EFFECTS OF FOUNDATION DISPLACEMENTS DUE TO EARTHQUAKES ON SPATIAL FRAMES

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SUMMARY

The influence of settlements and rocking of shallow foundations on the magnitude of parasitic stresses induced on steel and reinforced concrete spatial frames is obtained theoretically. For reinforced concrete frames the effects of the construction speed and concrete creep phenomena is included into the analysis. Both static and seismic loads are considered acting on the foundation system which is supported on cohesionless sand and gravel soil deposits. Results show the influence of static and cyclic foundation displacements on the parasitic stresses and the beneficial effects of using foundation beams for decreasing those stresses.

INTRODUCTION

Mostly, footing design for structures supported on shallow foundations is controlled by allowable settlements and rocking. These displacements are produced by static and dynamic loads which induce cyclic deformations into the soil. During earthquakes the normal and shear stresses associated with the soil-structure interaction are superposed with those stresses associated with the incident earthquake waves, making a very complicated picture of cyclic strains into the soil mass. Besides, if the soil is saturated, volume changes induced by the cyclic strains in the soil skeleton can produce pore pressure increments which in turns may produce a significant decrease of the soil bearing capacity (i.e. large settlements).

In order to simplify the analysis it is assumed that no significant volume changes occur into the soil due to strains associated with the incident earthquake waves. This means the soil has been compacted by previous events before the structure is erected, or that future events will not induce cyclic strains with an amplitude and a significative number of cycles larger than those associated with past events. Accordingly, the problem is constrained to the effects of cyclic strains induced into the soil by soil-structure interaction. On the other hand, when the soil is saturated no pore pressure increments are considered during the cyclic load, which means the soil is partially saturated or, if saturated, the amount of pore pressure increments are meaningless (i.e. less than 50% of the effective confining pressures).

This work presents the behaviour of steel and reinforced concrete spatial frames founded on cohesionless sand and gravel soil deposits when subjected to static and seismic forces. The analysis is focused to the evaluation of bending moments induced in the frame joints for a rigid-support condition and for a soil support condition. The later includes both static and cyclic foundation displacements.

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FOUNDATION DISPLACEMENTS

Figure 1 shows the foundation displacements considered in the frame analysis. These displacements were computed by using expressions based on the theory of elasticity, where the linear equivalent soil modulus of elasticity, E_{ST}, was introduced for computing static displacements. Elastic cyclic displacements were evaluated by introducing the linear equivalent modulus of elasticity, E_C, into those expressions. Constant values of E_C were assumed during the earthquake ($E_C \simeq 3\ E_{ST}$) in order to simplify the computations. More sophisticated analysis could be done by considering the E_C variation whith the cyclic strain levels. Cumulative cyclic settlements due to soil plastic strains were computed by using a simplified expression obtained from plate loading tests (Ref. 1). The expression is useful for granular soils when it is difficult to test undisturbed samples:

$$\rho_C = m_C \ \rho_{ST} \ \frac{\sigma max - \sigma min}{\sigma max + \sigma min} \tag{1}$$

where ρ_C = cumulative cyclic settlement after N significative number of cycles; ρ_{ST} = settlement at the mid-point of the foundation due to static loads; σmax and σmin are the maximum and minimum contact pressures at the mid point of the foundation for static plus cyclic loads. For seismic events σmax and σmin present an erratic variation which can be taken into account by considering the variation of m_C with the number of cycles (Ref. 1) along with the superposition criteria outlined in Ref. 2. The frame analysis presented herein was performed by using a pseudo-static approach which gives constant values of σmax and σmin. For this analysis condition, expression (1) can be used directly by replacing m_C values corresponding to the significative number of cycles of the design earthquake (N = 30 was used in the frame analysis).

Values of the cyclic displacement coefficient, m_C, will vary with the soil characteristics. According to Ref. 1 values ranging from 1.5 to 3.5 were considered for cohesionless gravel a sandy soils with N = 30, respectively. When selecting m_C values a 50% increase was considered in order to include the cyclic shear stresses, $\pm\ \tau_C$, which are not present in the plate loading tests.

