$$V_B \text{ and } V_C = -V_A \tag{27}$$

The settlement moments and forces using the above mentioned equations based on slope deflection method is calculated for a typical rigid frame of configuration shown in Figure 2. A uniform cross section of 600 x 600 mm is considered for all beams and columns. The height of all columns is 4000 mm. The length of end bay beams is 7000 mm while the length of mid bay beam is 10000mm. It is also assumed that the mid footings of the frame settle by an equal amount of 15 mm. The young's modulus of elasticity (E) of the concrete is 27386 N/mm^2 for M30 grade. For the same frame STAAD-III analysis is performed and the results are compared in Table 1. The results are in good comparison with Meyerhof's method. Since this method is cumbersome for braced structure with various load combinations, STAAD-III is used to study the effect of differential settlement of a typical boiler supporting structure.

DESCRIPTION OF STRUCTURE

The boiler supporting structure has an overall height of 27.682 m with a length of 25.3 m and 14.0 m width. It has thirteen columns and all are pinned at the base of foundation. There are totally 248 members in the structure containing beams, columns and bracings. Since single member cannot be taken for the column/beam, there are joints provided for continuity. These are considered as erection joints that are treated as pinned and hence not restrained against rotation. So the functionality of the member for uniformity is achieved. The beam members are separately designed for the various loads acting over that area. The various loads acting on the structure considered are as mentioned below:

1. Dead load,
2. Live load,
3. Wind load,
4. Seismic load,
5. Furnace load,
6. Contingency load

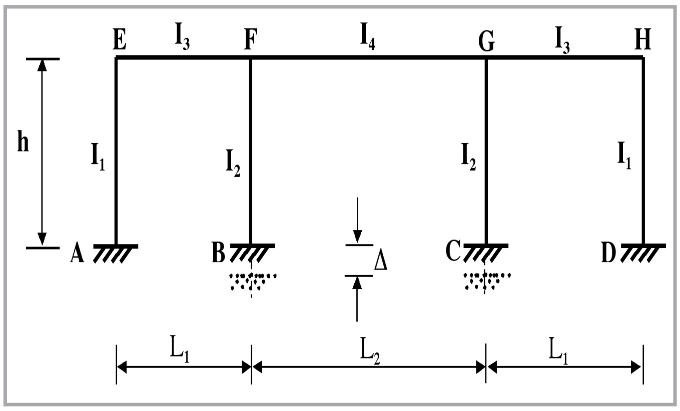

Figure 2: Typical rigid framed structure with differential settlement of supports

Table 1: Comparison of settlement moments and forces using STAAD-III

Sl. No.	Settlement Moments (kN-m)			Settlement Forces (kN)		
	Member	Meyerhof's Method	STAAD-III	Joint	Meyerhof's Method	STAAD-III
1	M_{EA} M_{EF}	+ 300.44 - 300.44	+ 300.44 - 300.44	V_A	+ 88.07	+ 82.30
2	M_{FB} M_{GC}	+ 245.83 - 245.83	+ 245.00 - 245.00	V_B	-88.07	- 82.30
3	M_{FG} M_{GF}	+ 70.20 - 70.20	+ 70.60 - 70.60	V_C	-88.07	- 82.30
4	M_{FE} M_{GH}	- 316.03 + 316.03	- 315.6 + 315.6	V_D	+88.07	+ 82.30

Self-weight of the section is also taken into account. The magnitude of dead load and live load are taken as 1.5 kN/m^2 and 5 kN/m^2 respectively. The values of wind load and seismic load are determined from IS: 875 (Part-3) [6] and IS: 1893 [7] correspondingly. Loads caused due to wind, seismic, and furnace guides are considered in both positive and negative directions of X and Z axes. It totally accounts for sixteen individual load cases and fourteen load combinations. The structure is completely analysed as space frame analysis with varying load factors for the load combinations along with individual load cases. The various members whose ends are released are considered in the modeled structure along with some other members acting as bracings. Due to practical reasons and joint specifications at the site, group members are considered to obtain reliable sections feasible for construction. The modeled structure is thus analysed using STAAD-III [9] considering with and without settlement of columns. A skeletal sketch of the supporting structure is shown in Figure 3.The layout consists of two rows of five columns each, along with a row of three columns in the longitudinal direction as shown in the Figure 4. As the auxiliary columns are not part of the main supporting structure, they does not get affected and hence not considered for the study.

