INTERNATIONAL JOURNAL OF OPTIMIZATION IN CIVIL ENGINEERING
Int. J. Optim. Civil Eng., 2020; 10(1):17-33

DETERMINATION OF OPTIMAL DISTANCE BETWEEN TWO ADJACENT STEEL FRAMES CONSIDERING STRUCTURE-SOIL-STRUCTURE INTERACTION EFFECTS USING PSO

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ABSTRACT

This paper aims to obtain the optimal distance between the adjacent structures using Particle Swarm Optimization (PSO) algorithm considering structure-soil-structure systems; The optimization algorithm has been prepared in MATLAB software and connected into OpenSees software (where the structure-soil-structure system has been analyzed by the direct approach). To this end, a series of adjacent structures with various slenderness have been modeled on the three soil types according to Iranian seismic code (Standard No. 2800) using the direct method. Then they have been analyzed under six earthquake excitations with different risk levels (low, moderate, and high).

The results are compared with the proposed values of separation gap between adjacent structures in the Iranian seismic code (Standard No. 2800). Results show that since structures with the same height constructed on a stiff soil will move in the same phase, there is no need to put distance between them. Although, the structures with the height more than 6-story frames where are located on a soft soil are needed to be separated. Additionally, the results show more separation gap between two adjacent structures when the risk level of earthquake is high. In general, the values which are presented in Standard No. 2800 are not suitable for low /moderate-rise structures specially when they are subjected to a high-risk level earthquake and are located on a soft soil and this separation gap should be increased about 10 to 90 percentage depend on the conditions but these values are appropriate for the adjacent structures with same height where are subjected to a low-risk level earthquakes built on soft soil.

Keywords: Structure-Soil-Structure Interaction (SSSI), Separation gap, Adjacent structures, Particle Swarm Optimization Algorithm (PSO), Time history analysis

Received: 25 July 2019; Accepted: 12 November 2019

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1. INTRODUCTION

Soil-structure interaction is a set of phenomena in the structure response that is caused by the soil-foundation flexibility and implement the response of the soil layers into the presence of the structure. An additional degree of freedom and wave propagation techniques are required to model soil's effects. In general, this phenomenon; (*i*) increase structure period, *(ii*) increase rocking mode share of total response and (*iii*) usually reduces the base shear [1].

Many studies have been conducted on the distance between two adjacent structures. Hong et al. presented a method for evaluating the required separation distance with or without considering possible uncertainty in structural properties based on reliability methods and random vibration theory. Moreover, the CQC law was used in obtaining the critical separation distance [2]. Barbato and Tubaldi conducted probabilistic methods for determining the appropriate separation distance between adjacent structures which in this study, both linear structures and nonlinear structures were considered [3]. Penzien conducted studies on the minimum required distance to avoid collisions between buildings during large earthquakes for buildings with linear and nonlinear behavior. He found that the SRSS and the ABS method increased the chance of collision between buildings [4]. Nasserakhaki et al. studied the separation distance between adjacent structures considering the Collision and soil-structure interaction [5]; where, a numerical model of buildings located on an Infinite half-space has been used, while they are connected by visco-elastic contact force model. When the separation distance is zero, this force is activated and the buildings collide each other. The seismic response of these buildings subjected to the acceleration of the time history of El Centro earthquake was calculated for both fixed base foundations (FB) and structure-soil-structure interaction (SSSI). They found that the soil changed the seismic response of the building and increased the seismic response even when the separation distance was relatively wider.

Some research on a detailed investigation on the pounding-involved response of two buildings of equal height with substantially different dynamic properties, done by [6]. Jeng et al. determined the required gap between the two buildings using a spectral differential method [7]. Anagnostopulos and Spiliopoulos challenged the effect of impact force in 1991 on increasing the relative response of two adjacent structures [8].

Lopez-Garcia and Soong have studied on the accuracy of the Double Difference Combination (DDC) rule (also known simply as the CQC rule) in predicting the necessary separation to prevent seismic pounding between linear structural systems [9]. In [10], Garcia examined the four existing methods to calculate the critical separation distance between nonlinear hysteresis structures through Monte-Carlo simulations and then calculated the critical separation distance.

Hao and Shen conducted a study to provide a sufficient separation distance between adjacent asymmetric buildings in [11], which completely prevented the impact of strong earthquakes. Similar studies have been carried out in the field of structure-soil-structure interaction (SSSI) by Aldaikh et al. [12]; in which they examined the adverse and beneficial effects of SSSI under seismic excitation on a group of three buildings.

Ghiocel et al. [13] have investigated the seismic SSSI effects in densely built urban areas for a 15-floor Multistory Building (MB), a Church Building (CB), and a Subway Station (SS) in the Bucharest city. The paper concludes that in the investigated case studies, the incoherent SSSI effects are significant, non-negligible for the MB and CB structures, and extremely large for the deeply embedded SS structure. The paper encourages the earthquake engineering communities to pay attention to the combined SSSI and motion incoherency effects in dense urban areas since these significant dynamic coupling effects are currently ignored in the seismic design. Many researches have been done for evaluating the effects of soil-structure-system such as [15, 16] and in [17, 18] the effects of topography irregularities on the site response analysis and a novel technique in order to reduce its amplification is studied.