FRAME CHARACTERISTICS

In order to point out the relative importance of the different footing displacements it was decided to analyze a simple structured four-storied frame. Figure 2 shows the geometric characteristics of the frames along with the footings dimensions. These dimensions were obtained using the allowable contact pressures specified in Table I, avoiding tensile stresses at the foundation level. When establishing footing dimensions it was not considered neither maximum settlement limitations nor a compensated footing design for reducing differential settlements. On the other hand, soil was assumed to have a uniform rigidity distribution along the structure plan.

Stress-strain behaviour for steel and reinforced concrete was assumed to be linear, beam-column and footing-column joints were rigid joints and floor slabs were modeled as diaphragms perfectly rigid in the horizontal direction and perfectly flexible in the vertical direction. When foundation beams were introduced in the analysis, a winkler type of support was used with a modulus of vertical subgrade reaction given by:

$$k = k_o \frac{1 + 0.5\ B/L}{1.5} \qquad (2)$$

where k_o = modulus of vertical subgrade reaction for a square plate B x B, computed by using expressions based on the theory of elasticity with a soil modulus equal to E_{ST} or E_C; k = modulus of vertical subgrade reaction for the foundation beam which was considered equal to the distance between column axis.

Table I presents the complete set of data used in the frame analysis which includes soil properties, structure properties and construction characteristics.

RESULTS

Beding moments in the right joint of type I beams were selected to illustrate the effects of footing displacements. Figures 3 and 4 shows the moment variation for reinforced concrete and steel frames, respectively. This variations are essentially similar to those observed at the left joint of type I beams and at the joints of type II beams (Refs. 3 to 6). Also shown in Figs. 3 and 4 are the beneficial effects of foundation beams on reducing parasitic stresses. A better picture of this effect can be appreciate in Fig. 5.

CONCLUSIONS

Cumulative settlements due to cyclic stresses acting on shallow foundations can be estimated by means of a simple empirical relationship based on conventional plate loading tests. For the present analysis it was considered that such settlements were originated by cyclic stresses associated with the soil-structure interaction. This assumption could be extended to seismic events as long as the soil deposit has been compacted by previous events, or when the incident waves during post construction earthquakes will not induce cyclic strains with an amplitude and a significative number of cycles larger than those associated with past events.

Cumulative settlements due to cyclic loads can induce parasitic stresses which are especially important for reinforced concrete frames supported on sand. Elastic cyclic displacements are mostly important in producing foundation rocking which induce parasitic bending moments in the first floor joints. The effect of rocking displacements show a rapid decrease for the upper stories.

Creep of concrete tends to move bending moments to values obtained for rigid support. However, the beneficial effects due to this phenomena need a large amount of time to be of practical importance.

When dimensioning for static plus seismic loads on rigid support, good coverage of parasitic effects due to static foundation displacements is obtained. However, reinforced concrete frames supported on soil can be overstressed when subjected to static plus seismic loads. The induced parasitic bending moments will demand an extra amount of ductility which has to be considered into seismic design. For steel frames the additional required ductility due to foundation displacements is meaningless from a practical point of view.

When using foundation beams the parasitic effects from both static and cyclic foundation displacements can be neutralized to a large extend. To accomplish this, flexural rigidity of foundation beams should be equal to 1-2 times that of the reinforced concrete frame beams and at least equal to 10-15 times that of the steel frame beams.