POSSIBILITIES OF SETTLEMENT

Differential settlement of foundation can be stated as the difference in the level of foundation that might be caused due to settlement of either the foundations or the settlement of any one foundation while the other being unsettled. It is assumed in this study that whenever the columns have undergone settlement, they tend to settle by same magnitude even though it will not settle in the same pattern in reality. It is taken so as to avoid innumerable set of combinations with varied magnitude and also for simplicity to perform a regular pattern

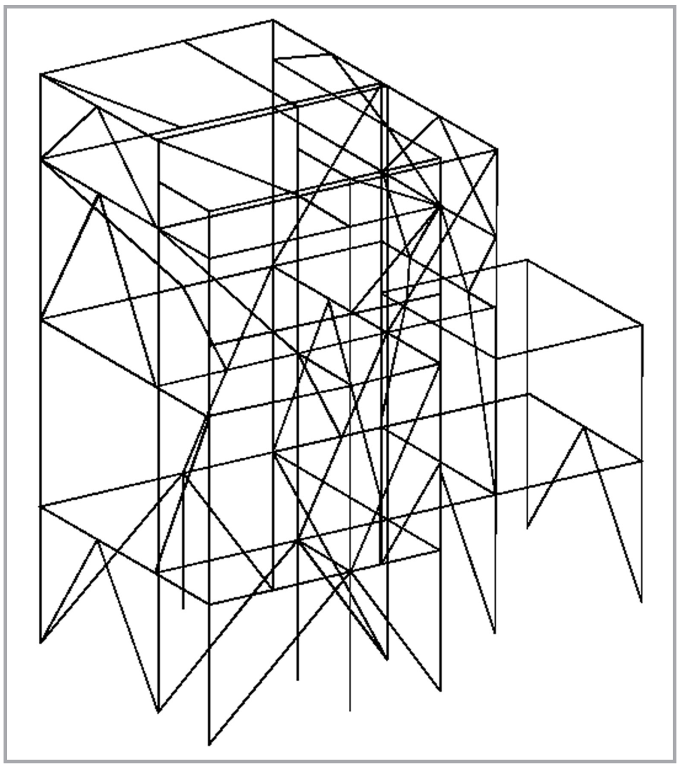

Figure 3: Schematic view of boiler supporting structure

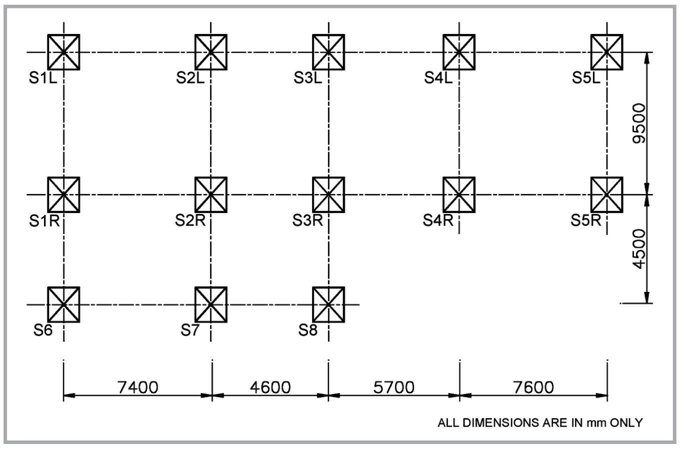

Figure 4: Plan showing arrangement of columns

of settlement. There does not exist any differential settlement with in the settled columns. Therefore there exists a difference in level of the settled columns to the unsettled columns leading to prevail a situation of differential settlement. Thus the settlement is given for the thirteen main columns in cyclic manner. The various column combinations that have been taken into account for the study:

1. Longitudinal direction
   a) Settlement of single column
   b) Settlement of two columns
   c) Settlement of three columns
   d) Settlement of four columns
   e) Settlement of five columns

7. Lateral direction
   a) Settlement of single column
   b) Settlement of two columns
   c) Settlement of three columns

The above mentioned trials are done as continuous column combinations within individual frame and also considering them as other combinations within that row itself to a maximum of the total number of columns in that particular frame considered.