In urban constructions, we encounter cases where adjacent buildings are stick together or spaced apart from each other. These structures do not have the same dynamic behavior due to their different mechanical and geometrical properties along a given direction; as a result, the impact between two adjacent structures may happen during an earthquake. Usually, a separation gap is placed between the adjacent structures to prevent this pounding. Unfortunately, despite the importance of the soil-structure interaction effect in the design of buildings, no instructions in the regulations apply to the separation distance between the two structures. Therefore, the study of the separation distance between two adjacent structures without considering the effect of soil will end up with unrealistic results.

In this paper, the separation gap between two adjacent steel moment frames is obtained using PSO algorithm considering SSSI effects. A series of pair adjacent frames consist of six steel frames with different heights (3, 6 and 12-story frames) and various width (3 and 5 bays) are considered on three soil types based on Iranian seismic code (Standard No. 2800 [19]). The results have been presented for the optimal distance between two adjacent structural frames exposed to different earthquake hazard level.

2. STATEMENT OF THE PROBLEMS

The studied models are in the medium-importance buildings group of special steel moment resistance frames. These structures are categorized as regular buildings along their height and plan. These frames are designed based on Iranian National Building Code (INBC) [20], Part 10: Steel Structures and according to Iranian seismic code (Standard No. 2800) three-dimensionally and one of the middle frame of each structures is selected in order in this study. Fig. 1 shows the schematic view of 9 frames which have been studied and used in this paper. The cross-section properties of the structural members of these frames are presented in Table 1 and Table 2 represents the name and geometrical properties of these frames.

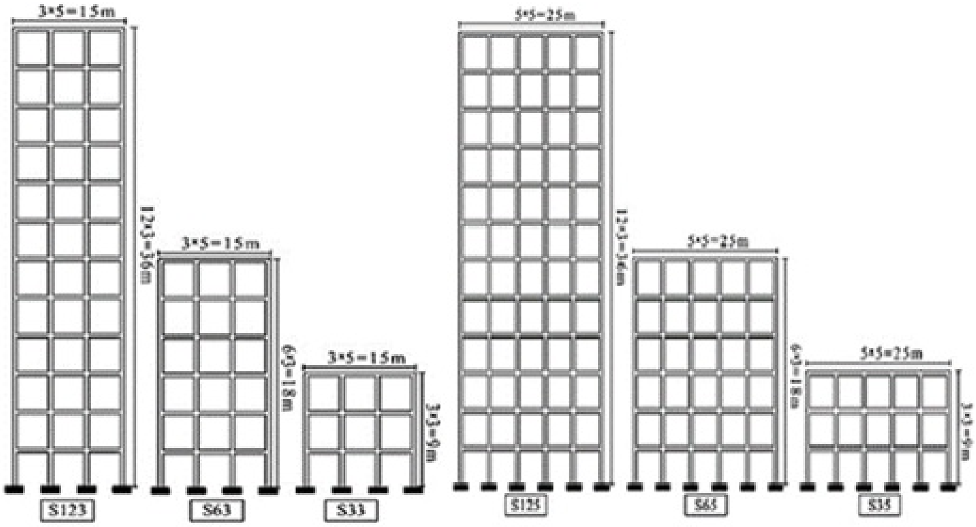


Figure 1. The schematic configuration of 2D steel frames with 3,6 and 12 stories and 3 and 5 bays

Table 1: Cross sectional properties of structural members of considered frames

Floor No.	**Beam sections**	**Column sections (*mm*)**
10-12	W 21×55	Box 400×16
7-9	W 24×62	Box 420×30
4-6	W 24×68	Box 470×20
1-3	W 24×76	Box 550×20

Table 2: Geometrical properties of considered structural frames.

Frame name	**Number of stories**	**Number of bays**	**Story height (m)**	**Bay width (m)**	**Total height (m)**
S33	3	3	3	5	9
S35	3	5	3	5	9
S63	6	3	3	5	18
S65	6	5	3	5	18
S123	12	3	3	5	36
S125	12	5	3	5	36

The goal of this paper is evaluate the optimum separation gap between two adjacent building considering SSI effects; to this end, a series of couples of above frames are simulated on three soil types and subjected to earthquake excitations with various risk level and employing a particle swarm optimization which conducted to simulation software calculates the adequate separation gap between frames for each conditions. In this regard, as same frames have same vibration configuration, so, it is assuming that no pounding will happen for same structures and these couples of structures are skipped in this study.

The code for the particle swarm optimization algorithm has been prepared in MATLAB software, and the condition to stop this algorithm was where the value of the distance between the maximum displacement of two adjacent frames is less than 0.01 *m*. The methodology is that the points taken from the optimization algorithm are considered as the distance between the two adjacent structures in the problem, then the software solves the problem with these conditions, and the displacement values in the roof level of shorter structure and in a parallel alignment with the roof of the shorter structure is read by the OpenSees software. These points are returned to the optimization algorithm and compared to the target function. The best points are determined to be the smallest value of the target function. If the condition for stopping is satisfied, these points will be considered as the answer to the problem. Otherwise, the analysis cycle will continue. The target function defined in this algorithm minimizes the amount of residual distance between the two structures after the displacement of both structures; so, the statement of the optimization problem in this study is as,

$$\begin{cases} \min imize: & Costfunction(t) = space - (Disp\_roof1(t) - Disp\_roof2(t)) \\ Subject\ to: & Disp\_roof1(t) < Disp\_roof2(t) \end{cases} \tag{1}$$

where, *space* is the separation gap between two structures, *Disp_roof1(t)* is the displacement of roof level of shorter structure and *Disp_roof2(t)* is the displacement of higher structure at the level of roof of shorter structure at time step *t*.