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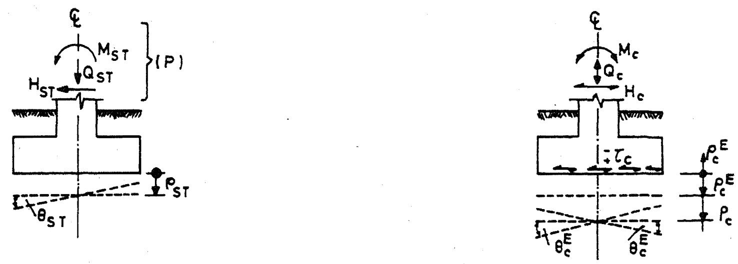
TABLA I

DATA FOR THE FRAME ANALYSIS

Gravel modulus	$E_{ST} = 1500$ kg/cm^2	$E_c = 3\ E_{ST}$
Sand modulus	$E_{ST} = 300$ kg/cm^2	$E_c = 3\ E_{ST}$
Poisson modulus (sand and gravel)	$\nu = 0.30$	
Allowable pressure on gravel	5/7.5 kg/cm^2 (Static/Static + Seismic)	
Allowable pressure on sand	2.5/3.8 kg/cm^2 (Static/Static + Seismic)	
Cyclic displacement coefficient on gravel	$m_c = 1.5$	
Cyclic displacement coefficient on sand	$m_c = 3.5$	
Dead + Live load R.C. Frame (static)	$q = 860$ kg/m^2/story	
Dead + Live load Steel Frame (static)	$q = 570$ kg/m^2/story	
Concrete elastic modulus	$E = 300.000$ kg/cm^2	
Steel elastic modulus	$E = 2.1 \times 10^6$ kg/cm^2	
Poisson modulus (concrete and steel)	$\nu = 0.25$	
Construction velocity	25 days/story	
Live load placement	6 months after end of construction	
Seismic forces	0.10 g at 2/3 height with 30 significative number of cycles	
Creep of concrete	According to the European Concrete Committee, 1973.	



STATIC COMPONENT

ρ_{ST} = STATIC SETTLEMENT (P)

θ_{ST} = STATIC ROTATION (P)

(P) = PERMANENT

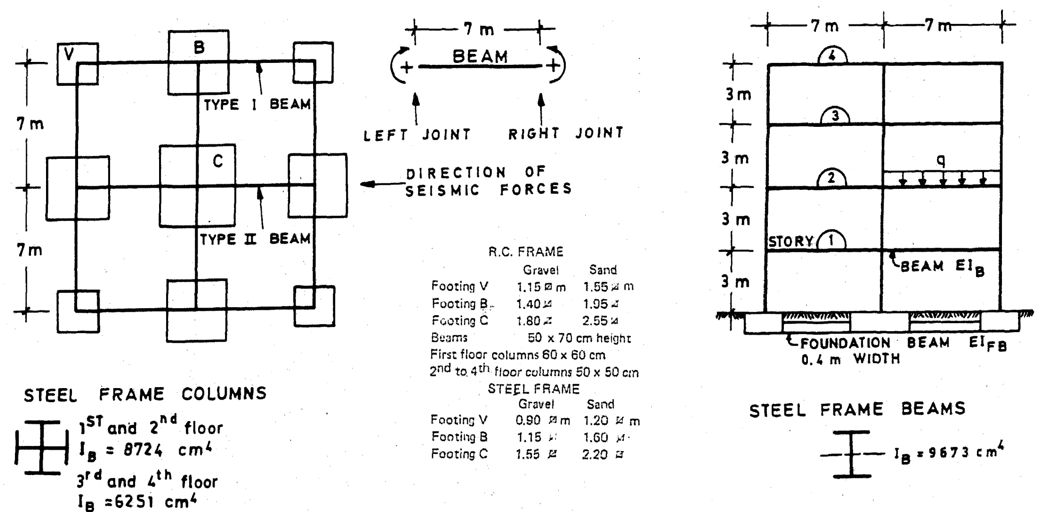
CYCLIC COMPONENT

ρ_c^E = CYCLIC ELASTIC SETTLEMENT

θ_c^E = CYCLIC ELASTIC ROTATION

ρ_c = CUMULATIVE CYCLIC SETTLEMENT (P)

FIG. 1 FOUNDATION DISPLACEMENTS INCLUDED IN THE ANALYSIS



R.C. FRAME

	Gravel	Sand
Footing V	1.15 ⌀ m	1.55 ⌀ m
Footing B	1.40 ⌀	1.95 ⌀
Footing C	1.80 ⌀	2.55 ⌀