METHODOLOGY

The foundations for the columns considered for the study are designed as individual footings. The settlements of various columns are taken as combinations as explained in Table 2. Every combination of settlement is done for the magnitude ranging from 10 mm to 50 mm for every increment of 10 mm. It is so obtained that a combination considered will have five trials to be performed. The structure modeled is analysed for the vertical load on the foundation without considering any settlement. For various trials, the corresponding columns are allowed to settle and the vertical loads on the foundation are obtained. It is done so as to determine the variation of the vertical loading due to varied set of combinations. The analysis for the structure with and without settlement is done as space frame analysis using STAAD-III [9].

RESULTS AND DISCUSSION

A total of varied set of three hundred and seventy five trials for the vertical loading acting on the foundations is obtained through STAAD output of support reactions. The percentage variation in loading due to settlements of 10 mm, 20 mm, 30 mm, 40 mm and 50 mm for all the combinations is obtained. The maximum values of variation along with the combination and the variation in the individual column are given in Table 3. Typical graphs for a particular combination of differential settlement are shown in Figures 5 to 9. These plots show the variation of vertical load in tons vs settlement in millimeters. It is observed that either the increase or the decrease in the vertical load is not uniform in a column, for a particular pattern of settlement though there is increase in the magnitude of differential settlement. This happens due to the presence of bracings connecting to the adjacent columns. The peak variation in load for corresponding settlement is shown in Figure 10. It suggests the increment in load to be incorporated corresponding to the settlement necessitated in the design of this structure.

Table 2: Details of column combinations considered for settlement

Sl.No.	Settlement of Column(s)	Direction	Continuous combination trials within individual frames	Other combination trials within individual frames	Total Trials
1	One column	Longitudinal	S1L, S2L, S3L, S4L, S5L, S1R,	-	65
		Lateral	S2R, S3R, S4R, S5R, S6, S7, S8		
2	Two columns	Longitudinal	S1LS2L, S2LS3L, S3LS4L, S4LS5L,S1RS2R, S2RS3R, S3RS4R, S4RS5R, S6S7, S7S8	S1LS3L, S1LS4L, S1LS5L,S2LS4L, S2LS5L, S3LS5L,S1RS3R, S1RS4R, S1RS5R, S2RS4R, S2RS5R, S3RS5R,S6S8	115
		Lateral	S1LS1R, S1RS6, S2LS2R, S2RS7, S3LS3R, S3RS8, S4LS4R, S5LS5R	S1LS6, S2LS7, S3LS8	55
3	Three columns	Longitudinal	S1LS2LS3L, S2LS3LS4L, S3LS4LS5L, S1RS2RS3R, S2RS3RS4R, S3RS4RS5R,S6S7S8	S1LS2LS4L, S1LS2LS5L, S1LS3LS4L, S1LS3LS5L, S1LS4LS5L, S2LS3LS5L,	65
		Lateral	S1LS1RS6, S2LS2RS7, S3LS3RS8	-	15
4	Four columns	Longitudinal	S1LS2LS3LS4L, S2LS3LS4LS5L, S1RS2RS3RS4R, S2RS3RS4RS5R	S1LS2LS4LS5L, S1LS3LS4LS5L, S1LS2LS3LS5L, S1RS2RS4RS5R, S1RS3RS4RS5R, S1RS2RS3RS5R	50
5	Five columns	Longitudinal	S1LS2LS3LS4LS5L, S1RS2RS3RS4RS5R	-	10

Table 3: Percentage of load variation for varied column combinations due to settlement