3. STRUCTURE-SOIL-STRUCTURE SYSTEM

In order to model and analyze the structure-soil-structure interaction a series of full model based on a direct approach using OpenSees software are prepared (see Fig. 2). In these models, the excitation is applied into the model from the bedrock which is placed at the bottom side of the soil model and the right and left side of the model are viscous absorbing boundaries which act along horizontal and vertical directions.

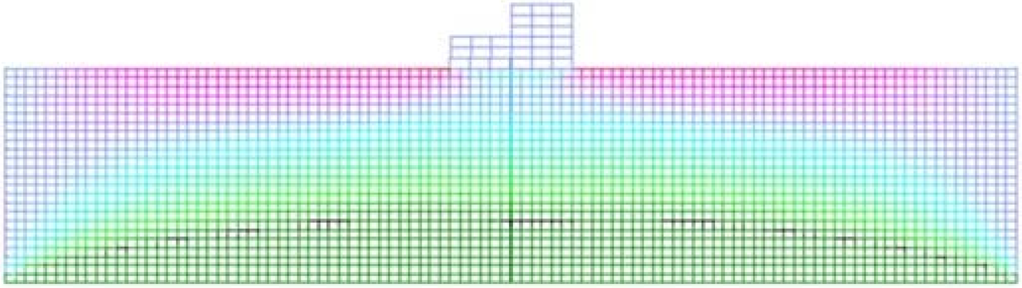


Figure 2. Modeling of structure-soil-structure system using direct method

The soil in these models are considered as a single-layered medium with the mechanical properties which are presented in Table 3; in which, *E* is the Young modulus, *G* is shear modulus, E_c is Bulk modulus, υ is Poisson' s ratio, γ is the unit density, v_s and v_p is shear and longitudinal wave velocity of soil, respectively. In this study the depth of oil layer is selected 60 *m* using sensitivity analysis.

Table 3: Mechanical properties of the considered soil layer.

Soil types	${}_{g}\xi$	**E (kN/m^2)**	**G (kN/m^2)**	**E$_c$ (kN/m^3)**	γ **(kg/m)**	υ	${}_{s}\nu$ **(m/s)**	${}_{p}\nu$ **(m/s)**
S1	5.00	7,000,000	269,2310	9,423,077	2000	0.30	1149.1	2149.89
S2	5.00	2,000,000	769,230	2,692,308	2000	0.30	614.25	1149.16
S3	5.00	500,000	192,310	673,077	1900	0.35	309.22	643.68

4. INPUT MOTIONS

Six different ground acceleration records have been employed for time history analysis of the presented models, all earthquake excitations are converted to the bedrock and then impose to the models. Fig. 3 shows the acceleration response spectra and Fig. 4 show the acceleration time-history of these earthquake records on the bedrock.

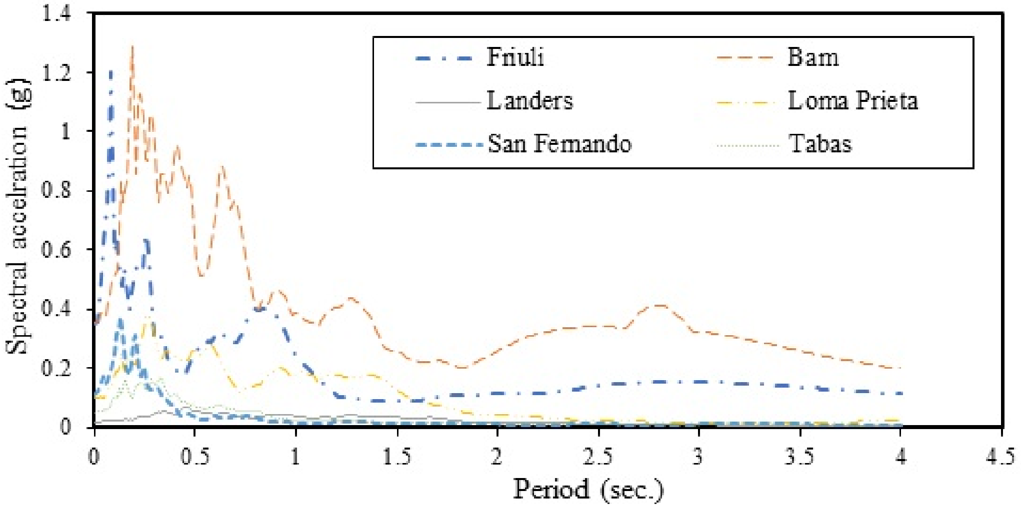


Figure 3. Spectral acceleration of considered ground motions at bedrock

Dynamic analysis of the frame system on the soil surface has been done using a direct method (flexible base). The properties the considered earthquakes are presented in Table 4 and these earthquakes are categorized based on their hazard-level according to FEMA 356 [21]. In a case that soil and structure are modeling simultaneously using direct method (flexible base), earthquake records are directly applied to a combination of soil and structure.

