A CRITERION FOR CONSIDERING SOIL-STRUCTURE INTERACTION EFFECTS IN SEISMIC DESIGN OF DUCTILE RC-MRFs ACCORDING TO IRANIAN CODES

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ABSTRACT:

During the last quarter of the 20th century, the importance of dynamic soil-structure interaction for several structures founded on soft soils was well recognized. If not accounted for in analysis, the accuracy in assessing structural safety in the face of earthquakes cannot be accounted for adequately. For this reason, seismic soil-structure interaction analysis has become a major topic in earthquake engineering. As the Iranian Code of Practice for Seismic Resistant Design of Buildings (Standard No. 2800-05) does not address the soil-structure interaction explicitly, the effects of such interaction on behavior of reinforced concrete buildings with ductile moment-resisting frames, loaded and designed according to the Iranian Building Codes, are studied in this research, using direct soil-structure interaction method. To achieve this objective, four types of structures consisting of 3, 5, 7 and 10 story buildings, which represent the typical buildings in a high risk earthquake prone zone, have been selected in conjunction with three types of soil, representing types II, III and IV, as classified in the Iranian Standard No. 2800-05. Ductile Reinforced Concrete Moment-Resisting Frames, as fixed-base structures, once without soil interaction and the next time considering their soil interaction by direct method are modeled and subjected to different earthquake records. The results of the two cases subjected each to different earthquake records are studied and compared. This Comparison led to a criterion indicate that consideration of soil-structure interaction for seismic design, in buildings higher than three stories on soil type IV (Vs<175 m/s) as well as buildings higher than seven stories on soil type III (175<Vs<375 m/s), is essential.

KEYWORDS: Soil-Structure Interaction, Seismic Behavior, Ductile RC-MRF

1. INTRODUCTION

The estimation of earthquake motions at the site of a structure is the most important phase of design as well as retrofit of a structure. In classical method for the Structural analysis, it's assumed that, the motion in the foundation level of equal structure is to ground free field motion. This assumption is correct only for the structures constructed on rock or very stiff soil. For the structures constructed on soft soil, foundation motion is usually different from the free field motion and a rocking component caused by the support flexibility on horizontal motion of foundation is added.

Traditionally, in analysis of the rigid base structures, input motion at the base of the structure is taken as equal to the free field ground motion. In the case of a flexible base structure, in addition to the added rocking component to the horizontal motion of the structure, a part of the structure's vibrating energy will transmit to the soil layer and can be dissipated because of the radiation damping resulted from the wave propagation and Hysteresis damping of the soil materials. However, in classical methods for the rigid base structures, this energy dissipation is not considered [7].

Therefore, soil structure interactions can be summarized as follows; decrease in the natural frequency of the system, increase in damping, increase of the lateral displacements of the structure and change in the base shear depending on the frequency content of the input motion and dynamic specification of soil and structure [11, 17].

The 1985 Mexico City and many recent earthquakes, clearly illustrate the importance of local soil properties on the earthquake response of structures. These earthquakes demonstrated that the rock motions could be amplified at the base of a structure by over a factor of five [15]. Therefore, there is a strong engineering motivation for a site dependent dynamic response analysis for many foundations in order to determine the free-field earthquake motions. The determination of a realistic site-dependent free field surface motion at the base of a structure can be the most important step in the earthquake resistant design of any structure.

2. MODELLING OF INFINITE SOIL MEDIA USING DIRECT METHOD

Modelling of infinite soil media in soil-structure interaction, play a vital role. In the direct method of interaction analysis between soil and structure, the soil is modelled by the Finite Element Method and the boundary conditions are implemented around the soil body. In this method, in addition to considering the geometrical damping, foundation burying and soil strata in horizontal and vertical directions may easily be modelled in the analysis. In this method there is a boundary limit obligation; thus, in order to consider the effect of energy distribution and its simulation, in direction of finite element boundaries, the primary boundaries are considered instead, in this research. These types of boundaries do not absorb energy and for reduction of reflexive wave's effects, the distance between the structure and the boundaries must be increased. Gosh & Wilson (1969) in their research came to the conclusion that if the distance of the structure centre to the soil finite element model boundaries are within 3 to 4 times of the Foundation radius in horizontal direction and 2 to 3 times of the foundation radius in the vertical direction, the effects of the reflexive waves are negligible [12]. It is noteworthy that for such boundaries, modelling is often extended to the top of bed rock in the vertical direction.

