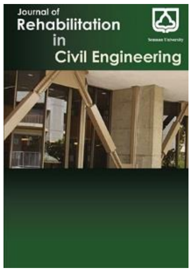
Journal of Rehabilitation in Civil Engineering 10-1 (2022) 101-125

journal homepage: http://civiljournal.semnan.ac.ir/



Investigation of Adequacy of Adjacent Building Seismic Joints in Tehran City Corresponding to Seismic Hazard Analysis, Site Effects and Nonlinear Dynamic Analysis

Hamid Saffari[1*], Mohammad Hossein Pouladvand[2]

1. Department of Structure & Earthquake Engineering, Faculty of Civil Engineering, Shahid Beheshti University, Tehran, 16589-53571, Iran.
2. Faculty of Civil Engineering, Shahid Beheshti University, Tehran, 16589-53571, Iran.
Corresponding author: hsaffari@sbu.ac.ir

ARTICLE INFO

Article history:
Received: 15 May 2020
Revised: 30 September 2020
Accepted: 17 January 2021

Keywords:
Seismic pounding;
Adjacent buildings;
Seismic joint;
Seismic microzonation;
Dynamic nonlinear analysis;
Deterministic seismic hazard analysis;
Site amplifications.

ABSTRACT

The topic of pounding of adjacent structures has greatly attracted the attention of researchers in recent years. Among the observed damages due to the earthquake, one could refer to those damages induced by pounding of the adjacent structures which is a prevalent phenomenon. The reason for this issue is the lack of separation joint or its inadequacy between two adjacent buildings. When an earthquake occurs, difference in the structures' frequencies would result in difference in their reaction relative to the ground acceleration and pounding would take place. In this article the effects of site soil type, structure type, its height and distance from the fault on the separation joint for the steel and reinforced concrete moment resisting buildings with 3, 5, 8 and 12 stories are investigated. The structural models are first designed by structural design software and then are analyzed under various time histories using Seismostruct software. The obtained results show that the highest hazard risks corresponding to collision between the adjacent buildings belong to areas near the faults located on soft soil types and collision of two buildings with different types is the most severe collision. Different conditions have been discussed in this paper and based on the results, some editions to criteria of seismic design code of Iran has been proposed considering to distance to active faults, soil conditions and type of structure.

How to cite this article:
Saffari, H., Pouladvand, M. (2022). Investigation of Adequacy of Adjacent Building Seismic Joints in Tehran City Corresponding to Seismic Hazard Analysis, Site Effects and Nonlinear Dynamic Analysis. Journal of Rehabilitation in Civil Engineering, 10(1), 101-125.
https://doi.org/10.22075/JRCE.2021.20421.1416

1. Introduction

When an earthquake occurs, the lateral and dynamic loads are exerted on the adjacent structures and a different behavior of structures is observed during the vibrations (Fig.1). In case the adjacent structures have different dynamic characteristics, they would not have similar lateral deformations. This dynamic property is different from the difference in plan, height, type, age of structure, type of lateral force resisting system, the code used in the design and even different soil conditions at the site etc. Difference in the seismic behavior of adjacent buildings increases the pounding probability between structures and occurrence of various structural and non-structural damages. To prevent pounding between structures during vibration, various codes have proposed different distances in proportion to the structure height under the name of separation or seismic joint per each structure. In most of these codes the nonlinear displacement of the building at each story is used for determination of the distance between two adjacent buildings. In spite of observing provisions of these codes, the previous earthquakes like Mexico City Earthquake (1985), Loma Prieta Earthquake (1989) and other examples have proven that contrary to the opinion of the researchers, there have been cases of pounding between adjacent structures. This issue showed that there is need for more complete research on pounding between adjacent buildings.

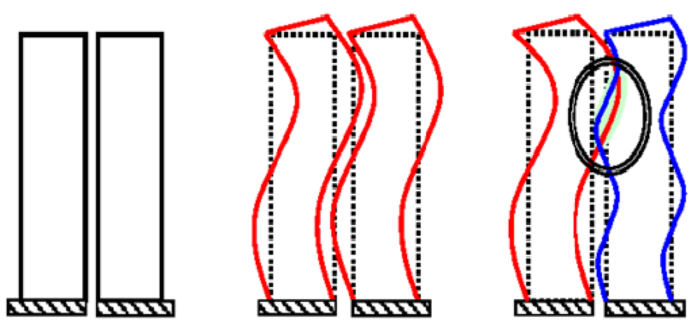


Fig. 1. Different behavior of structures during the vibration periods [1].

Development of the numerical methods and tools for nonlinear analysis of structures, also numerical simulation of pounding between structures and calculation of the separation joint have increasingly come under focus of attention of researchers. Anagnostopouls [2] in 1988 used three idealized structures implementing a multi-degree of freedom system with lumped mass in his research. Westermo [3] in 1989 linked the adjacent buildings with a beam to reduce the pounding effect and equalizing the two buildings responses. Weng et al. [4] in 2001 investigated the seismic pounding of adjacent buildings. They assumed that the dynamic response of a building could be appropriately expressed using a system of structures with lumped masses and excitation could be assumed as a Gaussian zero-mean non-stationary random process.

Garcia [5] in 2005 investigated the necessary separation joint between two adjacent buildings assuming elastic and inelastic behavior using the absolute sum (ABS), square root of the sum of the squares (SRSS), and double difference combination (DDC) rules. Also shaking table test was implemented for simulation of the separation joint between two structures. Dogan and Gunaydin [6] in 2009 numerically simulated the effect of distance between adjacent structures on the tangential force between them. Suma Devi et al. [7] in 2015, investigated the pounding effect of adjacent concrete buildings with fixed-base and base-isolated foundation types.

When the frequencies of the adjacent buildings come close to that of the soil in that area, the risk of pounding hazard of adjacent buildings increases [4]. On the other hand where the height of two adjacent structures are not equal and the shorter building has greater stiffness and mass with respect to the taller building, the body force causes a behavior similar to the whiplash force in the higher building and this issue results in increased lateral displacement and ductility [2].

2. Methodology

In this research attempt is made to perform a comprehensive study on the pounding hazard in the urban areas of metropolitan city of Tehran which have been presented in the Fig. 1. Hence in each part of the analysis maximum care is exercised. For example instead of referring to Iran's standard seismic spectra, deterministic seismic hazard analysis (DSHA) is performed for Tehran city regarding the seismic resources around it. As parts of Tehran are located on the faults, the damping relations that account for the geometry of the faults were incorporated. These relations had the capability of presenting seismic indices on or near the intended fault. To reduce the amount of error a number of attenuation relations were used and averaging was performed with appropriate weighing. Finally acceleration spectra were generated for sites with different soil types and various distance-to-fault values. In continuation, for each site three artificial accelerograms were generated with respect to the generated spectrum and were scaled to the PGA corresponding to that site. Different structures were modeled as explained below and were subjected to the three records generated for each site. Then the maximum outputs of the structure seismic analysis were extracted.

In this research modeling of the adjacent buildings was performed for soil types 1, 2 and 3, with distances of 0, 10, 20 km from the faults of Tehran city scenario under various records. In this respect first the structures were optimally designed based on the seismic input. Next utilizing the finite element software SeismoStruct 2016, they were subjected to the nonlinear time history analyses. The seismic analyses were performed for different patterns and conditions (in terms of type, height, geographical situation and the site soil type). It is recommended to conservatively modify the corresponding relations regarding all the properties and conditions to prevent pounding of adjacent buildings in the city of Tehran.

3. Tehran city faults scenario

Taking advantage from the earthquake scenario is very beneficial for planning and management of earthquake crisis in a city. In this respect, a deterministic seismic hazard analysis was done using the scenario faults of Tehran. It is predicted that the earthquake that might impact Tehran area would occur due to the fault activity with a high potential near the close to the city. The extent of area which has experienced severe damage would be limited in comparison to the case caused by large earthquakes of inter-plate subduction type. Tehran area is so large that some portions of it may experience sever damages but other portions of it may not experience much damage. It is very essential that studies and planning be arranged in proportion to such situation, thus various scenarios have been considered for the greater Tehran area. Among the most important of them one could refer to North Tehran Fault with an approximate length of 58 km and seismogenic capability of 7.2 Richter scale, Ray Fault with an approximate length of 29 km and seismogenic capability of 6.7 Richter scale. Finally Mosha Fault with an approximate length of 75 km and seismogenic capability of 7.4 Richter scale [8]. In Fig.2 the situation of Tehran active faults are shown with respect to each other.

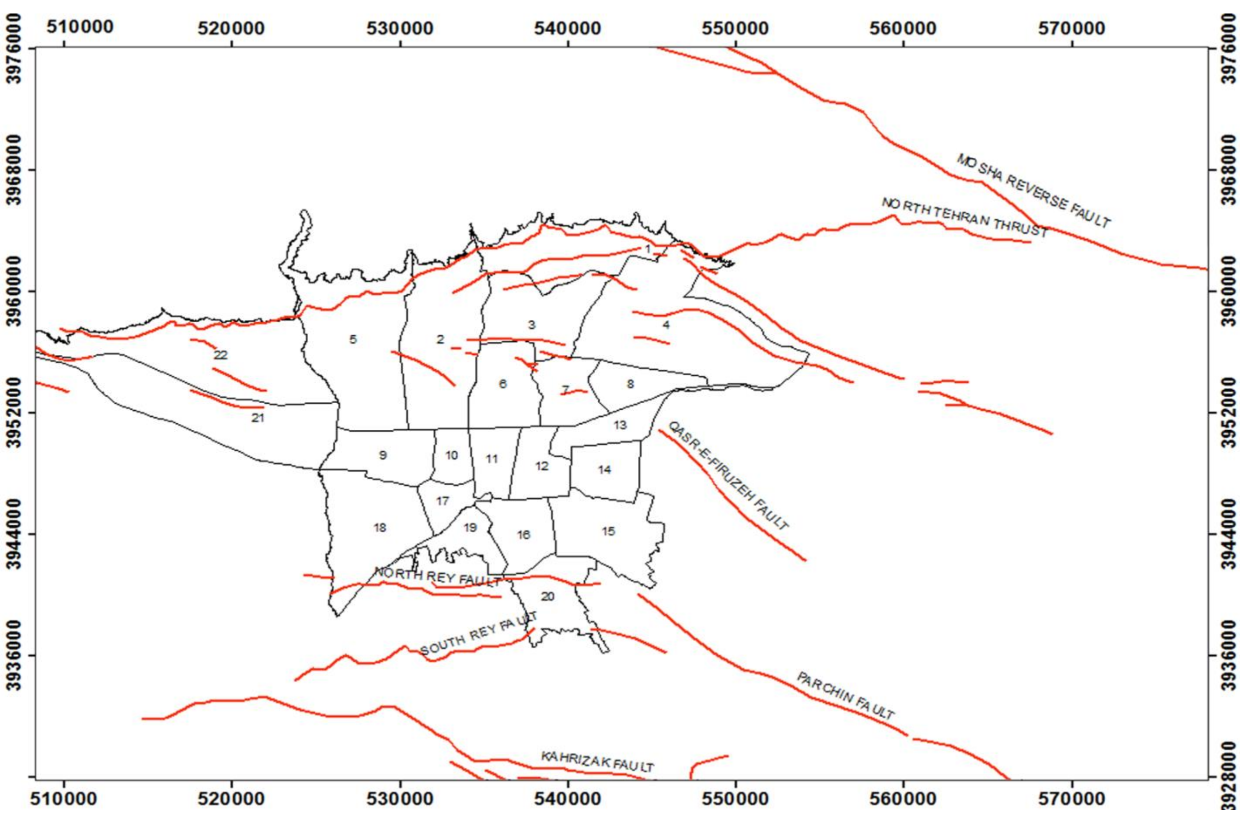


Fig. 2. Active faults around Tehran City [9] with study area.