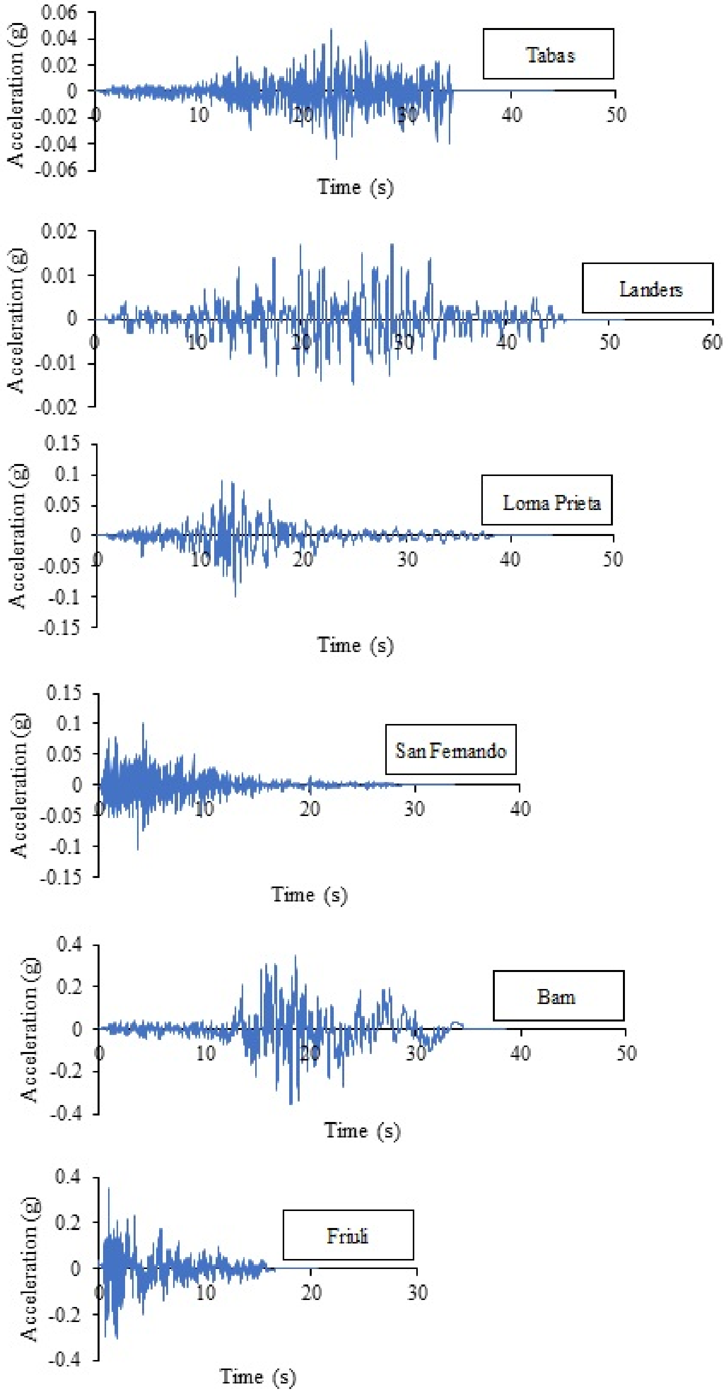


Figure 4. Acceleration time history of earthquakes excitation at bedrock

Table 4: Considered earthquakes

Earthquake	Year	PGA(g)	Magnitude (R)	Duration (sec.)	Seismic hazard level
Tabas	1978	0.047	7.35	24.2	Low
Landers	1992	0.017	7.28	23.7	Low
Loma Prieta	1989	0.09	6.93	13.0	Medium
San Fernando	1971	0.1	6.61	11.3	Medium
Bam	2003	0.35	6.6	15.9	High
Friuli	1976	0.35	6.5	10.4	High

5. VERIFICATION OF SSI SIMULATION

As the verification, a part of research which has been done by Raychowdhury and Chaudhuri [22] was simulated in order to assess if the present model works well for simulating the dynamic soil-structure-interaction? To this end, a 4-story flexural building has been simulated using OpenSees software, the dimensions and specifications of structural elements of this frame are presented in Fig. 5 and the earthquake record applied to this model are presented in Fig. 6. All mechanical and geometrical properties of this model are prepared based on what presented by [22] and the acceleration response of 2nd and 5th story are compared with the results which are depicted in [22]; as it is shown in Figs. 7 and 8, it is obviously clear that the results of the present study have a good agreement with the results are presented in [22].

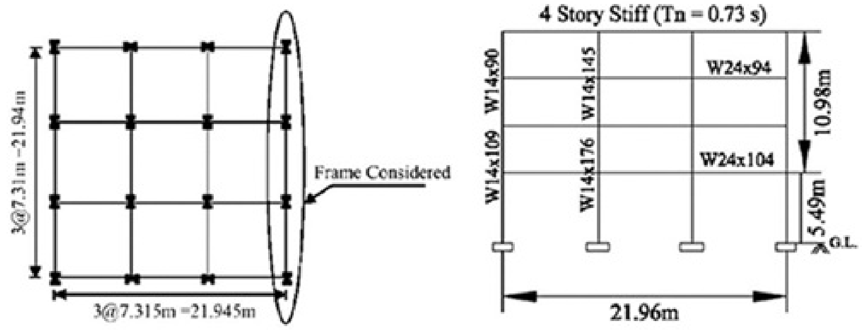


Figure 5. Configuration and geometry of the frame which is used in order to verification according to [22]