Three Dimensional Quadrilateral Elements (Solid Elements) with 4m, width, equal to the distance between frames in plan, have been used for finite element modelling of soil; and bending elements (Frame Elements) have been utilized for modelling the structural elements.

Horizontal distances between soil boundaries and centre of structures have been assumed 45m from each side and vertical distance of soil boundaries have been extended to the bed rock. Bed rock depth has been assumed to be 30m for all considered soil types. Soil boundary limit conditions have also been postulated as zero displacement (Figure 1).

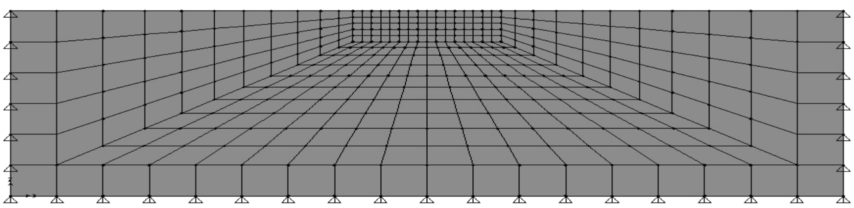


Figure 1 Finite element modeling of soil with primary boundaries

3. GEOTECHNICAL AND STRUCTURAL SPECIFICATION OF THE MODELS

In this research, four structural models, consisting of 3, 5, 7 and 10 story models, representing the conventional types of buildings in a relatively high risk earthquake prone zone and as per specifications mentioned in Table 1, have been selected.

Table 1 Dimensional Specification of the Studied Frames

Reference Name (Code)	Number of Stories	Number of Bays	Story Height (m)	Story Width (m)
S3	3	2	3	4
S5-a	5	2	3	4
S5-b	5	3	3	4
S7	7	3	3	4
S10	10	3	3	4

In the selection of the frames' span width, it has been tried to make this width to be conforming to architectural principles and constructional facts of the conventional buildings in mega cities. The above mentioned frames, as fixed-base structures, have been modelled by SAP2000 software. The models were then loaded vertically (dead and live loads) and laterally (seismic loads) according to the Iranian National Building Code (Part 6) [13] and Iranian Code of Practice for Seismic Resistant Design of Buildings (Standard No. 2800-05) respectively [3]. Seismic analyses of structures for design, been done using dynamic spectral (modal) analysis method according to standard design spectrums of the Iranian Standard No. 2800-05 for each type of soil (i.e. II, III, and IV) separately and implementing response modification factor (behaviour factor) R=10 on Ductile Reinforced Concrete Moment-Resisting Frames (RC-MRF) and Base Acceleration Ratio A=0.35 for a relatively high risk prone. Finally, after seismic analyses, structural sections were designed according to the Iranian Concrete Code (ABA) [6].

Three types of soil representing types II, III and IV according to classification of the Iranian Standard No. 2800-05 [3] have been selected in this research. Since in the frame structures for soils with shear wave velocity less than 600 m/sec the effect of soil-structure interaction is considerable [16], examination is carried out in this research only on those soil types which fall within this boundary. Specifications of the utilized soils are shown in Table 2.

Table 2 Geotechnical Specification of the utilized soils in research

Soil Type	Shear Wave Velocity Vs (m/s)	Elastic Module E (kg/cm^2)	Shear Module G_{max} (kg/cm^2)	ρ ($kg.s^2/m^4$)	Poisson Ratio
II	600	16400	6480	180	0.28
III	320	4945	1808	175	0.39
IV	150	935	335	150	0.40

Characteristics of the used soils have been extracted from the actual geotechnical studies of various projects. Therefore, they have priority over the assumed parameters which may not be completely conforming to reality.