4. Tehran soil classification based on the shear wave velocity

For Tehran soil classification, the studies performed by Japan International Cooperation Agency (JICA) were consulted [11]. According to this study, Tehran soils are classified into four groups of clayey, sandy, sandy-clayey and gravelly soils. Also each group of these soils is divided into four groups based on the standard penetration test (SPT) number (N). Ultimately regarding the depth of seismic bed rock and the overlying soil conditions, the soils of Tehran area are categorized in 41 classes according to Fig. 3.

The geotechnical characteristics of constituent materials of a site would have a major effect on the ground motion properties. Previous earthquakes have shown that damages to structures constructed on soft soils were much severe than damages to structures built on stiff soils. Studies on the strong ground motion clearly exhibit change in the amplitude and frequency content of the seismic waves due to alluvium. In this respect the shear wave velocity (Vs) of materials is an important parameter in analysis of the site effects. Hence to calculate magnification due to the soil effects on the seismic index (like PGA), it is essential to perform zoning of the mean shear wave velocity at the surface layers (upper 30 m).

As formulated and integrated relations were not available to calculate the shear wave velocity for greater Tehran area using the standard penetration test (SPT) number, use was made of two research works performed in Tehran City area. One of these studies is the one performed by International Institute of Earthquake Engineering and Seismology in 2003 on Tehran alluviums [12]. The other one is the study done by cooperation of Soil Conservation and Watershed Management Institute of Jihade-agricultural ministry and Tarbiat Modares University in 2003 for central Tehran area [13]. Therefore to calculate the shear wave velocity in gravel and sand the relation proposed by Tarbiat Modares University, and for the clayey soil the relation proposed by Earthquake Institute was implemented. In case the clayey and sandy soils were mixed the average of Earthquake Institute relation for the clayey soil and TarbiatModares University relation for the sandy soil is calculated. It should be noted that the shear wave velocity is increased from the non-cohesive soil to that of the cohesive soil, which is compatible with the presented data. In these relations the N value is taken equivalent to 30 cm penetration or N_{eq} in the calculations and Vs is the shear wave velocity.

Clay: $$V_{s1} = 27N^{0.73} \quad (1)$$
Sand: $$V_{s2} = 97.6N^{0.25} \quad (2)$$
Gravel: $$V_{s3} = 108.5N^{0.22} \quad (3)$$
clay-sand: $$V_{s4} = \frac{V_{s1} + V_{s2}}{2} \quad (4)$$

After calculation of the shear wave velocity at each layer using the above relation, utilizing the mean shear wave velocity (V_s) in Standard 2800 [14] (equation (5)), the mean velocity at the first 30 m of the surface layer is obtained. In continuation Tehran soil is categorized into types I, II and III regarding the calculated velocities. According to the soil classification presented in Iranian Standard 2800 (fourth version) also the calculated shear velocities, no region of Tehran belongs to the class of very soft soil (Type IV in the code).

$$V_s = \frac{\Sigma \mathrm{d_i}}{\Sigma(\frac{\mathrm{d_i}}{\mathrm{V_{si}}})} \quad (5)$$

Where di and Vsi are the thickness and shear wave velocity in each layer respectively.

The proposed relation By JICA institute (expression (6)) is given here. This relation is a general one given for all soil types and does not differentiate between soil types. Also it yields higher values of shear wave velocity compared to the more precise studies on Iran’s soils. Hence it is not used for greater Tehran area and the mean shear wave velocity was calculated from the sum of studies which consider a wide range of Iran’s soils.

$$V_s = 161N_{eq}^{0.277} \quad (\mathrm{Neq}<200) \quad (6)$$

In this article to calculate the ground motion parameters the precise value of the mean shear wave velocity of each mesh (totally 41 soil types and consequently 41 mean shear wave velocities) is used in seismic hazard calculations (see Table 1). Meshes are defined as squares with 500 m of each side.

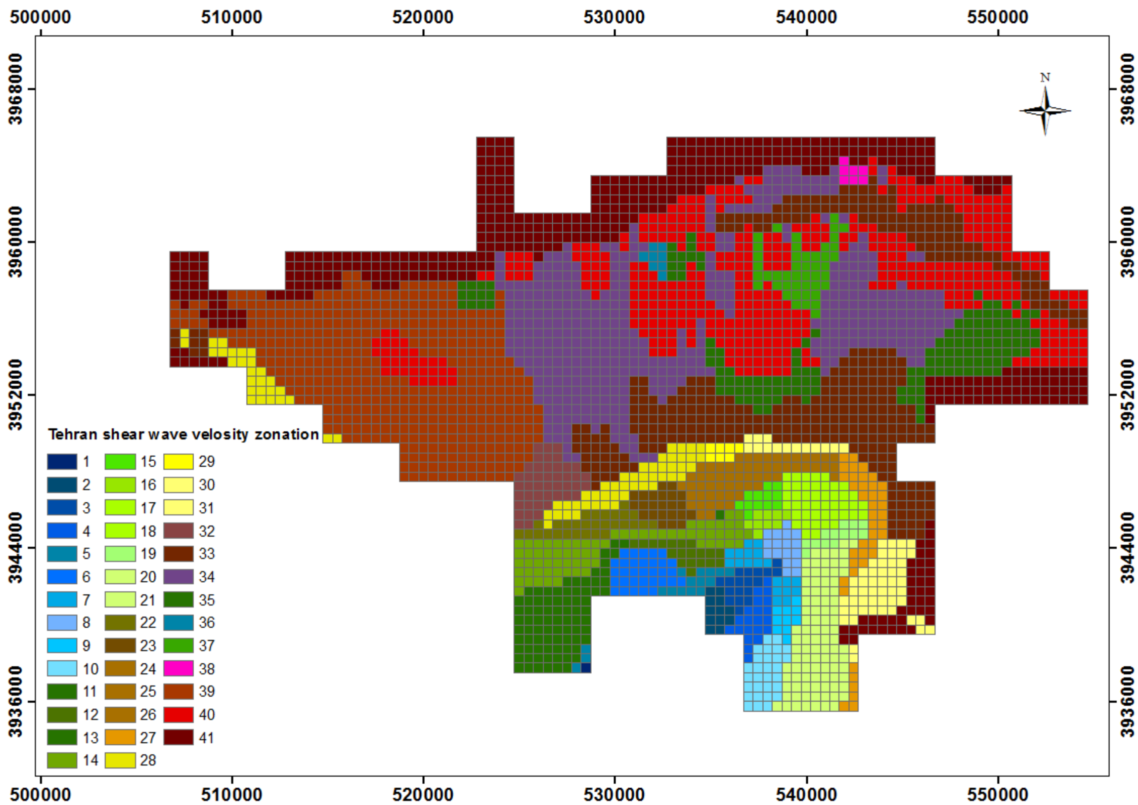


Fig. 3. Soil type classification of Tehran City (Based on the JICA study).

Table 1. Average shear wave velocity of first 30 meters of representative soil profiles of Tehran area.

Type	V_{ave}(m/s)	Type	V_{ave}(m/s)	Type	V_{ave}(m/s)	Type	V_{ave}(m/s)
1	194.94	12	361.85	23	361.85	34	427.31
2	281.51	13	361.85	24	299.62	35	435.06
3	193.99	14	361.85	25	254.14	36	607.33
4	281.51	15	280.51	26	315.02	37	320.25
5	194.94	16	361.85	27	269.61	38	515.60
6	361.85	17	229.03	28	306.62	39	572.72
7	281.51	18	206.17	29	289.09	40	1000.00
8	281.51	19	631.19	30	326.15	41	1000.00
9	317.84	20	505.72	31	283.40		
10	254.14	21	389.97	32	317.33		
11	505.72	22	194.94	33	340.79		

5. Generation of artificial accelerograms

As Tehran City lacks rich registered earthquake records, attempt was made to prepare the artificial accelerograms by implementing the damping relations and in proportion to the distance from the surrounding faults, geometry, faulting mechanism, and soil type. These accelerograms should be generated in a way that they contain the seismologic characteristics of desired area. Also they should be appropriate for analysis and design of structures. In this research the artificial accelerograms were generated using the site specific spectra prepared based on the deterministic hazard analysis of greater Tehran area and utilizing the PGA zoning. The process of generating artificial accelerograms is given in Fig.4.

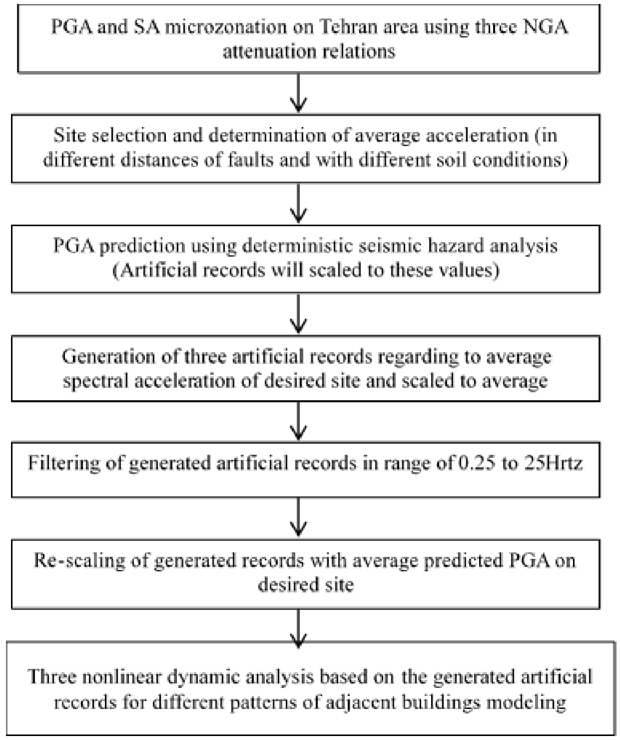


Fig 4. Artificial accelerogram simulation process.