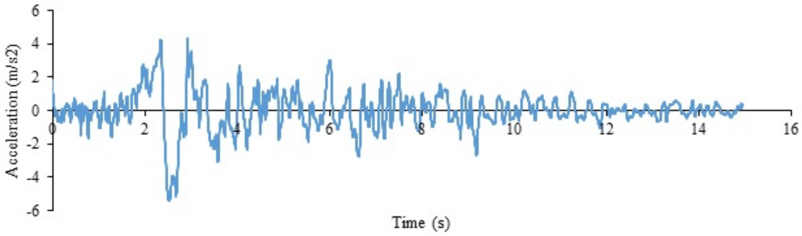


Figure 6. The earthquake record applied to the verification model

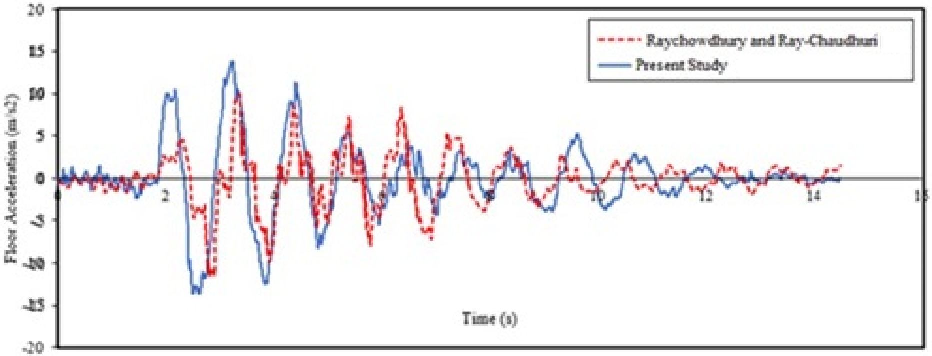


Figure 7. Comparison of acceleration time history of 2nd floor which is obtained by the present study and [22]

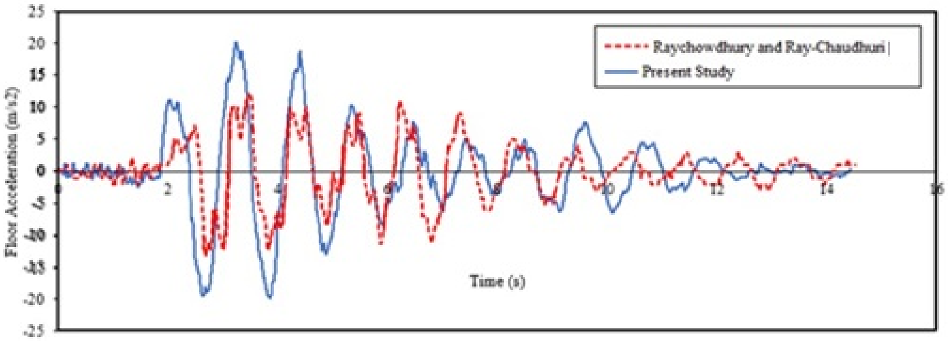


Figure 8. Comparison of acceleration time history of 5th floor which is obtained by the present study and [22]

6. PARTICLE SWARM OPTIMIZATION (PSO) ALGORITHM

Optimization in engineering usually uses the optimization techniques to achieve design goals in engineering; in this regard, many optimization algorithms are implemented for engineering problems. One of the powerful optimization technique for solving engineering problems is PSO. Kenndy (a social psychologist) Eberhart (an electrical engineer) are the main owners of the PSO algorithm's idea. They initially intended to use a combination of social models and existing social relationships to create a kind of computational intelligence that does not require specific individual abilities. Their first simulation was carried out in 1995 [23, 24], leading them to simulate the behavior of birds to find seeds. Due to the simple search mechanism, computational efficiency and easy implementation are widely applied in many optimization areas. In the particle pool algorithm, the particle term refers to members of the population that have a low mass and mass (or a small mass or volume). Each particle in the congestion represents a solution in a space with a high dimension with four vectors.

Its current position, the best position found in the round, the best position by its neighborhood and its speed, includes these four vectors. The position of each particle in the search space is determined by the best position obtained by itself (*pbest*) and the best position achieved by its neighbors (*gbest*) during the search process. Each repeat, each particle updates its position and velocity as follows:

$$v_j^i[t+1] = wv_j^i[t] + c_1r_1\left(x_j^{i,best}[t] - x_j^i[t]\right) + c_2r_2(x_j^{gbest}[t] - x_j^i[t]) \tag{2}$$

$$x_j^i[t+1] = x_j^i[t] + v_j^i[t+1] \tag{3}$$

Here $x_j^i[t]$ indicates the position of the particle and $v_j^i[t]$ represents its velocity. r_1,r_2 denotes random numbers between zero and one, and c_1, c_2 represent cognitive parameters [25]. According to this formulation, many researches have been carried out in order to optimize engineering problems such as [26-34].