Sl. No.	Settlement of Columns	Magnitude	Percentage of Load variation due to settlement												
			S1L	S2L	S3L	S4L	S5L	S1R	S2R	S3R	S4R	S5R	S6	S7	S8
1	S2R	10	-	-	-	-	-	4.81	16	6.94	-1.35	-	-	-	-
2	S2LS2RS7		-6.06	16.01	-8.57	-	-	-4.81	**16.06**	-6.94	1.35	-	8.95	3.40	-20.00
3	S7	20	-	-	-	-	-	-	-	-	-	-	7.46	19.12	14.00
4	S2LS3LS4L		-	19.31	8.33	-1.08	-	-	-	-	-	-	-	-	-
5	S1RS3RS4R		-	-	0.10	-	-4.33	-5.9	**19.33**	-3.27	-6.28	-	-0.03	-	0.04
6	S1RS3RS4RS5R		-	-	-	-	-	-5.86	18.98	-3.24	-6.76	-	-	-	-
7	S7S8	30	-	-	-	-	-	-					9.8	-33.56	**20.73**
8	S1LS2L	40	-11.51	26.52	-20.95	4.23	-3.13	2.14	-14.60	-11.11	14.86	-5.88	-2.98	-17.02	-
9	S3RS4RS5R		-0.05	-	0.08	-0.20	-	-7.99	**27.00**	-2.96	-11.04	0.65	-0.04	-	0.06
10	S3RS4RS5R	50	-14.32	**37.64**	-22.36	-0.79	-0.87	1.77	-14.55	-11.15	14.52	-0.83	-3.41	-16.85	-0.4