Three NGA attenuation relations used for seismic hazard are: Campbell-Bozorgnia [15], Boore-Atkinson[16] and Chiou-Young [17] as they have better compatibility with Iran seismic database[18]. The results show that at short periods, the acceleration spectrum value obtained from Campbell-Bozorgnia relation (2008) is superior to that of Boore-Atkinson. In another research by Saffari et al. [19] while presenting the attenuation relation based on Iran's records and comparing various NGA relations with it, they demonstrated that at periods of 0.1-1 seconds, Campbell-Bozorgnia relation (2008) is more compatible with Iran's data both for near-fault and far-fault earthquakes especially in the seismic zone of central Iran. For this reason when using the above relations, as Campbell relation was more compatible with Iran's data, its weighting coefficient was taken 0.5. Also the weighing coefficients of Boore-Atkinson and Chiou-Young were taken 0.3 and 0.2, respectively.

The characteristics of generated artificial records are given in Tables 2, 3 and 4 with respect to the distance pattern, Target PGA, scale and soil condition in accordance with the introduced structure in Fig.4.

Table 2. Characteristics of generated artificial records on soil type I.

Record	Mw	R(km)	Soil Type	PGA(g)	Duration(s)
0_1	7.2	0	I	0.66	30
0_2	7.2	0	I	0.60	30
0_3	7.2	0	I	0.62	30
10_1	7.2	10	I	0.30	30
10_2	7.2	10	I	0.31	30
10_3	7.2	10	I	0.28	30
20_1	7.2	20	I	0.19	40
20_2	7.2	20	I	0.16	40
20_3	7.2	20	I	0.16	40

Table 3. Characteristics of generated artificial records on soil type II.

Record	Mw	R(km)	Soil Type	PGA(g)	Duration(s)
0_1	7.2	0	II	0.83	30
0_2	7.2	0	II	0.78	30
0_3	7.2	0	II	0.74	30
10_1	7.2	10	II	0.33	30
10_2	7.2	10	II	0.38	30
10_3	7.2	10	II	0.32	30
20_1	7.2	20	II	0.23	40
20_2	7.2	20	II	0.22	40
20_3	7.2	20	II	0.21	40

Table 4. Characteristics of generated artificial records on soil type III.

Record(ID)	Mw	R(km)	Soil Type	PGA(g)	Duration(s)
0_1	7.2	0	III	1.00	35
0_2	7.2	0	III	1.03	35
0_3	7.2	0	III	1.00	35
10_1	7.2	10	III	0.47	35
10_2	7.2	10	III	0.47	35
10_3	7.2	10	III	0.46	35
20_1	7.2	20	III	0.29	45
20_2	7.2	20	III	0.28	45
20_3	7.2	20	III	0.27	45

Regarding the variety and extension of the structural models, bed soil type and structure distance from the fault, the analyses were limited to a number of cases as follows:

From the distance point of view: three distinct distances of 0, 10 and 20 km were considered.

From the view point of site soil type: Three soil types I, II and III.

Note: Soil type IV does not exist in Tehran.

From the point of view of structure type: Steel and concrete structures.

Note: As masonry buildings are limited maximum to two stories and have small displacements, and wooden buildings are rarely used in Tehran, they have not been considered.

From the view point of resisting the lateral force: moment resisting structure.

Note: According to the performed studies [7] on buildings with shear system, the maximum displacement value where use has been made of bracings, is reduced by 15-25% and where use has been made of the shear wall, is reduced by 35-40%. In this research regarding the small lateral displacement of the shear systems, their pounding analysis is omitted.

Out studies shows that the structures with shear wall system, steel bracing and/or combined moment resisting-shear resisting system, have much smaller displacements with respect to those with moment resisting systems and when the provision of Code 2800 was observed they had not any collision.

For each soil type and distance three artificial accelerograms were prepared and maximum response of the building is extracted by implementing the time history analysis.

For example from the seismic hazard analysis output, the generated artificial records for a distance of zero km from the North Tehran fault and also soil types I, II and III are given in Figs. 5-7.

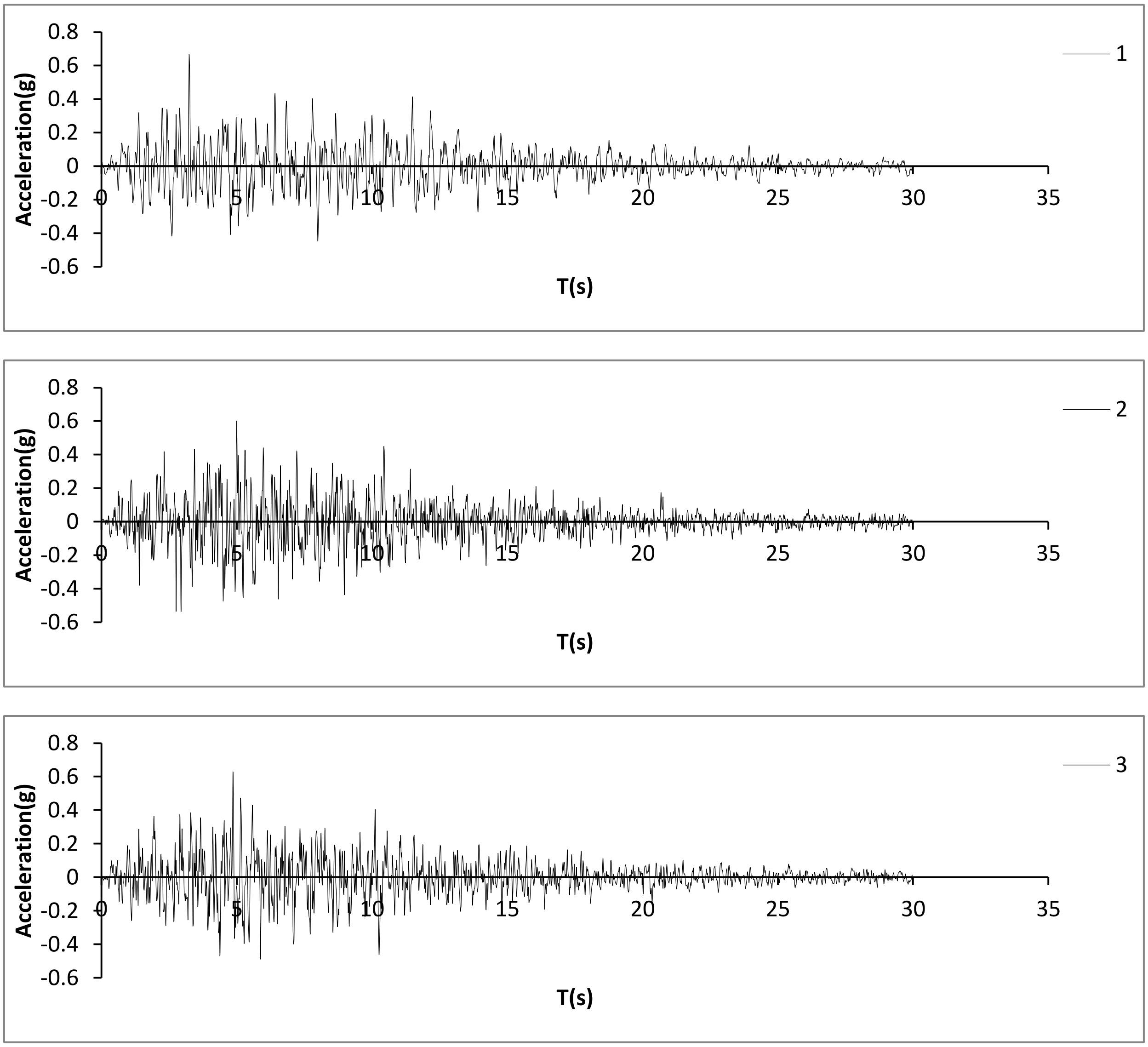


Figure 5: Generated artificial records for North Tehran fault and also soil type I