The methodology is that the points taken from the optimization algorithm are considered as the spacing between the two adjacent structures in the problem. Then the software solves the problem with these conditions, and the displacement values are shorter in the roughness of the structure and are read at a level equal to the floor of the structure with a shorter structure; These points are returned to the optimization algorithm and are compared by the objective function, the best points are determined as the smallest value of the target function. If the condition for stopping these points is considered as the answer to the problem, otherwise the analysis cycle will continue. The objective function defined in this algorithm minimizes the amount of residual distance between the two structures after the displacement of both structures.

7. RESULTS AND DISCUSSION

According to the procedure that explained in the above sections, several models are simulated and the optimum gap between two adjacent building are evaluated; Tables 5-9 present the proposed distance between neighbor structures considering SSSI due to various soil, structures and earthquake conditions.

In Table 5, earthquakes are arranged from a low-risk level to a high-risk level and the proposed distances in this milling plan are presented on three soil types S1, S2, and S3. Results show that for 3-story frames and 3 bays structure opposite the structure of the 3 stories and 5 bays is observed; in all types of soils, the distances are about millimeters, so it could be concluded that structures with equal height and no space among them, would not collide with each other since the structures move together in one phase. According to Table 5, the value of 0.09 m for two structures of 3 stories to each other is proposed more than the required value.

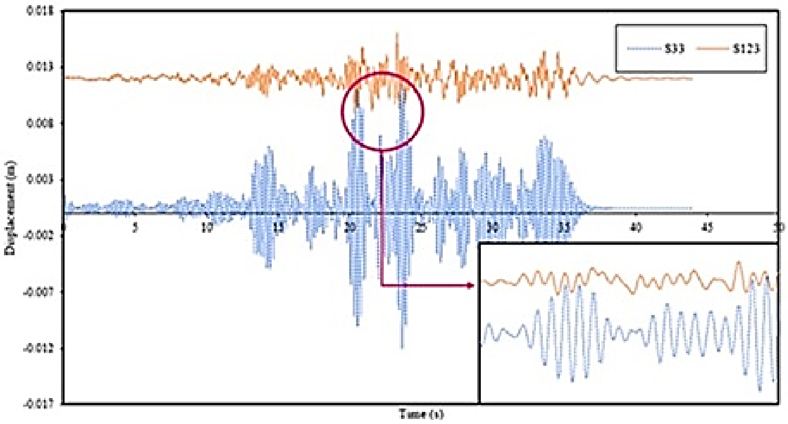
Comparison of the results of the construction of the 3-story and 3-bay against the structures of the 6-story 3-bay, the 6 stories and 5 bays, the structures of 12 stories and 3 bays, and 12 stories and 5 bays are observed, which results are very similar and this indicates that the number of bays, or the obesity and slimming structures, does not affect the distance between two adjacent structures.

In this table, it can be observed that the more softened soil, the amount of proposed spacing in this study increases. Moreover, the higher the hazard level of earthquakes, the amount of proposed spacing distance increases; Therefore, it can be concluded that the softness and hardness of the soil and the hazard level of earthquakes also affect the distance between two adjacent structures.

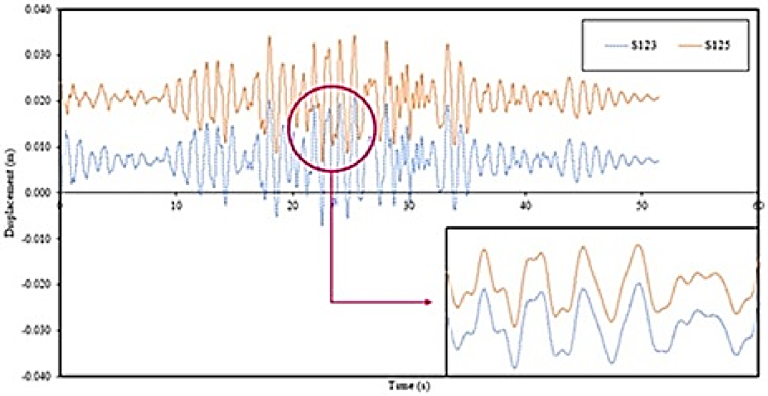
The Standard No. 2800 proposes a value of 0.18 m for 12-story against 6-story building because in case of a collision between these two structures they will be in the roof level of shorter structure, so a shorter structure will be used. The results obtained from the PSO algorithm show that the proposed spacing of Standard No. 2800 is only for 12 stories structures against the 6 stories based on type S1 soil and for type S2 and S3 soils with low and medium hazard level of earthquakes. The proposed spacing of Standard No. 2800 isn’t appropriate for type S2 and S3 soils, and can’t be used for a high hazard level earthquake of 0.30 or 0.35 meters.

From the results obtained from a 3-bay 12-story against a 5-bay 12-story structure, it can be observed that if these structures are built on type S1 and S2 soils, no space between them is required while if structures on the soil S3 are required to have a minimum distance of 0.15 meters to avoid collisions. Hence, structures above 6 stories having same height which are based on soft soils should be positioned at a distance from one another.

In Fig. 9, examples of time-displacement diagrams for different states of placement of structures alongside each other are presented for alignment of classes that can interact with each other. The time-displacement diagram is shown for the base structure with a line, and the diagram of the adjacent structure is transmitted to the top of the proposed distance in this study. As seen in these diagrams, the adjacent structures are not interacting with the proposed distance.



