Effect of Isolated Footing settlement on Structural Response under Lateral Loads

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Abstract

The structural frames are normally analyzed by assuming frames with fixed base, and role of foundation and soil properties, on member action is neglected. It implies that foundation of frame being analyzed is very heavy and soil on which the structure is going to be constructed is rock like material, therefore settlement at the base of frame is considered zero. Actions thus obtained are used in designing the foundations and other structural members like beams and columns. Since base is considered fixed which may not always be true the actions in members and loads transferred at foundation level in this manner do not depict the true structural behavior. A proper and economical design of foundation results in elastic behavior, which makes the foundations vulnerable to settlement under loads. When uniform gravity loads are applied this settlement is less at base of vertical members located at corners of a frame and more under vertical members located in interior spans. Whereas when lateral loads are applied settlement in bases at far ends is very high as compared to the bases located at the near ends. Theses settlements results in member actions, which are different from those obtained when analyses is carried on assumption, that frame has fixed base. Also different types of foundations have different effect on member actions. Response of foundation in terms of settlement in the structure varies with nature and direction of loading. The cross sectional properties of foundation depend upon the soil properties. When the structural frame and the foundation are modeled together and analyzed, real response of the structural frame can be observed. Due to advancement in computational technology i.e. availability of high-speed computers and efficient softwares it has become possible and economical now to conduct analyses in this way. This work is focused on analyzing frame and isolated foundations together and studying the results in terms of foundation reactions and member actions. All results were than compared. It was concluded from the comparison of results that modeling of structure along with foundation affects its response. Under lateral forces the accumulation of stresses at certain points in the foundation resulted in large settlements. The settlements, which occurred in the modeled foundation directly, affected the member forces in the structural members.

The research work can be helpful for the practicing engineers to achieve the more realistic response of the structure and more economical and safe design of reinforced concrete structures under gravity as well as seismic loadings.

Keywords: Settlement; Structural response; isolated footings, member actions; modulus of sub grade reaction; Finite Element.

1. Introduction

1.1 Interaction of deformable bodies

According to Selvadurai (1979) there are three situations in which deformable bodies interact with each other. First case is the interaction between elastic bodies. Second situation arises when elastic mediums interact with rigid bodies. In second case shape of contact region is known and it remains constant for all magnitude of forces that are applied to intending rigid bodies. Third situation which is particularly related to civil engineering arises when elastic bodies interact with structural elements. Under such situation mechanical behaviour of one of the media is represented in terms of behaviour of structural elements of other body. These elements may be beams, plates and columns resting on idealized linearly deformable elastic media. Such types of problems are related to soil mechanics and foundation engineering. Solution to such problems is helpful in analysis and design of structural foundation.

The mechanical response of naturally occurring soils can be influenced by a variety of factors. These include (i) the shape, size mechanical properties of the individual soil particles, (ii) the configuration of the soil structure, (iii) the intergranular stresses and stresses and stress history, and (iv) The presence of soil moister, the degree of saturation and the soil permeability. These factors generally contribute to stress–strain phenomenon which displays markedly non-linear, irreversible and time dependent characteristics, and to soil masses which exhibits anisotropic and non-homogenous material properties.

The simplest assumption that the soils behave as linear elastic medium is not always rigorously satisfied by naturally occurring soils. Linear elastic behaviour, on the other hand, considerably reduces the analytical rigour expended in the solution of a particular boundary value problem and provides useful information to many practical problems of soil mechanics and foundation engineering which would otherwise be intractable.

In the analysis of the soil- foundation interaction problem is generally assumed that an elastic half space region can adequately represent the soil medium. In practice of course foundation is usually located at some depth below the ground surface the surface of the soil medium is assumed to form the soil foundation interface the linear elastic idealization of the supporting soil, medium is usually represented by mechanical or mathematical model which exhibits the particular characteristics of soil behaviour. Several such idealizations have been developed.