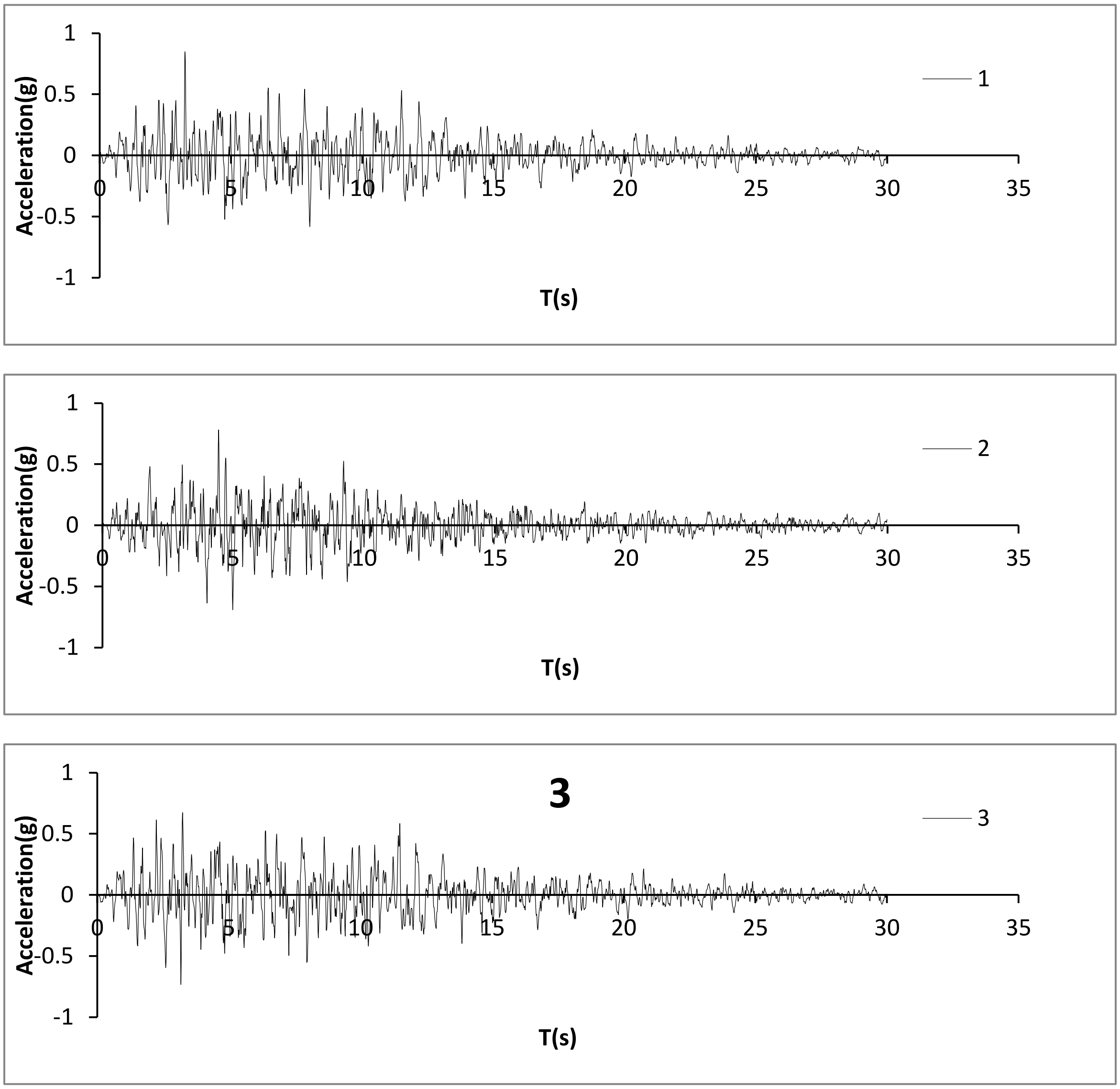
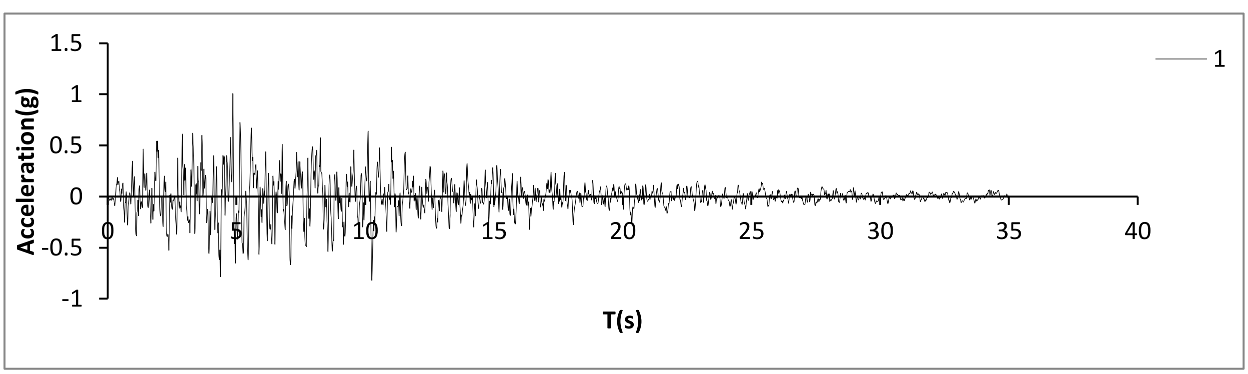
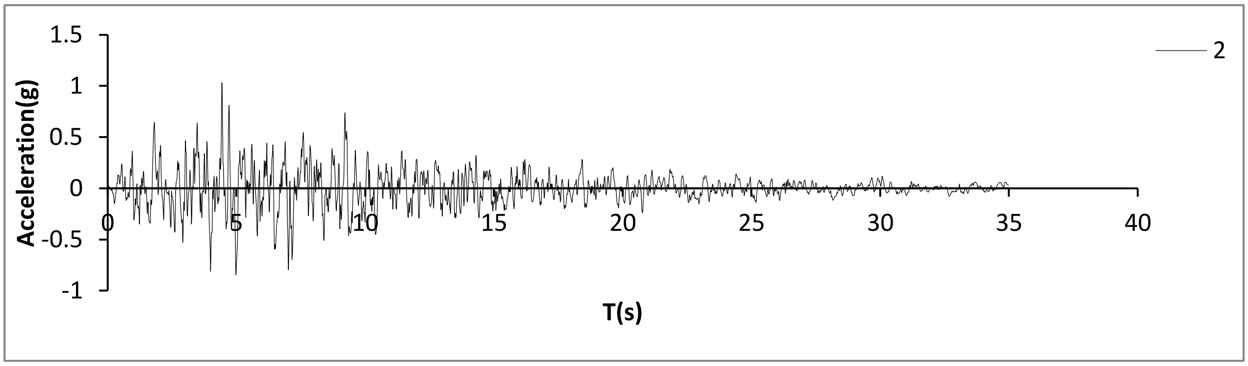


Fig. 6. Generated artificial records for North Tehran fault and also soil type II.





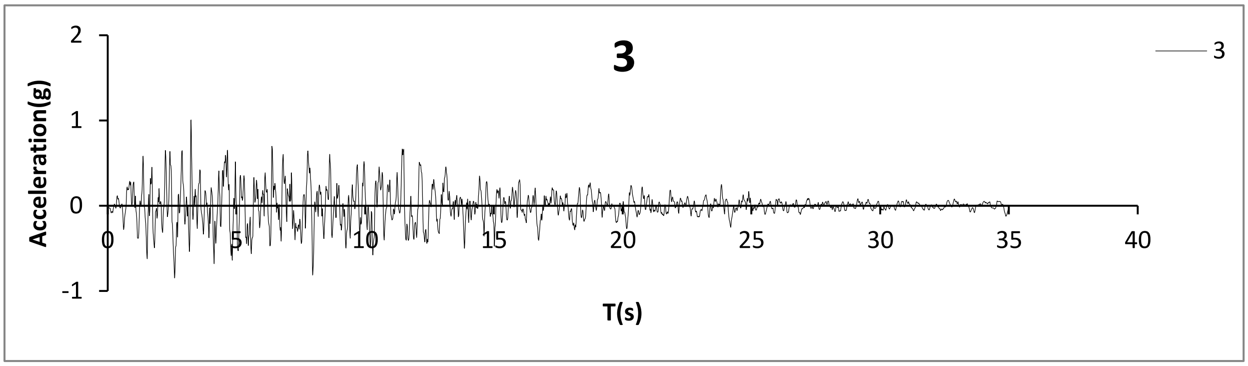


Fig. 7. Generated artificial records for North Tehran fault and also soil type III.

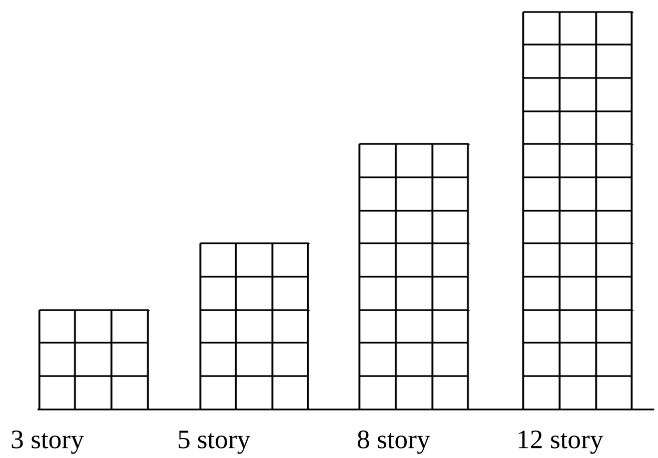


Fig. 8. Model of buildings used for the analysis.

The assumed plan is according to the plan of existing buildings in Tehran City. The plan is selected as symmetric to neglect the effects of torsion in analysis and design. The dead and live loads are assumed to be linear with values of 3100 and 1000 kg/m which are applied over the beam length. The models are optimally designed according to provisions of Ninth [20] and Tenth [21] Topics of Iran's national building regulations and Iran's Standard 2800 (Ver. 4). Then the models were subjected to time history analysis using ETABS 2015 and SeismoStruct 2016 software. The separation distance assumed for these models is equal to that given in Standard 2800 and their pounding is analyzed and assessed. The steel profile and concrete material properties used in the models are as Table 5 & 6:

Table 5: Steel profile properties used in the steel buildings.

Yield strength of the steel profile	2400 kg/cm^2
Ultimate strength	3700 kg/cm^2
Modulus of elasticity	2.1 x10^6 kg/cm^2

Table 6: Concrete material properties

Concrete density	2500 kg/m^3
Compressive strength	250 kg/cm^2
Yield stress of the longitudinal rebar	4000 kg/cm^2

Yield stress of the transverse rebar: 3000 kg/cm^2

6,1. Specifications of steel sections

The sections used in steel buildings are a combination of standard HEB and IPE sections, as well as boxes and plate girder, which in the design have tried to use the most optimal sections with different controls. The sections used in different floors of each building are as follows:

Three-story building: The ground floor columns are in the form of HEB200, which are gradually reduced to HEB160 on the third floor. The beam sections are also a combination of plate girder and IPE, which degrade from the first floor to the last floor.

Five-story building: The ground floor columns are from HEB220, which are gradually reduced to HEB160 on the fifth floor. The beam sections are also a combination of plate girder and IPE, which are reduced from the first floor to the last floor.

Eight-story building: The ground floor columns are in the form of BOX300x300x10, which are gradually reduced to BOX150x150x120 on the eighth floor. The beam sections are also a combination of plate girder and IPE, which are reduced from the first floor to the last floor.
Twelve-story building: The ground floor columns are from BOX300x300x200, which are gradually reduced to BOX200x200x100 on the eighth floor. The beam sections are also a combination of plate girder and IPE, which are reduced from the first floor to the last floor.

Explanation: The sections of the plate girder are as follows:

The wings thickness's are from 10 to 14 mm, the widths differ from 150 to 240 mm, the heights are from 180 to 290 mm, and the thickness of the webs is from 8 to 12 mm.

6,2, Specifications of concrete sections

The specifications of the sections used in the first floor of reinforced concrete buildings are as follows:

Table 7. Specifications of concrete sections in Floor 1.