Beams 50 x 70 cm height

First floor columns 60 x 60 cm

2nd to 4th floor columns 50 x 50 cm

STEEL FRAME

	Gravel	Sand
Footing V	0.90 ⌀ m	1.20 ⌀ m
Footing B	1.15 ⌀	1.60 ⌀
Footing C	1.55 ⌀	2.20 ⌀

FIG. 2 GEOMETRICAL CHARACTERISTICS OF THE FRAMES

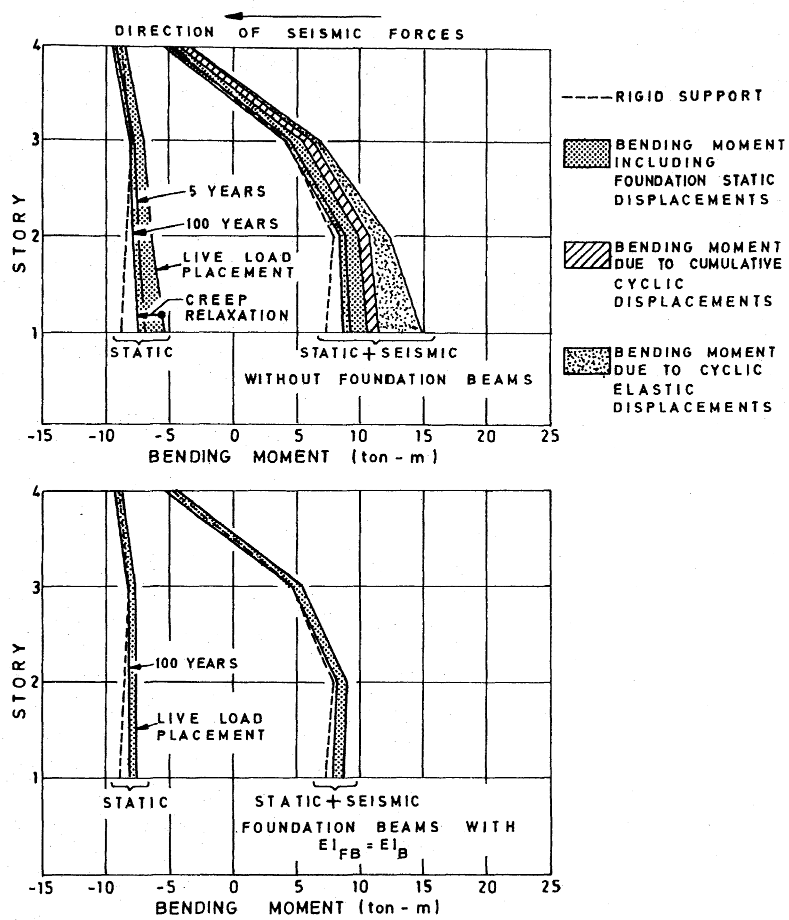


FIG.3A BENDING MOMENTS IN RIGHT JOINT OF TYPE I BEAM - REINFORCED CONCRETE FRAME ON GRAVEL.