The shear wave velocity mentioned in Table 2, obtained from Down Hole test, which is a low strain in-situ test. This test generates a shear strain of about 10^{-4} percent where obtained shear module is called Gmax. In the event of a great earthquake, the shear strain value would be about 10^{-1} [11]; thus, the shear strain module, called G0 and used for modelling of all types of soils, was extracted from the Idriss and Seed (1970) studies [1]. In addition, the internal soil damping, which is a function of strain amplitude and type of soil for all considered soil types have been extracted from curves represented by Idriss and Seed (1970) [1] and implemented to the models.

4. DYNAMIC ANALYSIS OF SOIL - STRUCTURE INTERACTION

Four different ground acceleration records have been used for dynamic analysis of systems. Table 3 provides some relevant information for the records. In addition, response spectra of these earthquake records are shown in Figur2. The reason behind selecting Abbar, Naghan and Rudbar records is because of high rigidity of soil in these regions which complies with the rigidity of soil type I of the Iranian Standard No. 2800-05 [3].Thus, the recorded accelerations are equivalent to bed rock record.

Table 3 Earthquake ground motions used in analyses

Earthquake	Station	Year	PGA (g)
Abbar	Iran	1990	0.526
El Centro	USA	1940	0.319
Naghan	Iran	1977	0.349
Rudbar	Iran	1991	0.285

Earthquake records have been applied to systems in two different manners. In case of modelling soil and structures together in a direct method (flexible base), the earthquake records have been applied to all combination of soil and structure directly. But in case of modelling the structures as fixed base (without soil), the earthquake records have been separately scaled according to the Iranian Standard No. 2800-05 [3] for each type of soil (i.e. II, III and IV) and implemented to the models.

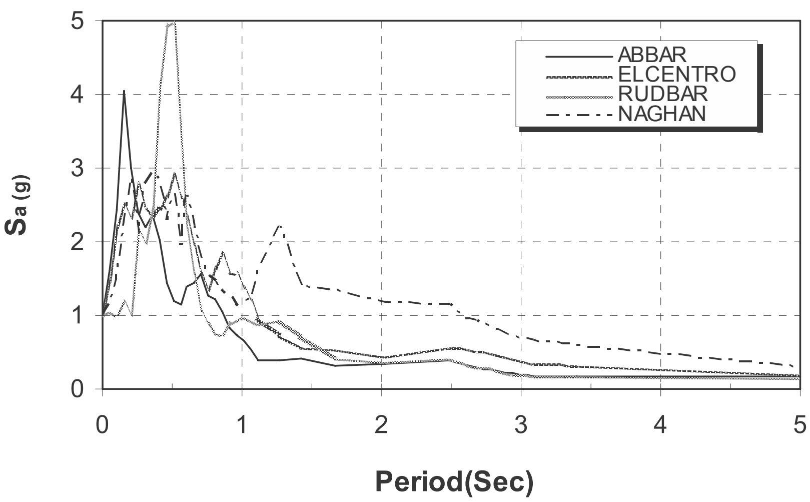


Figure 2 Respond Spectra of used acceleration records

As the objective of this research is to study soil-structure interaction effects on seismic behaviour of ductile reinforced concrete structures, loaded and designed according to the Iranian Building Codes; therefore, considered structural models have been analysed (Time History) under Abbar, El Centro, Naghan and Rudbar ground motion records, for all three considered soil types, separately. The time history analyses are conducted for systems in two different ways: (i) as fixed-base columns on rigid ground (Figure 3); and (ii) by modelling frames together with soil (Figure 4) using direct method of soil-structure interaction analysis which called flexible base.