	3 Floors		5 Floors		8 Floors		12 Floors	
	Beam	Column	Beam	Column	Beam	Column	Beam	Column
Floor 1	B35x35	C40x40	B35x35	C40x40	B40x40	C50x50	B40x45	C60x60

The sections used in different floors are as follows:

Three-story building: The column cross section on the first floor is C40x40 and gradually decreases to C35x35 on the upper floors. The cross section of the beams in all floors is B35x35.

Five-story building: The column cross section on the first floor is C40x40 and gradually decreases to C35x35 on the upper floors. The cross section of the beams in all floors is B35x35.

Eight-story building: The column cross section on the first floor is C50x50 and gradually decreases to C40x40 on the upper floors. The cross section of the beams in lower floor is B40x40 which gradually decreases to B35x35 on the upper floors.

Twelve-story building: The column cross section on the first floor is C60x60 and gradually decreases to C40x40 on the upper floors. The cross section of the beams in lower floor is B40x45 which gradually decreases to B30x30 on the upper floors.

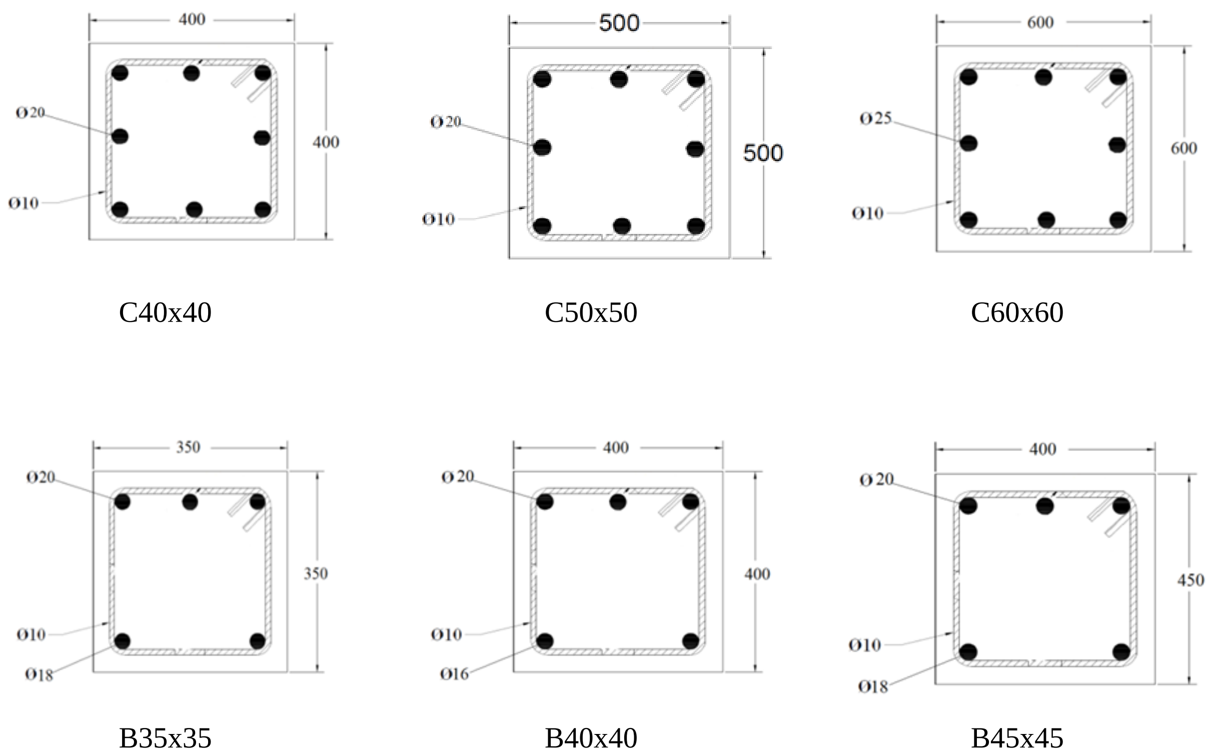


Fig. 9. Section properties of Columns & Beams. Dimensions are in millimeter.

7. Standard provisions of separation joint

ASCE_SEI_7_16 Code [22] considers separation between two buildings equal to the maximum nonlinear displacement (δ_M).δ_M at the critical position is calculated by taking into account the translational-torsional displacement together with amplified torsion by one of the two following methods:

$$\delta_M = \frac{C_d \delta_{max}}{I_e} \quad (7)$$

Where:

δ_{max} =maximum linear displacement at the critical position

c_d=displacement amplification factor

I_e=importance factor of building

The adjacent buildings should have a minimum distance of δ_{MT} with respect to each other where its formula is as follows:

$$\delta_{MT} = \sqrt{(\delta_{M1})^2 + (\delta_{M2})^2} \tag{8}$$

In which δ_{M1} and δ_{M2} are the maximum nonlinear lateral displacements of the structures.

FEMA 356 guideline [23] on the issue of pounding between structures recommends that the information of the adjacent buildings should be collected to prevent damages due to pounding which might include falling of things, leakage of chemical fluids, and fire or explosion. For this purpose the owners of buildings should be aware of these effects and should resolve this problem.

But the minimum required distance that should be observed between two buildings is calculated as follows:

$$S_i = \sqrt{(\Delta_{i1})^2 + (\Delta_{i2})^2} \tag{9}$$

Where:

Δ_{i1}= Lateral displacement of the structure at ith level with respect to the ground level, calculated from provisions of this standard

Δ_{i2}= Lateral displacement of the adjacent building at ith level with respect to the ground level

UBC97 Code states that the distance between two buildings follows the lateral displacement of the two structures. The distance between two adjacent structures should be at least equal to Δ_{MT}:

Where, Δ_M denotes the maximum nonlinear displacement of the structure.

The fourth version of Standard 2800, entitled "Iranian code of practice for seismic resistant design of buildings" in article1-4-1 states that: for removal or reduction of damage and destruction due to pounding of the adjacent structures, the buildings should be separated by a separation joint or they should be constructed with a minimum distance from the common border with the adjacent lands. For this purpose in buildings with 8 stories or less, the distance of each story from the border of the adjacent land should be minimum 0.005 times the height of that story from the base level. In buildings with more than 8 stories and/or buildings with "very high importance" or "high importance" and with any number of stories, the joint width should be determined according to the provision of article 3-5-6.

Article 3-5-6: In buildings with "very high importance" and "high importance" and with any number of stories and/or in buildings with 8 stories or more, the width of separation joint between two adjacent buildings should be determined using the design nonlinear lateral displacement of that story (considering the P-Δ effect). For this purpose after calculation of this displacement for both buildings, the SRSS of the two values is used for determining the separation joint. In case where the adjacent building properties are unknown, the minimum distance of each story of the building from the adjacent land should be taken 70% of the design nonlinear lateral displacement at that story of the building.

The space in between the separation joint could be filled with low strength materials. These are easily crushed during an earthquake and when the buildings are pounding so they could be easily replaced or rehabilitated. The provisions of Standard 2800 are illustrated in Figs. 10 and 11.

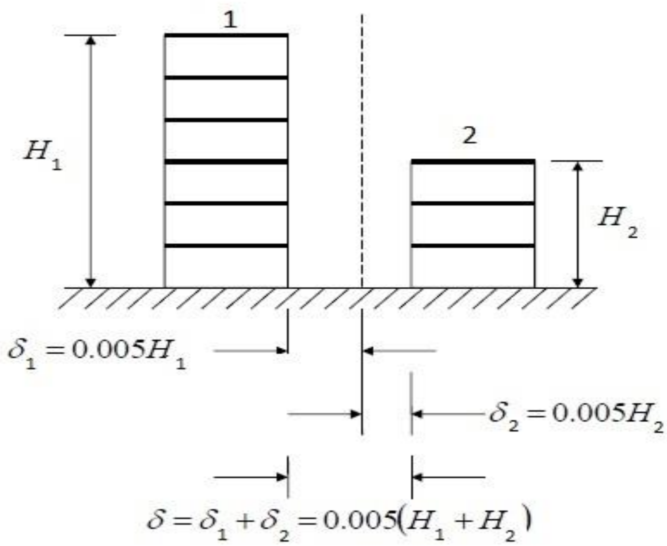


Fig. 10. Minimum separation distance for buildings with importance of low and medium up to 8 floors (Standard 2800[14]).

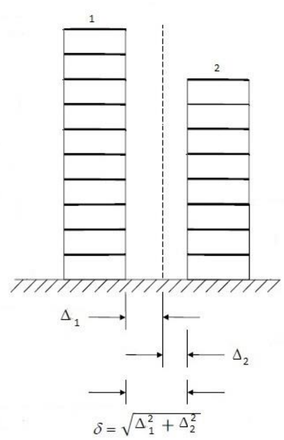
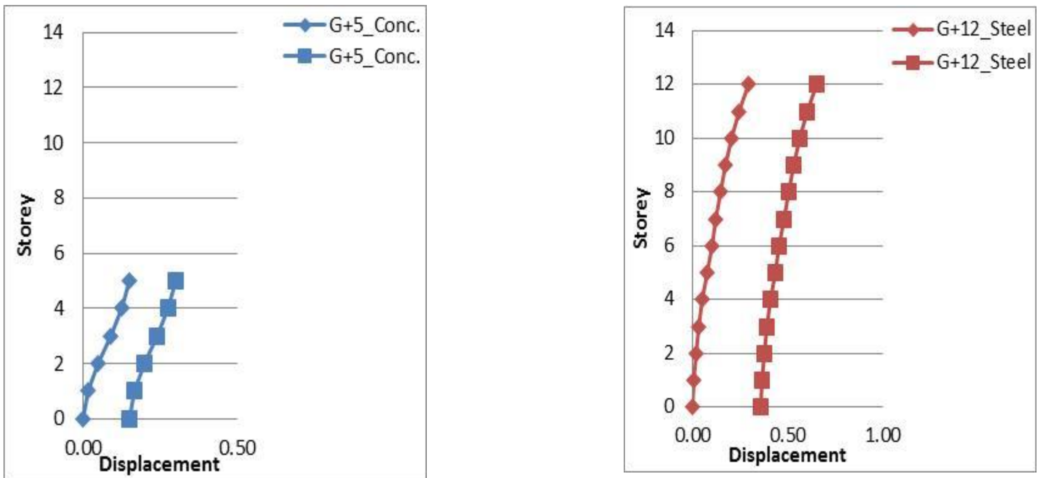


Fig. 11. Minimumseparation distance for buildings with importance of high and very high or buildings with importance of medium and low over 8 floors (Standard 2800[14]).