1.2 Behaviour of supporting soil medium

Behaviour of supporting soil medium can be viewed by two extreme situations. The first and the simplest model of linear elastic behaviour of the supporting soil medium is generally attributed to Winkler (1867) .He assumed that the surface displacement of the soil medium at every point is directly proportional to the stress applied to it and is completely independent of stresses or displacements at other, even immediately neighbouring, points of the soil-foundation interface. Winkler's idealization of the soil medium can be physically represented as a system of closely spaced spring elements, each of which will be deformed by the stress applied directly to it while the neighbouring elements remain unaffected. The surface deflections that occur in Winkler model are limited to the loaded region. The characteristic feature of this representation of the soil medium is its discontinuous behaviour of the surface displacement.

In case of soil media surface deflection will occur not only immediately under the loaded region but also within certain limited zone outside the loaded region. Another idealization assumes continuum behaviour of the soil, and an elastic half-space thus represents the soil medium. Although the continuum behaviour is usually regarded as a more accurate description of soil behaviour in general, the analysis of the soil foundation interaction problem is mathematically complex.

The two models for elastic soil behaviour described above can be regarded as two extreme cases of soil behaviour, represented on the one hand by the completely discontinuous Winkler medium and the other by the completely continuous elastic solid. Both experimental and theoretical investigations have emphasized the need to provide a transition between these two types of idealized soil behaviour. For example, it is observed that, for soil media, surface displacement occurs not only within the loaded area but also outside it. These displacements, however, decrease more rapidly than that predicted by the elastic continuum model. The two-parameter models of idealized soil behaviour developed by Filonenko-Borodich (1940), Hetenyi (1966) Pasternak & Reissner (1959) and Vlazov and Leontiev (1966) attempt to over come some of these discrepancies. In one category of two-parameter soil models (Filonenko-Borodich, Hetenyi, and Pasternak) mechanical interaction is introduced between the spring elements of the Winkler medium and in the second kind (Reissner, Vlazov and Leontiev) limitations are imposed on the type of displacement and stress distribution, which can occur in the elastic half-space model.

From a theoretical point of view, several assumptions can be made. These include from the completely smooth to the completely adhering interfaces with Coulomb friction, finite friction or combinations thereof occupying an intermediate position.

Most structural foundations will exhibit some frictional characteristics at the interface Selvadurai (1979) In general the overall effect of adhesion or friction is to reduce the settlement experienced by the foundation Valzov (1949a). When the extreme flexibility of the foundation is taken into consideration the influence of friction or adhesion on the settlement becomes far more prominent. When dealing with the interaction of highly flexible foundations resting on compressible soil media adhesion effect become more prominent Owing to the finite strength of soil media, the frictional forces, if developed, will also have finite values. The presence of pore pressure can modify the magnitude and distribution of the frictional forces throughout the consolidation process Selvadurai (1979). In addition, factors such as the distributing and the character of the external loads on the foundation, the relative flexibility of the foundation and time-dependent effects can significantly influence the condition at the soil-foundation interface.

From a physical point of view it is reasonable to assume that frictionless interfaces are only capable of sustaining compressive surface tractions (i.e. the contact of tensionless or unilateral). With most structural foundations, the self-weight involved would be sufficient to prevent any loss of contact.

Idealized behaviour of the soil-foundation interaction problem is not necessarily unique; it will depend on different factors that may include the type of soil and soil condition, the type of foundation and the type of external loading. In addition to these, due consideration should be given to more practical aspects of the problem such as method of construction, the purpose and life span of the structure and economical consideration.

2 Methodology

In this research work a model of five-storey and four bay reinforced cement concrete frames is selected and analyzed to study the structural response for isolated foundation. The response parameters, which are focused in the study, are foundation settlement and member actions. In order to facilitate the comparison of results member properties were selected to result in enlarged deformations and member actions.

The structural frame was analyzed under gravity loads and seismic lateral loads. The lateral forces were calculated using equivalent lateral force procedure of uniform building code. Both model were analyzed using computer software.

Under lateral loads foundation settlement and member actions for both type of frames were compared and conclusions were drawn.

2.1 Model description

A five story frame structure shown in figure 1 and 2 is taken as a model structure the plain dimension of the building are 80 feet X 80 feet and the total height of building is 63 feet. The inter story height is 12 feet except first story which is 15’ high, and bay width along X-axis is 20 feet and along Y-axis is 20 feet. Some additional detail of frame is given below.