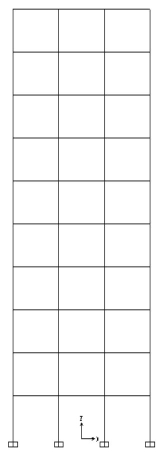


Figure 3 Fixed-base models

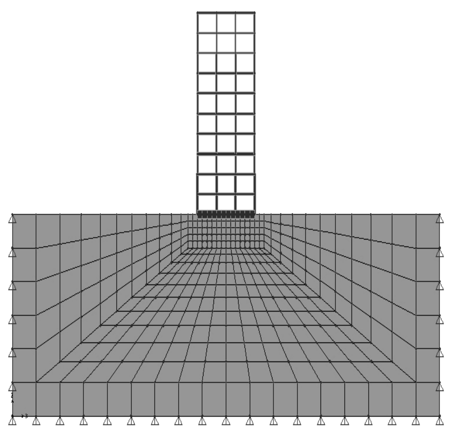


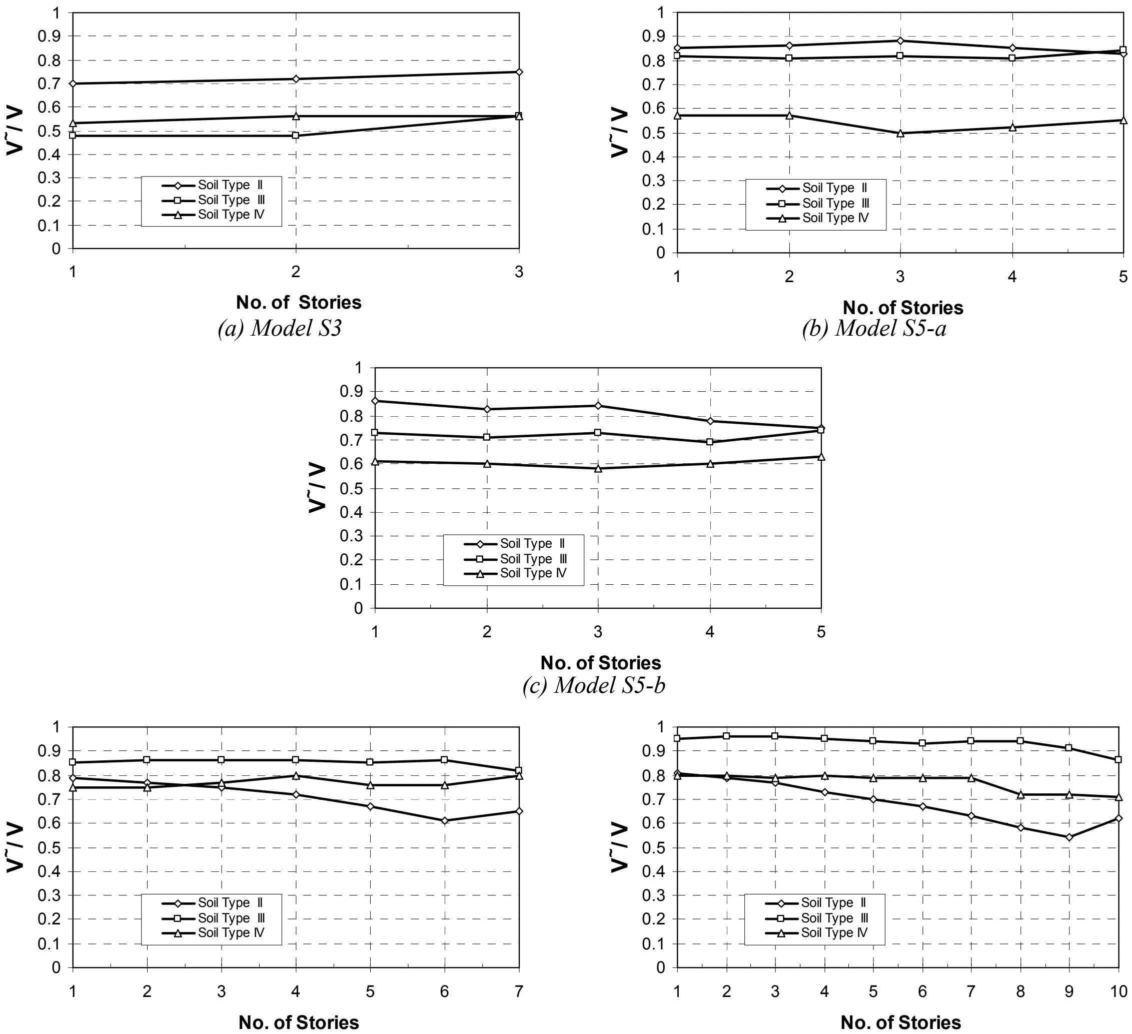
Figure 4 Modeling of frames with soil in direct method (flexible-base)