(a)



(b)

Figure 9. Time history of displacement of two adjacent frames without any pounding; (a) S33 and S123, (b) S123 and S125

In Fig. 10, a sample of convergence charts derived from the code written for the PSO algorithm is shown. As can be seen, these models are achieved by performing 8 and 6 repetitions, provided that the convergence is stopped, and the values of the spacing between the two structures are presented.

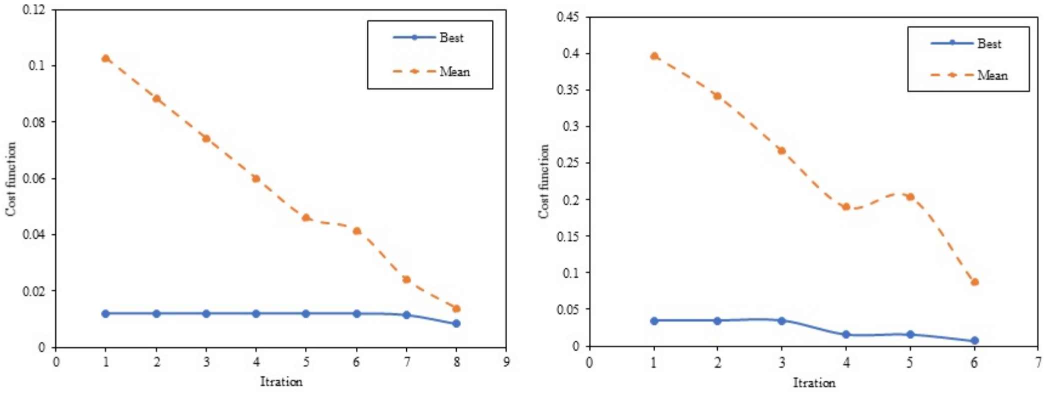


Figure 10. Convergence diagram of optimization algorithm

Figs. 11-13 show the counters of difference percentage (PD) between the separation gap which is proposed in this study (gap_{new}) and the Standard No. 2800 (gap_{2800}) for every conditions related to structures, soil and earthquakes by:

$$PD(\%) = \frac{gap_{new} - gap_{2800}}{gap_{2800}} \times 100 \tag{4}$$

where, the value of the proposed spacing by Standard No. 2800 for the two adjacent structures is according to Table 10.

The positive percent shows the increase in the spacing proposed by the Standard No. 2800 for the non-collision between the two adjacent structures and the negative percent represents the distance reduction proposed by the Standard No. 2800 to the percentages given in the contours (see Figs. 11-13).

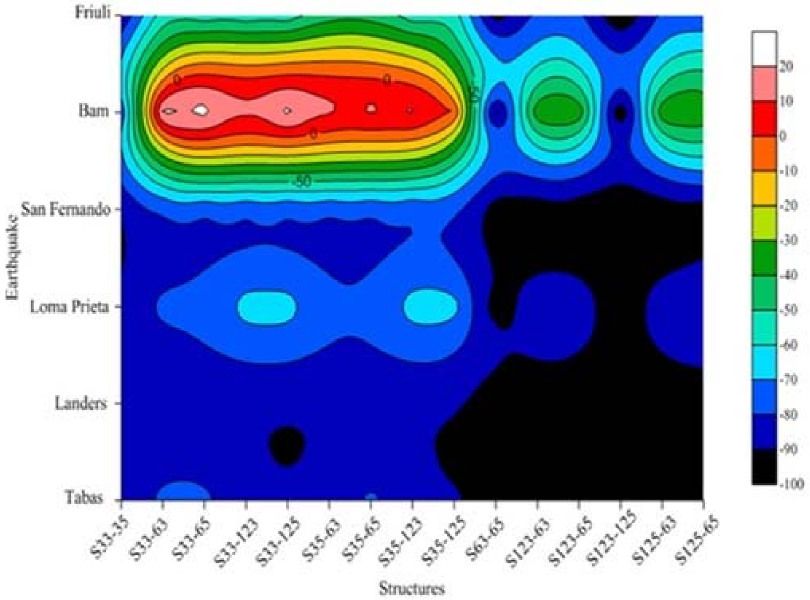


Figure 11. The percentage difference (PD) between the proposed values in this study and the Standard No. 2800 for soil type S1

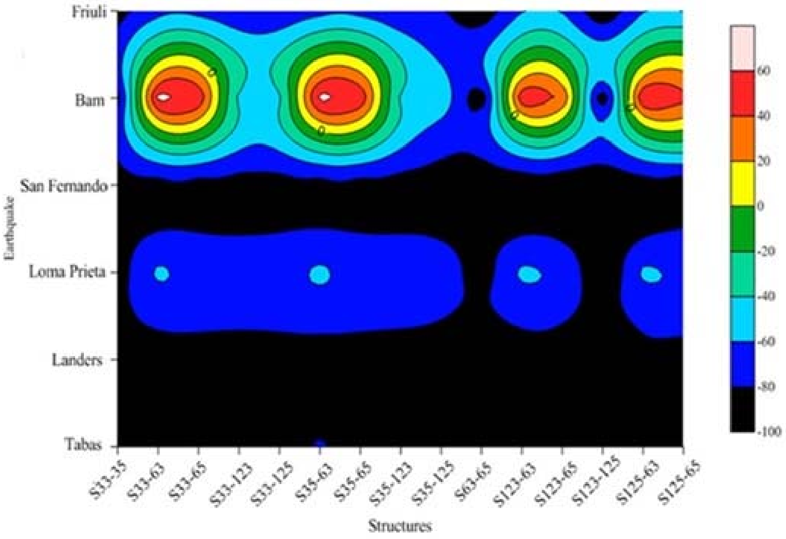


Figure 12. The percentage difference (PD) between the proposed values in this study and the Standard No. 2800 for soil type S2