Number of stories =5

Total height of building =63ft

Height of first story =12 ft

Other storeys = 10 ft

Number of bays (X-direction) =4

Number of bays (Y-direction) =4

Total width of building (X-direction) =80 ft

Bay width (X-direction) =20 ft

Total width of building (Y-direction) =80 ft

Bay width (Y- direction) =20 ft

Column dimension =18 in X 18 in

Beam dimension =18 in X 24 in

Compressive strength of concrete =3,000 psi (column)

Compressive strength of concrete =3,000 psi (beam)

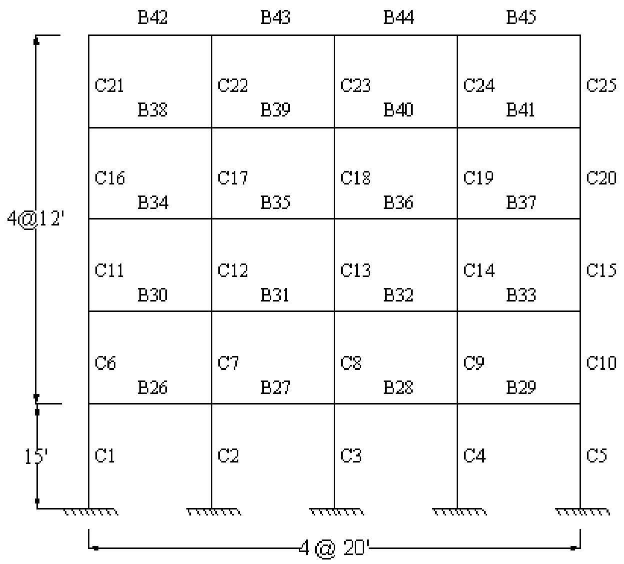

Fig. 1: Elevation of Frame

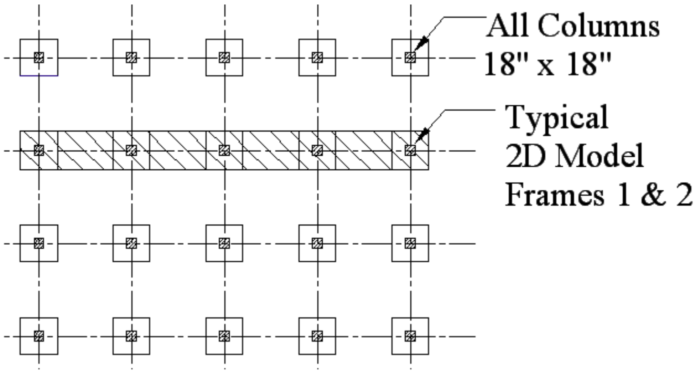

Fig. 2: Plan of Frame showing typical 2D frame that was analyzed.

2.2 Soil Properties

On the basis of bearing capacity analyses for strip, square, and raft foundations on shear as well as settlement basis. Net allowable bearing pressures recommended for the design of foundation was 0.521 Kg/cm^2 (1.067 K/ft^2)

2.3 Modulus of Sub Grade Reaction

The constant of proportionality between applied normal stress at a point and the corresponding surface displacement is therefore the modulus of sub grade reaction “K“ for the soil mass or soil configuration at that point. For a homogeneous Winkler medium the value of “K” should, by definition, be independent of the magnitude or the area of application of external stress. Consider also the idealization of the soil medium as homogeneous isotropic linearly elastic continuum; in this case we assume that the mechanical response of every element within the soil mass can be described in terms of the elastic constants of the soil, ES and νS. These are resumed to be intrinsic properties of the soil and therefore independent of the method of the testing or the particular configuration of the soil mass.