By comparison of the outputs, obtained from each model under the influence of four accelerograms in two mentioned states it was revealed that since the judgment made on the effect of soil-structure interaction, based on one single accelerogram would not be adequately comprehensive, In order to reach an acceptable and comprehensive criterion for comparison of two states and analysis of soil-structure interaction effect on seismic behaviour of considered models, it is suggested to average ratio of results obtained from models under the influence of four accelerograms of El Centro, Abbar, Naghan and Rudbar earthquakes in two states (fixed-base and flexible base).

For this purpose, in each S3, S5-a, S5-b, S7 and S10 model, been separately modelled on soil types of II, III, IV, once together with soil as flexible base, then considered as fixed base structures, the ratio of story shear, story deflection and story drift in two states been calculated separately for each mentioned earthquake, then, all obtained ratios been averaged.

5. RESULTS AND DISCUSSIONS

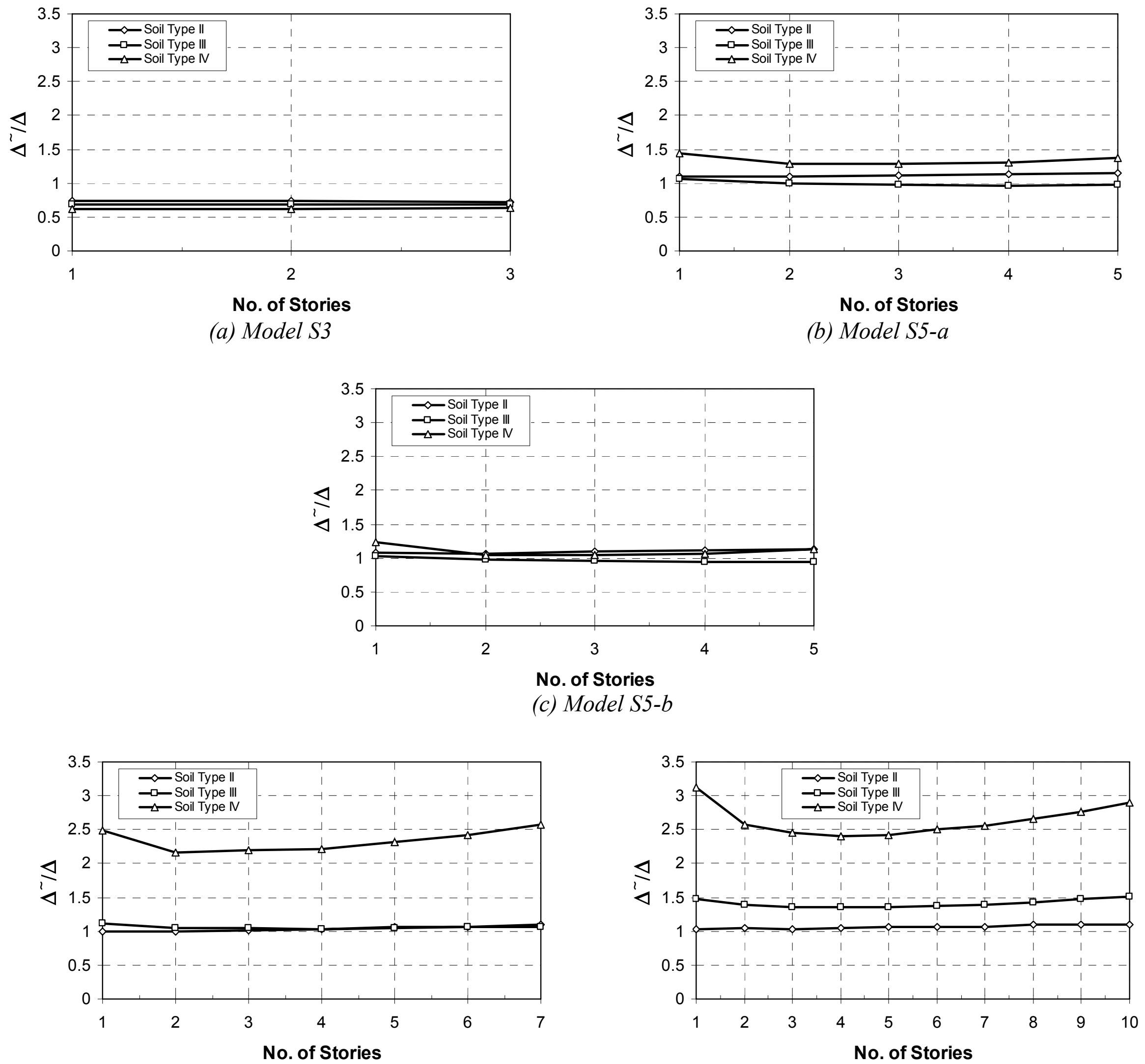
Now it is possible to compare and analyse the effect of soil-structure interaction in each model on soil types II, III, IV comprehensively, by using the average ratio of story shear, story deflection and story drift in flexible base and fixed-base states. These average values have been placed in Figures 5, 6 and 7.