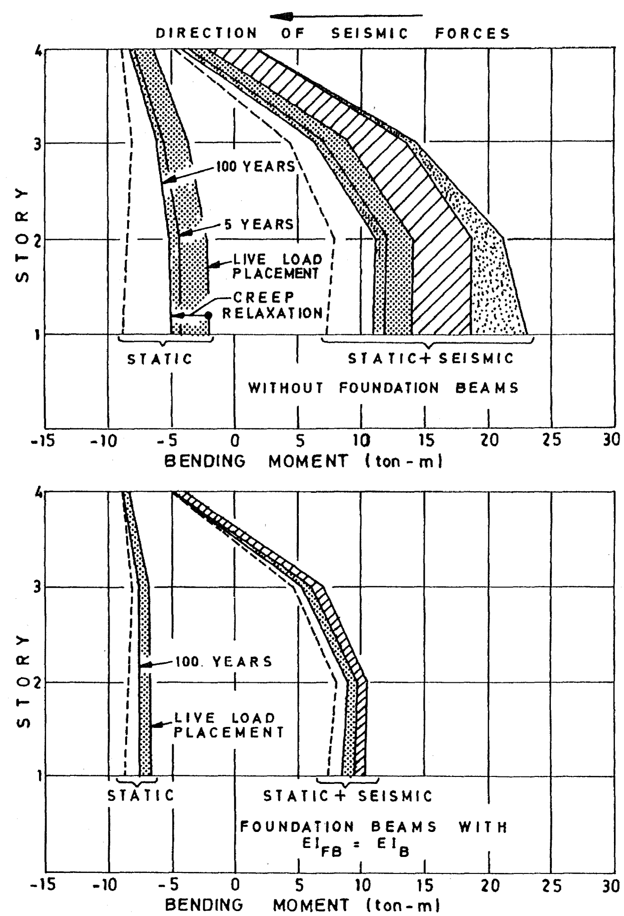


FIG.3B BENDING MOMENTS IN RIGHT JOINT OF TYPE I BEAM - REINFORCED CONCRETE FRAME ON SAND

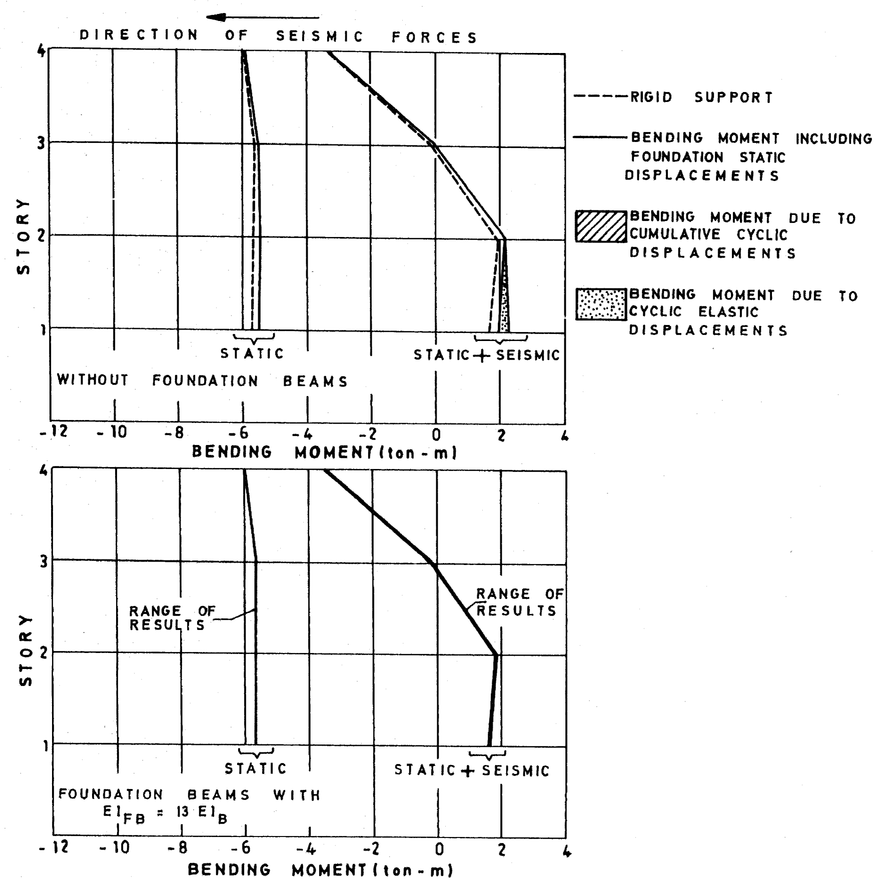


FIG. 4A BENDING MOMENTS IN RIGHT JOINT OF TYPE I BEAM-STEEL FRAME ON GRAVEL.