As stated before, the prestigious and important codes around the world have common ideas on the separation joint in buildings and most of them calculate the separation distance value using the SRSS of nonlinear displacements of the two buildings. But as this research is performed for the greater Tehran area and is a case study, the obtained displacements due to nonlinear analysis are compared with relations in Standard 2800 code which is a seismic code specific to Iran.

8. Patterns of investigating the minimum distance between two buildings

Not observing the separation joint between two adjacent buildings results in structural and non-structural damages to buildings during the earthquake. The level at which pounding occurs and the pounding force value are greatly affected by the heights of two adjacent structures, the bed soil parameters, building type and the lateral force resisting system. If the two buildings are equal in height, type and weight or in other words have similar dynamic characteristics, no pounding would occur between them and they could be executed without assuming a distance between them (Fig.12). In what follows various pounding patterns are discussed.



a) Two reinforcement concrete buildings (5 floors).

b) Two steel structure buildings (5 floors).

Fig. 12. Pounding assessment of two buildings with similar dynamic characteristics. Note: G+ means number of floors above the ground level, and Displacement in Meter.

8,1. Height patterns

The analysis of this research show that when the two adjacent buildings have different heights relative to each other, due to difference in their dynamic characteristics, the shorter building impacts the adjacent building and causes a high story shear force at the level above the impact position. It should be noted that the higher the level of impact position, the taller building would endure more severe responses. By increase in the height, the predominant period is increased thus increasing the displacement value. Hence by increase in the displacement, the impact forces are increased thus causing more sever damages and destructions. According to Standard 2800 the predominant period of a structure is calculated using the following relations:

A-For buildings with moment resisting frame system

- In case the in-fill isolators do not prevent ement of the frames

In steel frames: $T = 0.08H^{0.75}$

In RC frames: $T = 0.05H^{0.9}$

- In case the in-fill isolators prevent movement of the frames

The T value should be selected equal to 80% of the above mentioned values.

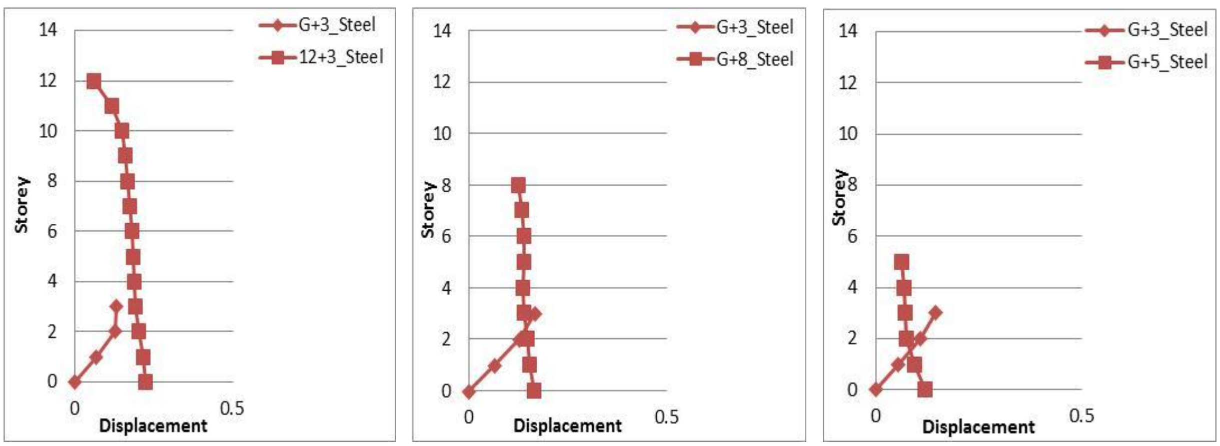
B-For buildings with eccentric bracing system, it is calculated similar to the steel frames

C-For buildings with other systems except for console system with or without infill isolators

$T = 0.05H^{0.75}$

It is clear that in unconventional buildings where the mass and stiffness distribution are not in proportion with their height such as the mosques, amphitheaters, sport complex buildings …., the vibration frequency should be determined by dynamic analysis of the building with respect to the infill isolators.

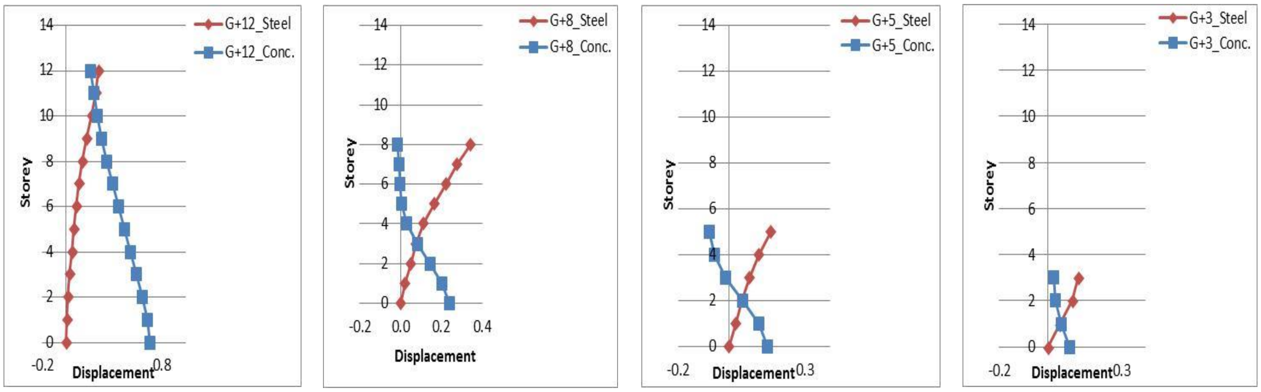
In this research the buildings are modeled with low, mid and high heights and their sensitivity is investigated with respect to each other. As seen in Fig.13, during pounding between a short building AND a mid-rise and high-rise building, the greatest effect belongs to the pounding between a short building and a mid-rise building (3 to 5-story buildings).The more the adjacent building height is increased, the effects of pounding are reduced so between the 3 and 12-story buildings no pounding is observed.



a) Steel (3F) & Steel (12F). b) Steel (3F) & Steel (8F). c) Steel (3F) & Steel (5F).

Fig. 13. Effect of height on pounding assessment of two buildings located near North Tehran Fault and over soil type III, Displacement in Meter.

In case the heights of two adjacent structures are equal but are different in type, then due to difference in the dynamic characteristics and out-of-phase vibration, in various times the two structures move toward each other and collide. Therefore in terms of the hazards and damages associated with pounding, the most sever and hazardous one is the pounding between a steel structure and a concrete one with equal heights (Fig. 14).

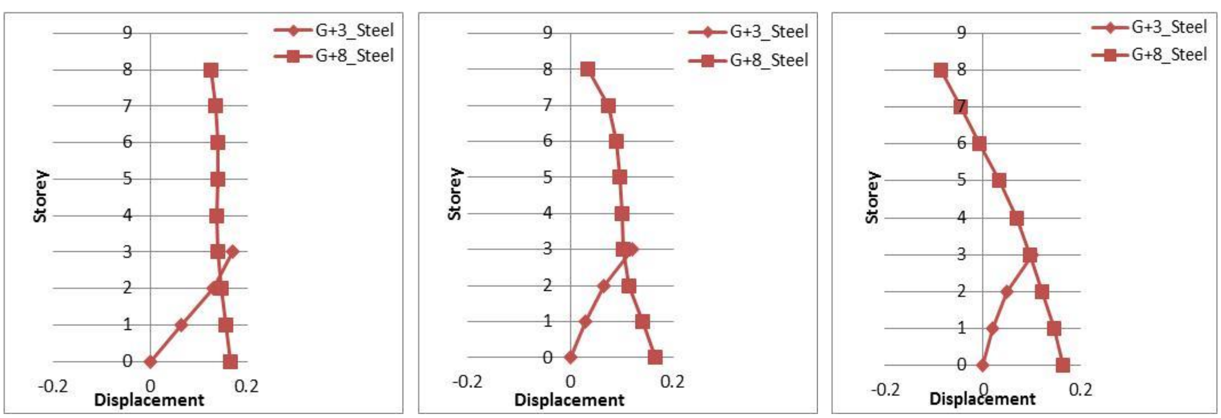


a) Steel (12F) & RC (12F). b) Steel (8F) & RC (8F). c) Steel (5F) & RC (5F). d) Steel (3F) & RC (3F).

Fig. 14. Effect of material on pounding assessment of two buildings located near North Tehran Fault with same height, Displacement in Meter.

8,2. Bed soil patterns

The local effects corresponding to a site have a great impact on the acceleration exerted upon the structure and significantly affect the important characteristics of strong ground motion including the frequency content and time. As Tehran city has only three soil types I, II and III, the artificial accelerograms generated for different distances from the faults per each soil type are used as shown in Fig.15.



a) Soil type III. b) Soil type II. c) Soil type I.

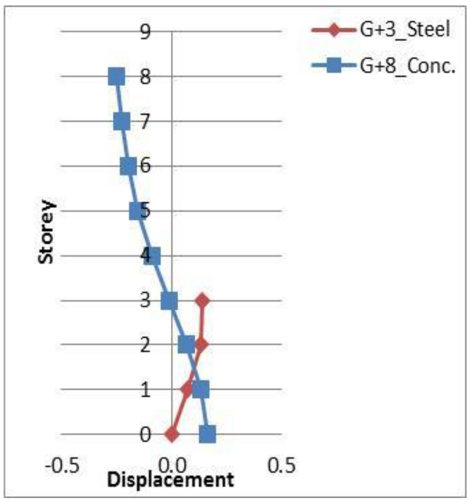
Fig. 15. Effect of soil type on pounding assessment of two steel buildings with 3 & 8 floors located near North Tehran Fault, Displacement in Meter.

From Fig.14 it is seen that the displacement and consequently the need for the separation joint increases from soil type I which is a stiff soil to soil types II and III which are looser soils. Hence soil type III is the worst and loosest soil in Tehran city area and to construct upon it special provisions should be observed.

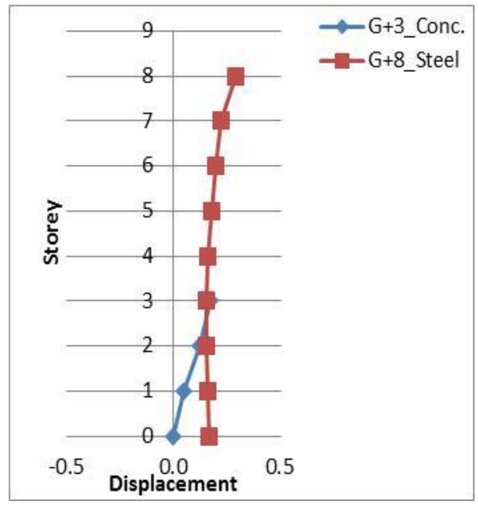
8,3. Type of building patterns

Type of the structure also affects its dynamic behavior, lateral displacement and stiffness.