According to the results shown in Figure 5, average ratio of story shear of flexible base to that of fixed-base in all models are less than one, therefore stories shear of structures modelled with soil as flexible base are almost less than the stories shear of structures modelled as fixed base. These results have a good conformity to the NEHRP-1997 regulations [2].



(a) Model S3
(b) Model S5-a
(c) Model S5-b
(d) Model S7
(e) Model S10

Figure 5 Average Ratio of story shear of flexible base to fixed-base on soil types II, III and IV

According to the average ratio of story displacements and drifts shown in Figures 6 and 7, it was also revealed that in soil type II (375<Vs<750 m/s), the story displacement and drift of structures modelled with soil as flexible base, does not differ much from that of structures modelled as fixed base because average ratio is nearby one in all models. However, for 10 story structures founded on soil type III (175<Vs<375 m/s) as it shown in Figure 6-e and Figure 7-e average ratio is more than one; thus, the difference between two cases would be considerable. In 5, 7 and 10 story structures founded on soil type IV (Vs<175 m/s) as it mentioned in Figures 6-b, c, d, e and 7-b, c, d and e, the story displacements and story drifts of flexible base structures are considerably more than that of structures modelled as fixed base. Such a big difference in story displacement and drifts is not negligible; thus, the effect of soil-structure interaction must be taken into account in dynamic analyses. The difference of stories displacement and drift of above mentioned models is due to the fact that vibration period for structures, modelled with soil, is more than that of structures modelled as fixed base [17, 18].