In practical situations, of course, the fundamental assumption of idealized soil behaviour may not be completely satisfied. In such circumstances the intrinsic properties of either the soil mass (Modulus of sub grade reaction, Shear modulus of elasticity etc), or soil (Modulus of elasticity of soil, poisons ration of soil medium) May no longer be unique parameters. For example the tests indicate that the modulus of sub grade reaction depends upon applied stress and dimensions of loaded area. Similarly the elastic constants for certain soils depend upon number of factors such including the magnitude of applied stress and stress history. Such departures from the assumed idealized behaviour naturally impose restrictions on the effectiveness of these mathematical idealizations.

In order to determine the modulus of sub grade reaction to be used in the computer model approximate method proposed by Joseph Bowels has been used. In the absence of any data, such as plate load test results, from which modulus of sub grade reaction can be computed, approximate formulae has been proposed. Bending moments, where Ks has greatest application are relatively insensitive to the sub grade modulus. It is because the flexural rigidity of the member is so much greater than the effective rigidity of soil. On the bases of this, Joseph Bowels proposed the following method for approximating modulus of sub grade reaction. This method is based on the bearing capacity

$$K_s = 12 F q_a \ (\text{K/sqft/ft})$$

This equation is based on reasoning that allowable bearing capacity "qa" is based on the ultimate soil pressure divided by safety factor "F" and the ultimate soil pressure is at about a settlement ΔH of 1in or .0254m. For isolated and strip footing factor "F" of safety is 3.

2.4 Gravity Loads

Gravity loads and other member dimensions are given below.

Dead load of the story =140 psf

Live load of the story (For Offices ASCE 7-95) =50 psf

Live Load per running foot on beams =20 X 50 / 1000 =1 K/ft

Live Load per running foot on corner beams =0.5 K/ft

Dead Load per running foot on beams =20 X 140/1000 =2.8 K/ft

Dead Load per running foot on corner beams =1.4 K/ft

2.5 Lateral Loads

Lateral earth quake loads were calculated as per UBC 1997 static load procedure and are presented in table 1 below.

Table 1: lateral loads applied at each storey level

Level	Story Weight W_i (kips)	H_X (ft)	W_x h_x (K-ft)	Lateral Forces F_x (kips)	Lateral Forces at on node
6	896.2	63	56460.6	90.261	18.052
5	1056	51	53856	86.097	17.219
4	1056	39	41184	65.839	13.168
3	1056	27	28512	45.581	9.116
2	1056	15	15840	25.323	5.065
1(base)	1056	0	-	-	
			195852.6		

2.6 Spring Constant

Value of spring constants for each node was calculated using methodology given by the Bowels (1996) and values are presented in table 2 below.

Table 2 Spring Constants for Isolated Footing

Location	Node No	Area sqft	Ks (K/Sqft)	Factor of Contributing area	K K/cft
corner	1	0.5X0.5	38.412	4	38.412
side	2	0.5X1	38.412	2	38.412
centre	3	1X1	38.412	1	38.412
centre	4	0.5X0.5	38.412	1	38.412
centre	5	0.5X0.75	38.412	1	14.404
centre	6	0.5X1	38.412	1	19.206
centre	7	0.75X0.75	38.412	1	21.61
centre	8	0.75X1	38.412	1	28.81
side	9	0.5X0.5	38.412	2	19.206
side	10	0.75X0.5	38.412	2	28.81

3 Analysis of Frame

Structure was analyzed for the following three types of load combinations

1- D+L

2- 1.2D+1.6L

3- 1.1 (1.2D+1.0E) =1.32D+1.1E

Analysis result for frame reactions are given in table 3 below:

Based on above analysis results suitable foundation dimensions were selected.

Footing Area at Node N 1, 9 = 3X13 ft

Footing Area at Node N 3, 5, 7 = 9 X 19 ft

Thickness of footing satisfied checked against one way and two way shear and bending moment.