For example the structure period and consequently its stiffness are calculated using different relations for the steel and concrete structures and also the masonry structure. Therefore each of these structures would exhibit a different behavior during the earthquake and this difference in behavior causes pounding of the two structures during the earthquake and creation of damages. It should be noted that the concrete structural system due to the increased weight and stiffness, bear greater forces during the earthquake. Ductility and the ability to absorb energy in the steel frame are higher compared to the concrete frame thus there is a high potential for large displacements in this type of structures. Hence the pounding issue is of great importance in them.



a) Steel (3F) & RC (8F).



b) Steel (8F) & RC (3F).

Fig. 16. Effect of structure type (Steel/Concrete) on pounding assessment near North Tehran Fault, Displacement in Meter.

If the two adjacent buildings are of different types and also differ in height, then the highest pounding hazard corresponds to the low-rise steel building adjacent to the high-rise concrete building (Fig. 16-a). In Fig.16 two low-rise steel and high-rise concrete structures are located adjacent to each other. In Fig. 15-a the shorter building is the steel building and in Fig. 15-b the shorter building is the concrete building. As is seen the low-rise steel building has exerted a strong impact on the high-rise concrete building but in Fig. 16-b the intensity of impact is much lower.

8,4. Lateral resisting system

The type of lateral resisting system directly influences the behavior and lateral deformations in the structure and could impact lateral ductility. Various systems are used as lateral bearing systems in structures which include" shear wall system, steel bracing system, moment resisting frame system, double systems, and systems with specific application. The moment resisting frames are more flexible and ductile than the braced frames or shear walls. The ductile behavior of this system absorbs the energy due to the earthquake but increases lateral displacement which is essential for tranquility and safety of their inhabitants.

The discussed systems in this research are divided into the moment and shear resisting systems. It is clear that in the shear systems due to high stiffness and low frequency, the displacement amount is not critical and damages due to pounding of buildings are less severe. Also in the braced structures, the separation joint between two structures is reduced and becomes less than that in the moment resisting system.

8,5. Analysis of pounding of adjacent buildings

In continuation the analyses performed based on different models are summarized. In this respect first the required separation joint for the two buildings was calculated according to Iran's Standard 2800. Then the two adjacent buildings were subjected to nonlinear dynamic analysis and for those buildings which collided, the needed increased values were given in Tables 6 and 7 for different patterns.

In Tables 6 and 7 the shortage in separation joint value between two buildings with similar and different structural types are given with respect to the relation in Standard 2800 (ver. 4). In these tables the cases such as difference in the number of stories, various soil types and various distances from north Tehran fault are considered. It is clear that soil type III, having low shear velocity and high acceleration amplification, would have destructive effects on the buildings in comparison to other soil types. Therefore it would be a critical and destructive soil for buildings especially for those built near the faults.

Table 8. Minimum needed increase of separation distance between adjacent buildings (in cm) near faults (according to the Standard 2800).

a) Two steel adjacent buildings.

Steel / Steel		Type I				Type II				Type III			
		3	5	8	12	3	5	8	12	3	5	8	12
Story	3	---	0.3	0.5	---	---	1.0	1.5	---	---	7.6	3.2	---
	5	0.3	---	3.5	---	1.0	---	6.5	---	7.6	---	12.1	---
	8	0.5	3.5	---	---	1.5	6.5	---	---	3.2	12.1	---	---
	12	---	---	---	---	---	---	---	---	---	---	---	---

b) Two RC adjacent buildings.

Concrete / Concrete		Type I				Type II				Type III			
		3	5	8	12	3	5	8	12	3	5	8	12
Story	3	---	3.5	---	---	---	11.8	---	---	---	15.8	16.5	---
	5	3.5	---	---	---	11.8	---	---	---	15.8	---	7.5	---
	8	---	---	---	---	---	---	---	---	16.5	7.5	---	---
	12	---	---	---	---	---	---	---	---	---	---	---	---

c) Steel-RC adjacent buildings.

Concrete / Steel		Type I				Type II				Type III			
		3	5	8	12	3	5	8	12	3	5	8	12
Story	3	---	6.6	---	---	---	11.4	1.0	---	10.06	18.0	15.1	---
	5	---	12.0	---	---	---	20.0	8.8	---	---	25.0	27.9	---
	8	---	---	---	---	---	---	7.1	---	2.0	7.5	36.5	---
	12	---	---	---	---	---	---	---	---	---	---	---	---

Table 9. Minimum needed increase of separation distance between adjacent buildings (in cm) at distance of 10km from faults (according to the Standard 2800).

a) Two steel adjacent buildings.

Steel / Steel		Type I				Type II				Type III			
		3	5	8	12	3	5	8	12	3	5	8	12
Story	3	---	---	---	---	---	---	---	---	---	0.3	---	---
	5	---	---	---	---	---	---	---	---	0.3	---	5.3	---
	8	---	---	---	---	---	---	---	---	---	5.3	---	---
	12	---	---	---	---	---	---	---	---	---	---	---	---

b) Two RC adjacent buildings.

Concrete / Concrete		Type I				Type II				Type III			
		3	5	8	12	3	5	8	12	3	5	8	12
Story	3	---	---	---	---	---	---	---	---	---	0.9	---	---
	5	---	---	---	---	---	---	---	---	0.9	---	---	---
	8	---	---	---	---	---	---	---	---	---	---	---	---
	12	---	---	---	---	---	---	---	---	---	---	---	---

c) Steel-RC adjacent buildings.

Concrete / Steel		Type I				Type II				Type III			
		3	5	8	12	3	5	8	12	3	5	8	12
Story	3	---	---	---	---	---	---	---	---	---	3.6	---	---
	5	---	---	---	---	---	---	---	---	---	8.0	---	---
	8	---	---	---	---	---	---	---	----	---	---	---	---
	12	---	---	---	---	---	---	---	---	---	---	---	---

Regarding Tables 6 and 7 the following issues are stated:

Among the three existing soil types in Tehran city area, soil type III is the most critical one and structures built on this soil experience large displacements.

If the two adjacent buildings are not of the same type i.e. one of them is made of concrete and the other of steel, the effects and intensity of pounding are higher than the case where both of them are of the same type. Now if both of them have equal heights then according to Table 5-C the intensity of impact and consequent outcomes would be much higher

Concerning soil type III, and regarding the intensity of impact and reverse displacements in a specific moment, first the effect associated with difference in type would be a determining factor, then are ranked the buildings which both of them are of concrete type and finally those that both of them are of steel type.

Regarding what was said also Tables 5 and 6, it could be stated that among the various cases including the type, height, site etc., the more severe and critical effects of pounding between two adjacent buildings, are associated mainly with the site soil type (where soil type III is the worst one) and then with the type of two structures located on a specific soil.

It should be noted that in buildings higher than 8 stories, considering the applied SRSS rule in most of the codes and also Standard 2800, no pounding occurs and calculated separation joint by this method is totally safe.

9. Zoning of tehran city in terms of pounding

Tehran City regarding its large area and population is divided into 22 municipality districts. In Figs. 16 and 17 the 22 districts of Tehran city together with the defined soil types in Standard 2800 are illustrated. Fig. 16 illustrates the range of 0-5 km of Tehran's active faults and Fig.17 illustrates the range of 5-15 km and the representative of this range is the 10km distance. Regarding these two maps and the soil type and distance from the fault, one could easily identify the hazardous urban areas and implement special measures during construction in these areas.

Districts no. 1, 3 and 4 at north of Tehran are the three seismic hazard zones. These districts are located close to the North Tehran fault. On the other hand large portions of these districts contain soil type III. Among the seismic hazard zones of southern Tehran one could refer to districts no. 15, 16, 18 and 19 because these are located close to Ray fault also over 90% of soils in these districts are of the weak type III soil (Fig.17).

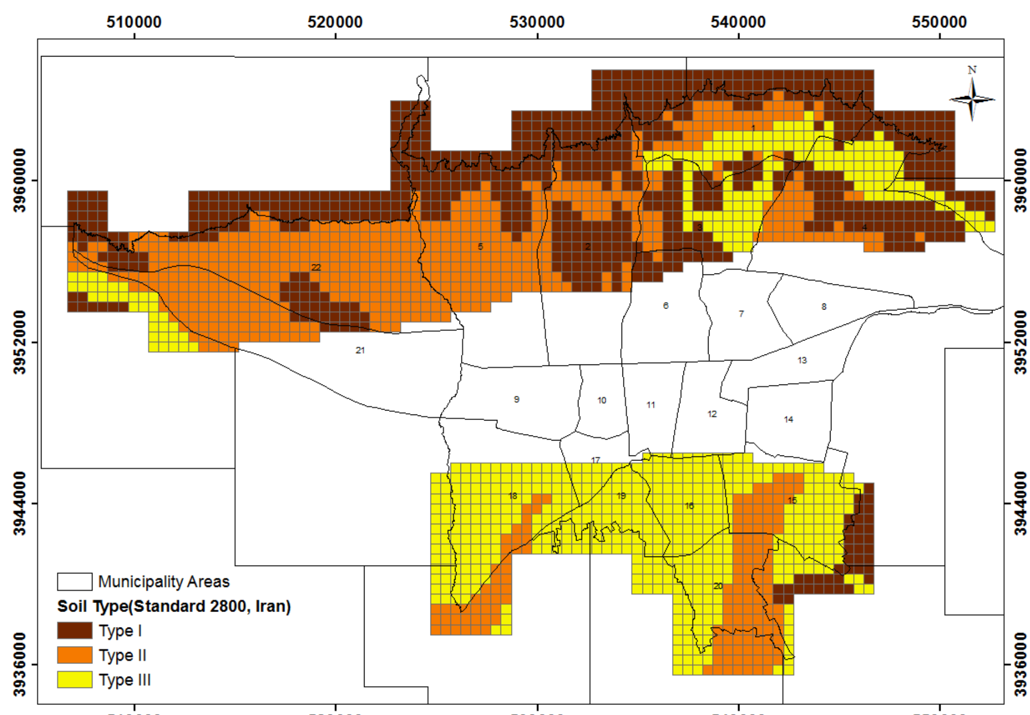


Fig. 17. Areas with 0-5 kilometers far from faults.