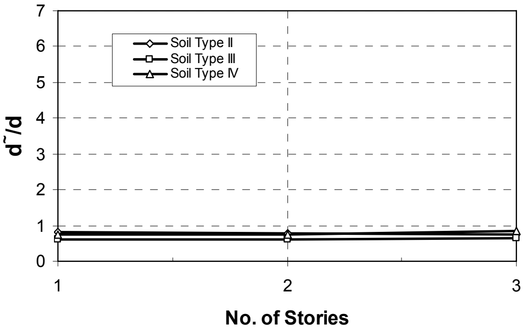
(a) Model S3 *(b) Model S5-a*

(c) Model S5-b

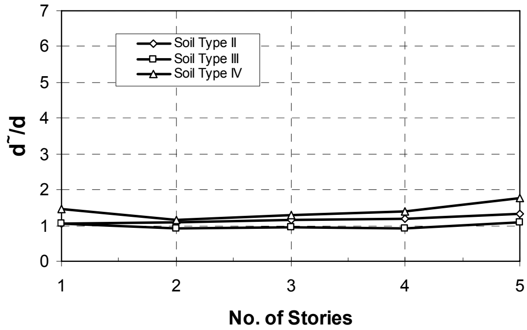
(d) Model S7 *(e) Model S10*

Figure 6 Average Ratio of story deflection of flexible base to fixed-base on soil types II, III and IV

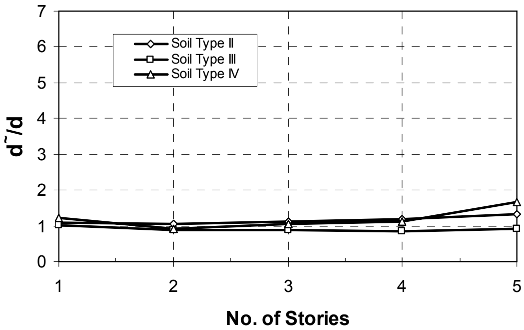
In fact, by decreasing the rigidity of soil, the difference between period of vibrations in two cases (structures modelled on flexible soils and structures modelled as fixed base) will be increased; consequently, the effect of soil-structure interaction for soil types III & IV is considerable while for relatively rigid ground, it is negligible.



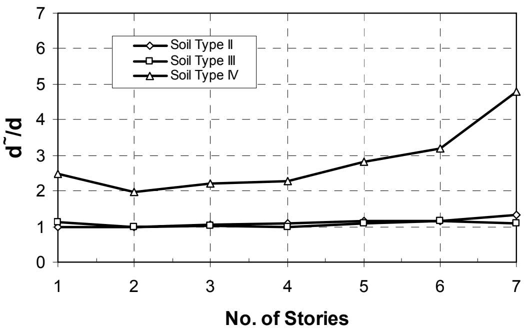
(a) Model S3



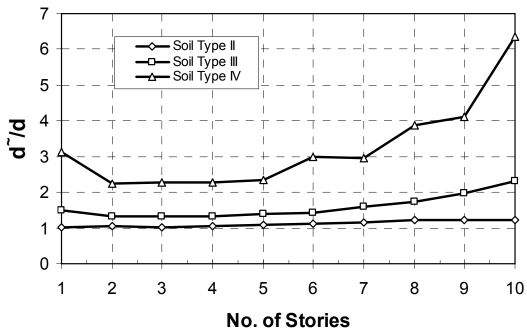
(b) Model S5-a



(c) Model S5-b



(d) Model S7



(e) Model S10

Figure 7 Average Ratio of story drift of flexible base to fixed-base on soil types II, III and IV

Based on Veletsos and Meek studies [16], considering the effect of soil - structure interaction is necessary when the following criterion exists:

$$\frac{V_s}{f \cdot h} < 20 \qquad (5.1)$$

Where *Vs* = Soil shear velocity; *f* = Natural frequency of fixed-base structure; *h* = Total height of structure.
The above criterion covers all lateral forces resisting systems including soft and ductile systems. As the rigidity of a structure against the soil on which it is rested, is the main factor in determining necessity of considering the effect of soil-structure interaction[4, 18], the structures with more lateral ductility or low response modification factor (behaviour factor), can be influenced by the criterion No.1 more extensively in comparison with ductile structures.