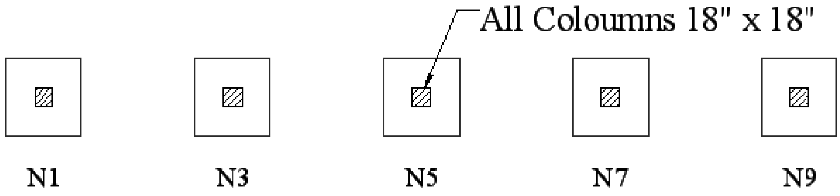

Fig. 2 Nomenclature of footings for frames

Table 3: Nodal Reactions

Node	Load Case	FX (K)	FY (K)	MZ ((K-ft)
N1	DL+LL	4.4222	187.52	-22.73
N3	DL+LL	-0.0368	382.38	-0.1184
N5	DL+LL	0.0000	380.20	-0.0000
N7	DL+LL	0.0368	382.38	0.1184
N9	DL+LL	-4.4222	187.52	22.73

3.1 Modelling of Isolated Footing in Computer

Foundation was modelled as shell elements in computer software. Thickness of shell element for n\both membrane and bending was taken equal to 24in. Analysis of both frames was performed in computer software. As already mentioned base of column of one frame was kept fixed while in other frame isolated footing was placed instead of fixed supports. Foundation settlement for both types of frames was recorded and compared. Moreover actions in structural elements

4 Settlement under Isolated Footing

In conventional analysis procedure supports were modelled fixed, as a result no support settlement was observed. However when analysis was performed after modelling foundation and superstructure together more realistic results was obtained. For example As shown in table 4 when only gravity loads were considered (Winkler COM-II) settlement in interior supports was more than outer supports. But when lateral loads were also considered remote supports settle more than near supports. Graphically this result can be seen in figure 5. Due to these foundation settlements resulting structure behaviour also changed.

Table 4: Nodal displacements

COM	1.32DL+1.1EQ		1.2DL+1.6LL
	MODEL TYPE		
JOINT	FIXED COM-III &II	WINKLER COM-III	WINKLER COM-II
	(in)	(in)	(in)
1	0	-0.24615	-0.39682
3	0	-0.30538	-0.41111
5	0	-0.30537	-0.40974
7	0	-0.30739	-0.41111
9	0	-0.34498	-0.39682

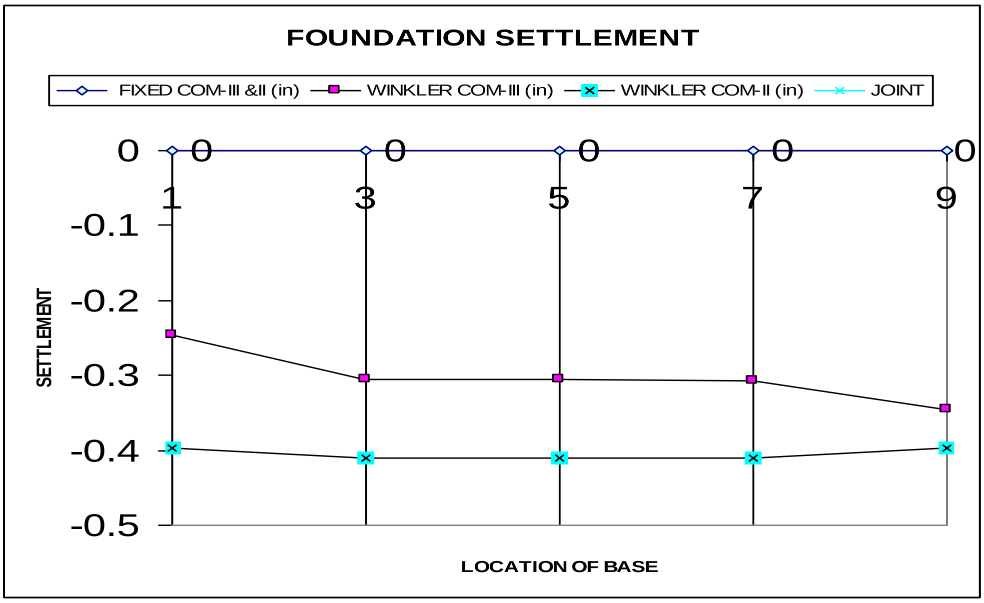

Fig. 2 Nomenclature of footings for frames

5 Discussion

Analysis of both frames was performed in computer software. As already mentioned base of column of one frame was kept fixed while in other frame isolated footing was placed instead of fixed supports. Actions in each span at all floors for both types of frames were compared and following observations were recorded.