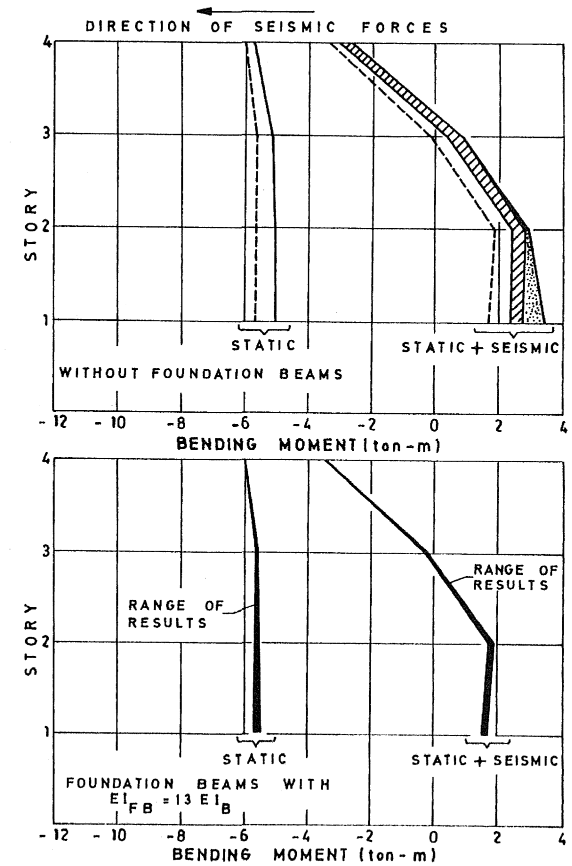


FIG. 4B BENDING MOMENTS IN RIGHT JOINT OF TYPE I BEAM-STEEL FRAME ON SAND.

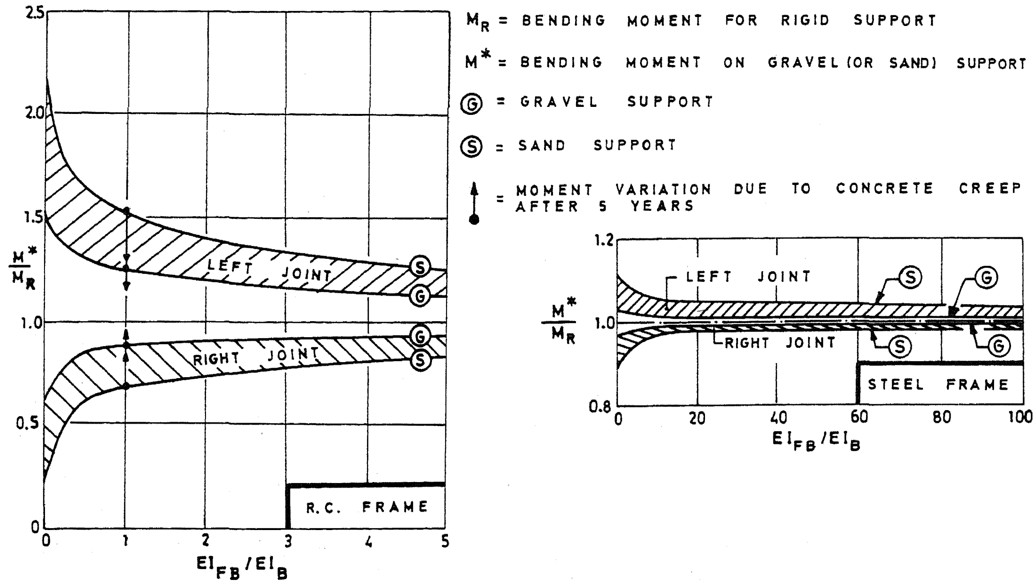


FIG. 5 BENDING MOMENTS DUE TO STATIC LOADS ON THE FIRST FLOOR TYPE I BEAMS