To estimate the above criterion, natural frequency of the structure obtained from analytical methods, have been used instead of natural frequency obtained from experimental relations. As using natural frequency of structure obtained from analytical methods, is possible only after analysing the structure, to determine the necessity of considering the effect of soil-structure interaction in seismic design of building frames before analysis, it is suggested to use the natural frequency of structure obtained from the experimental relations. In this case, the structure designer is capable of making decision regarding considering the effect of soil- structure interaction prior to its seismic designing. As a result, to find a specific criterion for determining the consideration of the effect of soil-structure interaction, in seismic design of ductile moment resisting reinforced concrete frames with high response modification factor (behaviour factor), Veletsos and Meek criterion have been calculated for all models and been placed in Table 4.

To increase conformity of this criterion to Iranian Code of Practice for Seismic Resistant Design of Buildings (Standard No. 2800-05) [3],the natural frequency of the structure used in Table4,obtained from the experimental relation for moment resisting reinforced concrete frames which mentioned in this standard. This relation is as following:

$$T = 0.07 \cdot h^{3/4} \tag{5.2}$$

As according to Figures 5-a, 6-a and 7-a neglecting of the effect of soil-structure interaction is reliable in seismic design of 3 story structures on all soil types under the influence of all accelerograms, the calculation of the criterion for determining necessity of considering the effect of soil- structure interaction is applicable for structures of more than 3 story.

Table 4 Calculation of the criterion

Soil Type	Reference Name (Code)	Natural frequency of structure (Hz)	Story Height(m)	$\frac{h}{r}$	$\frac{V_s}{f.h}$
Type II Vs=600 (m/s)	S5-a	1.87	15	1.87	21.39
	S5-b	1.87	15	1.25	21.39
	S7	1.45	21	1.75	19.70
	S10	1.11	30	2.50	18.01
Type III Vs=320 (m/s)	S5-a	1.87	15	1.87	11.40
	S5-b	1.87	15	1.25	11.40
	S7	1.45	21	1.75	10.50
	S10	1.11	30	2.50	9.60
Type IV Vs=150 (m/s)	S5-a	1.87	15	1.87	5.34
	S5-b	1.87	15	1.25	5.34
	S7	1.45	21	1.75	4.92
	S10	1.11	30	2.50	4.50

As it mentioned, in accordance with the results obtained in this research, it is essential to consider the effect of soil-structure interaction for seismic design of ductile reinforced concrete moment resisting frames of more than 7 stories founded on soil type III and more than 3 story buildings founded on soil type IV. By consideration of these structures (Table 4) it was revealed that for all structures in which the necessity of this consideration exists, Veletsos and Meek criterion is less than 10.

The upper limit of this relation could be easily recognized through consideration of model S7 and S10 on soil type III. It is not necessary to consider the effect of soil- structure interaction in model S7 on soil type III with a criterion of 10.5, while, for model S10 with the criterion of 9.6 on the same soil, this consideration is really required.

In conclusion, according to above cases, in ductile reinforced concrete moment resisting frames (studied in this research) of more than 3 stories, considering the effect of soil - structure is essential when the following criterion works out:

$$\frac{V_s}{f \cdot h} < 10 \tag{5.3}$$

6. CONCLUSIONS

The following conclusions may be drawn from the analytical investigation reported in this paper on ductile reinforced concrete frame structures designed based on the Iranian Codes and modelled with and without soil:

- It is not necessary to consider the effect of soil-structure interaction for seismic design of RC-MRF buildings founded on soil type II (375<Vs<750 m/s).
- It is essential to consider the effect of soil-structure interactions for seismic design of RC-MRF buildings higher than 7 stories founded on soil type III (175<Vs<375 m/s).
- It is essential to consider the effect of soil - structure interactions for seismic design of RC-MRF buildings higher than 3 stories founded on soil type IV (Vs<175 m/s).
- On the whole, it is essential to consider the effect of soil-structure interactions for seismic design of RC-MRF buildings when the following criterion exists: $\frac{V_s}{f \cdot h} < 10$

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