5.1 Comparison of actions, in beams, between floors

The study of results inferred following.

In 1st span axial forces generally decrease as we move from lower to upper floors. However the decrease is more in the beams located at first floors.

Shear forces generally increased but in all floors in beams Negative moments have little decrease in the values. However positive moments remained unaffected.

In 4^{th} span at ground and first floor level axial forces in beams increased, whereas there was very little increase in the Shear forces and Moments on the same floor.

5.2 Comparison of actions, in beams, between spans

In Beams of ground floor, axial forces increase in the direction of application of lateral loads. There is very little effect on moments and shear forces.

Generally all actions increase in first span, however in interior floors axial forces decrease whereas in exterior spans it increases. In farther exterior spans moments and shear forces decrease a little.

At fifth floor level in 1st span generally all actions increase by a little amount. However Axial forces in all beams showed an increasing trend. Magnitude of Shear forces decreased a little in the beams located in inner spans. In neared spans moment increase is nominal.

5.3 Comparison of actions, in columns, between floors

In al columns there was increase in axial forces. The increase is constant in all floors. Shear forces and bending moments of interior floors increase. Increase in shear force is more than the increase in bending moments.

In 4th span general trend is the decrease in values of all actions. There is very little effect on axial forces. However decrease in shear forces and bending moments is more in lower floors.

5.4 Comparison of actions, in columns, between spans

At ground floor level in near spans axial force increased. Shear forces in nearer columns increase and in outermost columns it decreases and bending moments generally increase.

In 5th floor actions of corner columns generally increase. In remote spans there is a little decrease in moments and shear forces. Interior spans have more increase of shear forces and moments than exterior spans.

6 Conclusions

The conclusions drawn and observations made from the study of effects of foundation type on structural response under lateral loads are given below:

Modelling of footing along with the structure after analysis will indicate such locations where member actions are critical. Over all structural behaviour can be improved by specially considering these overstressed structural elements.

At footing level location where extra ordinary settlement appears, can be dealt with prior to actual construction

As the design varies with the designer's perception, it is not possible to develop strict rules regarding the structural response. However general idea regarding extent to which various actions may vary can be obtained. These ideas are helpful to practicing engineers in making more realistic decisions.

References

Winkler, E1867.Die Lehre von der Elastzitat and Festigkeit. Dominiicuss, Prague.

A.P.S. Selvadurai , (1979) "Elastic analyses of soil foundation interaction, developments in geotechnical engineering" Vol 17. Elsevier Scintific Publishing Company, New York

Filonenko-Borodich, M.M, (1940) "Some approximate theories of the elastic foundation" Uch. Zap. Mosk.Gos. UnivMekh.,46:3-18.

Filonenko-Borodich,M.M., (1945). "A very simple model of an elastic foundation capable of spreading the load". Sb Tr. Mosk. Elektro.inst.inzh. Trans. No: 53 Transzheldorizdat.

Hetenyi, (1966). "Beams and plates on elastic foundations and related problems". Appl. Mech. Rev.19 (2); 95-102.

Pasternak, P.L on a new method o f analysis of an elastic foundation by means of two foundation constants , Gosudarstvenno Izadatelstro Liberaturi po Stroitelset Arkhitekture, *Moscow.*

Reissener, E,1959, on theory of beams ol elastic foundations , Federhofer Girkman Anniersary Volume.

Shield, R.T and Anderson, C.A., (1966. "Some latest work principles for elastic bodies".z. Angew. Math. Phy., 17:663-676.

Hetenyi, M., (1946). "Beams on elastic foundations" University of Michigan Press, Ann Arbor, Michigan.

Valzov, V.Z., (1949a). "Structural Mechanics of thin-walled Three-Dimensional Systems" Gosstroiizdat, Moscow, Leningrad (in Russia)

Valzov, V.Z., (1949b). "general theory of shells and its application in Engineering Gosstroiizdat, Moscow, Leningrad (in Russia)

Joseph E. Bowels, P.E., S.E. (1996) "Foundation Analysis and Design 5th edition." *P 537-587.*