*** Bold values indicate maximum increase in percentage of load for that magnitude of settlement**

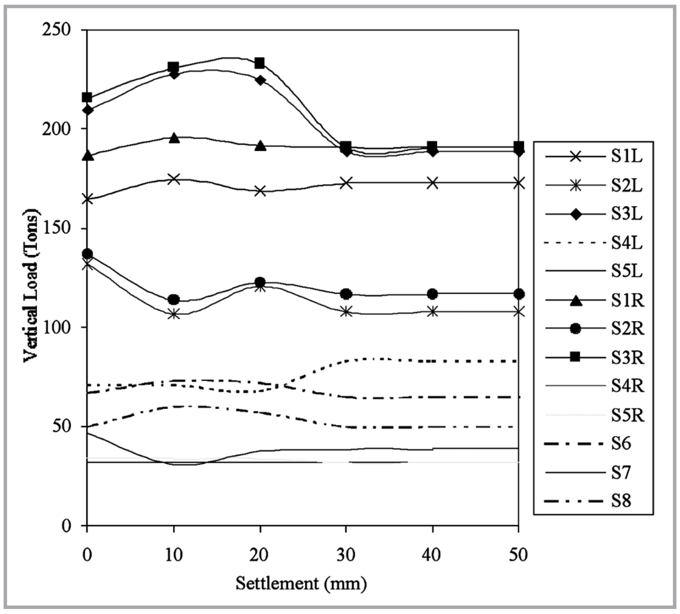

Figure 5: Settlement in S2L S2R and S7 only

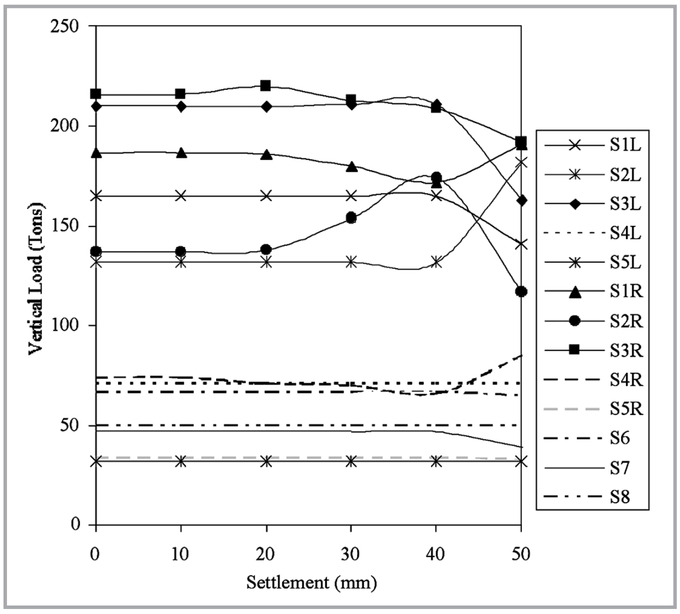

Figure 8: Settlement in S3R S4R and S5R only

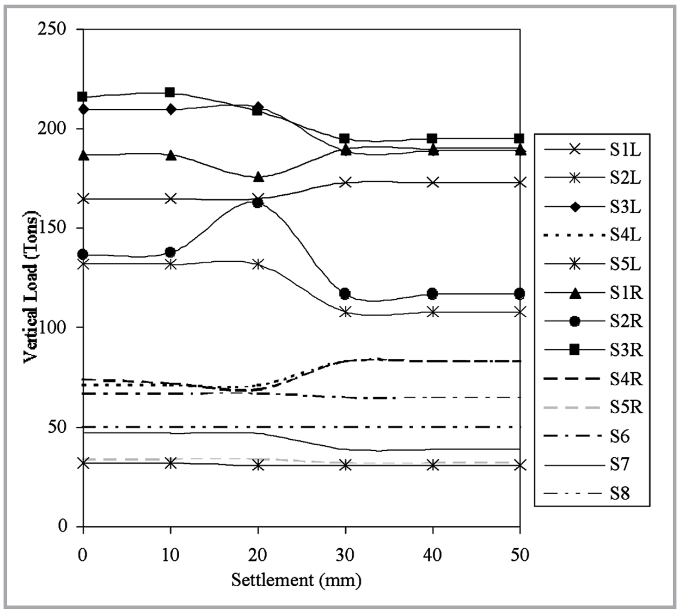

Figure 6: Settlement in S1R S3R and S4R only

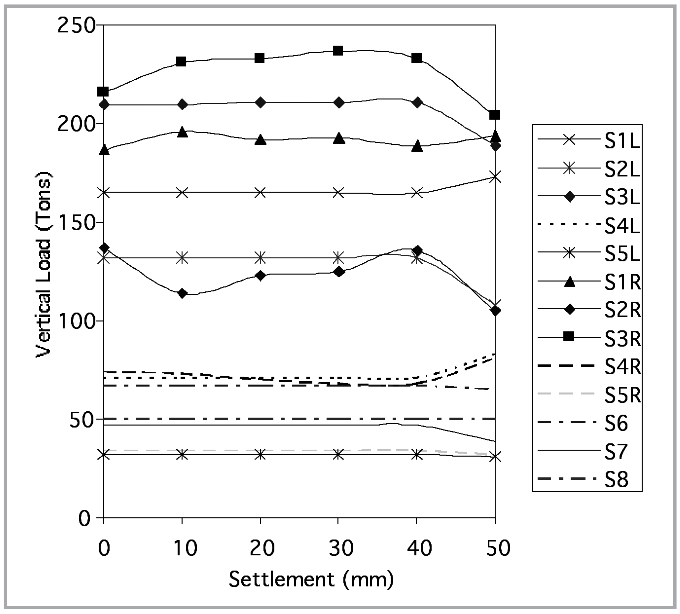

Figure 9: Settlement in S2R only

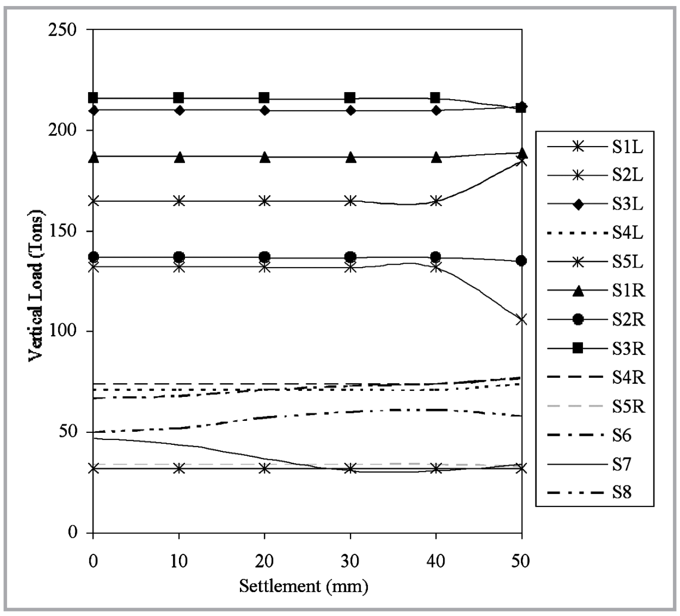

Figure 7: Settlement in S7 and S8 only

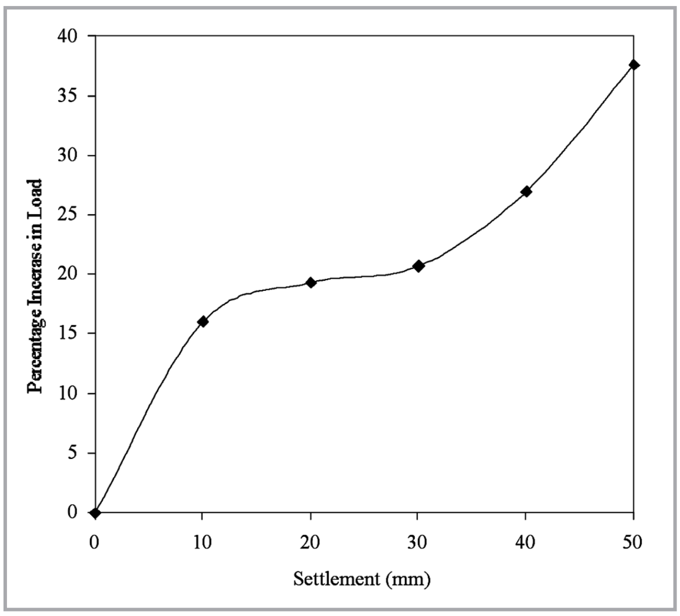

Figure 10: Plot for Load Factor vs Settlement

CONCLUSION

The following conclusions are drawn based on the study obtained from three hundred and seventy five trials considering various combination of settlement of columns.

1. Up to 10 mm differential settlement of a column or a group of columns, the increase in the vertical load on the footing of the column S2R is 16%, while the maximum reduction in the vertical load is observed in the footing of the column S8 of the order of 20%.

2. For 20 mm differential settlement, the increase in the vertical load on the footing of the column S2R is 19%, while the maximum reduction in the vertical load is observed in the footing of the column S4R of the order of 7%.

3. For 30 mm settlement, the increase in the vertical load on the footing of the column S8 is 21%, while the maximum reduction in the vertical load is observed in the footing of the column S7 of the order of 34%.

4. For 40 mm settlement, the increase in the vertical load on the footing of the column S2R is 27%, while the maximum reduction in the vertical load is observed in the footing of the column S3L of the order of 21%.

5. For 50 mm settlement, the increase in the vertical load on the footing of the column S2L is 38%, while the maximum reduction in the vertical load is observed in the footing of the column S3L of the order of 22%.

This study has evaluated the increase in the vertical load on the foundation caused due to differential settlement. Thus, for an extra load of 10% is adequate to permit an allowable differential settlement of 6mm. This load factor is applicable to this structure only and cannot be generalised to use it for any other structure as the loads and configuration of the bracings apart from the spacing of various columns plays an important role. This study has assessed the worst affected columns as S2L, S2R and S8 if differential settlement happens at a later stage of construction. Thus, if the foundation of these columns is accounted for 10% additional load in the preliminary design, it can withstand from the consequences of differential settlement safely. ■

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PROFILES

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