Fig. 18 shows the areas which are located between 5-15 kilometers far from scenario faults of Tehran. There are three soil types in this area as shown in the figure which can help to pounding assessment as mentioned before.

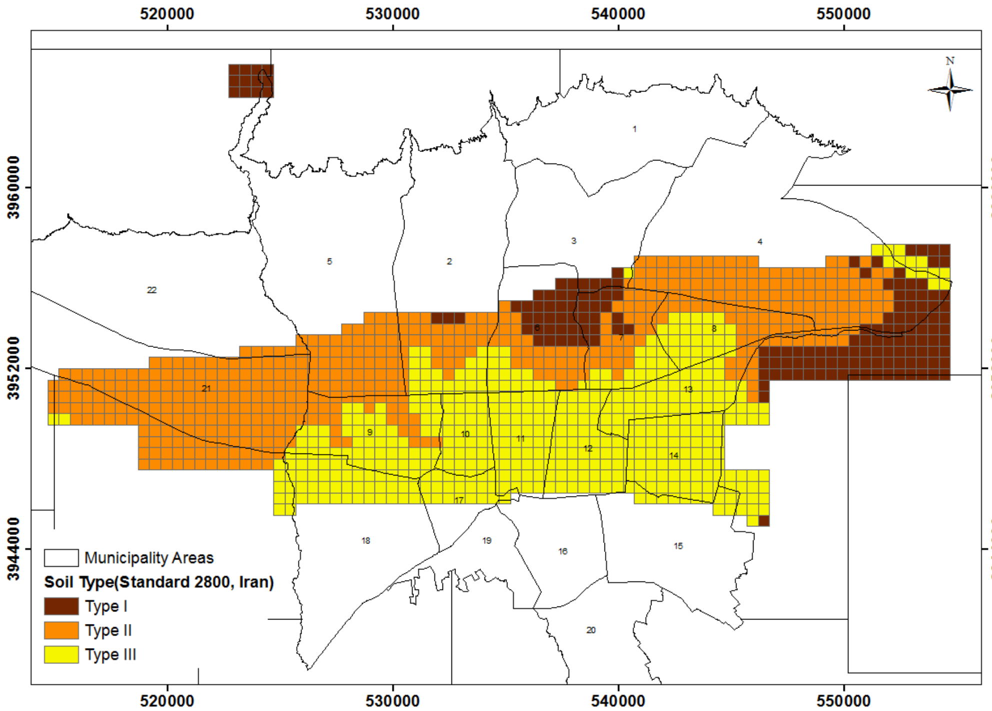


Fig. 18. Areas with 5-15 kilometers far from faults.

10. Proposed modifications for the separation joint in iran's standard 2800 provisions.

The separation joint presented by Standard 2800 Ver. 4 is not adequate with respect to the nonlinear analyses performed for buildings up to 8 stories, especially for those areas located on the faults as shown in table 7. Therefore for construction in areas close to the faults especially up to 5 km distance there is need for revision in the relation given in this code and increasing the separation joint size. The amount of this increase is given in Table 8 in percentage.

Table 10. Minimum needed increase of separation distance between bending adjacent buildings (in cm) (applied to the Standard 2800).

Distance to fault	Soil Type	Steel - Steel	Concrete - Concrete	Steel - Concrete
Over the fault	I	For buildings with 5 to 8 floors: 10% for each floor difference	For buildings with 3 to 5 floors: 15% for each floor difference	For same height buildings: 80%
	II	For buildings with 5 to 8 floors: 15% for each floor difference	For buildings with 3 to 5 floors: 50% for each floor difference	For same height buildings: 130%
	III	For buildings with 5 to 8 floors: 20% for each floor difference	For buildings with 3 to 5 floors: 65% for each floor difference	For same height buildings: 170%
10 Km	III	For buildings with 5 to 8 floors: 10% for each floor difference	For buildings with 3 to 5 floors: 5% for each floor difference	For same height buildings: 50%

Note: The increase percentage must be added to 100% of separation distance of Standard 2800

11. Results

In this research based on the deterministic hazard analysis of Tehran area and considering the soil conditions at each site, attempt was made to generate artificial accelerograms corresponding to the site conditions. In continuation, nonlinear dynamic analysis was performed with different height, type, soil condition and distance to faults patterns to estimate pounding of the adjacent buildings. Then by modeling of steel and concrete moment resisting frames located adjacent to each other their behavior was investigated under the effect of artificial accelerogramsmatched to deterministic hazard analysis for Tehran city. In the modeling the effects of different soil types, various distances from north Tehran fault, also various heights were taken into account.

From the all performed analyses, the following results were obtained:

- Among all soil types and distances, the most hazardous situation belongs to soil type III which has a low shear velocity and high acceleration amplification in areas close to the faults.
- If the two adjacent buildings are exactly similar to each other, or in other words have identical dynamic characteristics there would not be notable pounding between them.
- Generally, the adjacent buildings with a small difference in their number of stories would have more sever collision than two buildings with great difference in their number of stories.
- In case the two buildings are equal in height but differ in type, their collision would be very severe and significant and this collision is considered the most severe kind of all collisions
- Concerning two buildings with difference in type and height, in case the short building is of steel type the collision between them is much more severe than the case where the short building is of concrete type.
- Municipality districts no. 1, 3 and 4 are the three hazard zones at north of Tehran city and during construction the designers should pay special attention to these areas. Also districts no. 15, 16, 18 and 19 due to their loose soil are accounted as hazardous zones.

Finally, it should be noted that modal parameters can also be included in studies for future research. Furthermore, the effects of soil-structure interaction, structure-soil-structure interaction, asymmetric seismic excitation, torsional structural response, and so on can be studied as more parameters which can affect the result.

REFERENCES

[1] Chetan J. Chitte, Anand S. Jadhav, Hemraj R. Kumavat. (2014). "Seismic Pounding Between Adjacent Building Structures Subjected To Near Field Ground Motion". International Journal of Research in Engineering and Technology, Volume 03 Special Issue 09.

[2] Anagnostopulos, S. A. (1988). "Pounding of buildings in series during earthquakes." Earthquake Engineering and structural Dynamics., VOL. 16, PP. 443-456.

[3] Westermo, B. D. (1989). "The dynamics of interstructural connection to prevent pounding." Earthquake engineering and structural Dynamics., VOL. 18, PP 687-699.

[4] Lin, J. H. Weng, C. C. (2001). "Probability analysis of seismic pounding of adjacent building." Earthquake Engineering and structural Dynamics., Vol. 30, PP. 1539-1557.

[5] Garcia, D. L. (2005). "Critical building separation distance in reducing pounding risk under earthquake excitation." Earthquake Engineering and structural Dynamics., Vol. 27, pp. 393-396.

[6] Dogan, M., Gunaydın, A. (2009). Pounding of adjacent RC buildings during seismic loads. Journal of Engineering and Architecture Faculty of Eskişehir Osmangazi University, Vol: XXII, No:1.

[7] Raghunandan M H, Suma Devi. (2015). "SEISMIC POUNDING BETWEEN ADJACENT RC BUILDINGS WITH AND WITHOUT BASE ISOLATION SYSTEM". International Journal of Research in Engineering and Technology. Volume04 Issue 06 June-2015.

[8] Zafarani, H., Noorzad, A., Ansari, A., and Bargi, K. (2008). Stochastic modeling of Iranian earthquakes and estimation of ground motion for future earthquakes in Greater Tehran. Soil Dynamics and Earthquake Engineering, 29 (2009) 722–741.

[9] International Institute of Earthquake Engineering and Seismology (IIEES), 2003. Major Active faults of Iran.

[10] Japan International Cooperation Agency. (2000). The Study on Seismic Microzoning of the Greater Tehran Area in the Islamic Republic of Iran, Tehran.

[11] Japan International Cooperation Agency (JICA), Centre for Earthquake and Environmental Studies of Tehran (CEST), The Study on Seismic microzoning of the greater Tehran area in the islamic republic of Iran, Tehran Municipality, November 2000.

[12] Jafari,M.K, Razmkhah, A., KeshavarzBakhshayesh, M., (2003). Microzonation of shear wave velocity of Tehran area deposits, Journal of technical faculty of Tehran University, Volume 37, No2. Pages 213-225. (in Persian).

[13] Ghayomian, J., Khamechian, M.,Movahhedi, A. A. (2003). Relations of estimation of shear wave velocity in the range of Quaternary deposits in central Tehran. Conference Proceedings of Geological Society of Iran, Isfahan University, (in Persian).

[14] Building & Housing Research Center (BHRC) of Iran, 2014. Iranian code of practice for seismic resistant design of buildings standard No. 2800, 4th edition, Iran.

[15] Campbell, K. W., and Bozorgnia, Y. (2008). NGA Ground Motion Model for the Geometric Mean Horizontal Component of PGA, PGV, PGD and 5% Damped Linear Elastic Response Spectra for Periods Ranging from 0.01 to 10 s. Earthquake Spectra, Volume 24, pages 139–171

[16] Boore, D. M., and Atkinson, G. M. (2008). Ground-motion prediction equations for the average horizontal 99 component of PGA, PGV, and 5%-damped PSA at spectral periods between 0.01 s and 10.0 s, Earthquake Spectra 24, 99–138.

[17] Chiou, B., and Youngs, R. R. (2008). An NGA model for the average horizontal component of peak 173 ground motion and response spectra, Earthquake Spectra 24, 173–216.

[18] Shoja-Taheri, J., Naserieh, S., and Hadi, G. (2008). A test of the applicability of NGA models to the strong ground-motion data in the Iranian plateau. Journal of Earthquake Engineering 14, 278–292.

[19] Saffari, H., Kuwata, Y., Takada, S., and Mahdavian, A. (2012). Updated PGA, PGV, and Spectral Acceleration Attenuation Relations for Iran. Earthquake Spectra, Volume 28, pages 257–276

[20] Iranian national regulations for construction, 2013, Design and Construction of the reinforced concrete buildings (Volume9), Tosehe Iran Publisher, 304pp, (in Persian).

[21] Iranian national regulations for construction, 2013, Design and Construction of the steel buildings (Volume10), Tosehe Iran Publisher, 373pp, (in Persian).

[22] American Society of Civil Engineers (2016). Seismic design criteria for structures, systems, and components in nuclear facilities, Structural Engineering Institute, Working Group for Seismic Design Criteria for Nuclear Facilities.

[23] Federal Emergency Management Agancy, (2000). PrestandardAnd Commentary for The Seismic Reabilitation of Building, (Fema 356), Washington, D. C.