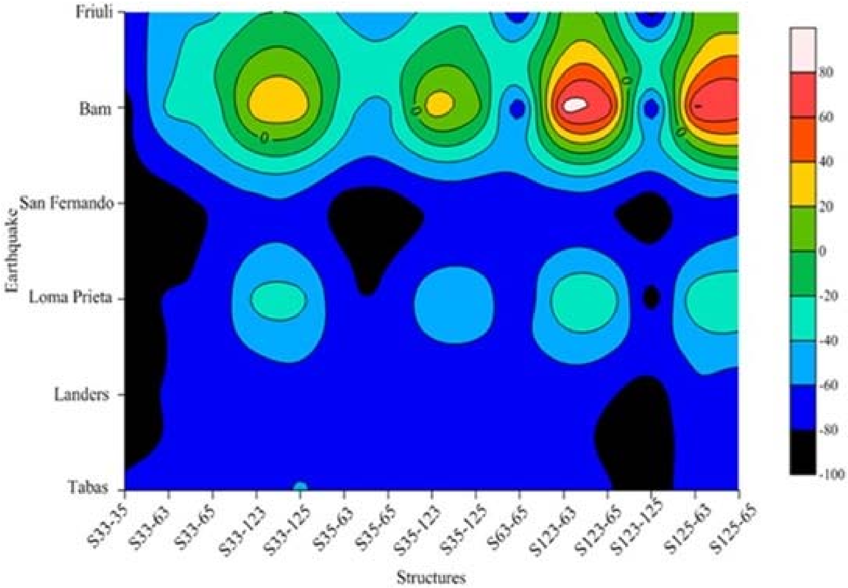


Figure 13. The percentage difference (PD) between the proposed values in this study and the Standard No. 2800 for soil type S3

As can be seen, for three-story structures against other structures and under high-risk Bam earthquakes, the proposed spave which is proposed by Standard No. 2800 should increase by about 10 to 20 percent. This amount should be reduced to about 80% for structures and under other earthquakes; for 6-floor and 12-floor structures, this amount has arrived by more than 80%; Therefore, the distance proposed by Standard No. 2800 for two adjacent structures is not suitable for high-risk earthquakes.

In the above contour, the percentage difference between the proposed values in this study and the Standard No. 2800, for type II soil and under all earthquakes considered in this study, is shown; As can be seen, for 6-story structures against other structures and under a high-risk Bam earthquake, the proposed by Standard No. 2800 should increase by more than 40% and for all structures and under other earthquakes this amount has arrived by more than 60%; Therefore, the distance proposed by Standard No. 2800 for two adjacent structures is not suitable for high-risk earthquakes.

In the above contour, the percentage difference between the proposed values in this study and the Standard No. 2800, for type III soil and under all the earthquakes considered in this study, has been shown. As can be seen, for three-story structures against other structures under the high-risk Bam earthquake, the proposed by Standard No. 2800 should increase by about 10 to 30%, and for 6-story and 12-story structures increased by more than 40 percent. For all structures and under other earthquakes, this amount has increased by more than 60 percent, and for 12-story structures against each other, this amount has increased by more than 80 percent; Therefore, the distance proposed by Standard No. 2800 for two adjacent structures is not suitable for high-risk earthquakes.

8. CONCLUSIONS

The achievements of this study are to obtain an optimum distance between two adjacent steel frames considering the effects of structure-soil-structure interaction using the PSO algorithm by MATLAB and SSSI simulation based on direct method by OpenSees software. In this study, soil effects were considered in the event that the distance that the Standard No. 2800 provides for two adjacent structures, regardless of these effects, and not consider the large displacements that occur by the soil. The results of this study show that, if adjacent same-height structures are constructed on hard soil, they wouldn't require being separated from each other, because they are moved in the same phase. But if these structures are taller than 6 stories and are built on soft soil, they have to be about 15 cm away from each other.

Also, the hazard level of an earthquake is higher, the amount of proposed in this study has increased, so it can be concluded that the hazard level of earthquakes also affects the distance between two adjacent structures.

In general, it can be said that for 3 stories structures against the 6 stories, which are based on S1 type soil and the hazard level of earthquake is high, to avoid collisions between two structures, the proposed spacing of Standard No. 2800 should be raised at least 10%, and for these adjacent structures and built on type S2 soil, this space should have increased by at least 55%.

For 3-story structures against the 12-story based on type S1 and S2 soils and high seismic hazard level, the proposed amount of distance of Standard No. 2800 should increase by at least 10 to 20%.

For a 6-story structure against 6-story based on type S3 soils and all hazard levels of the earthquake, the proposed amount of distance of Standard No. 2800 is suitable, and if the same type of structures built on other soils, requires no distance between each other.

For a 12-story building against a 6-story built on S2 type soil and high seismic hazard level, the proposed amount of distance of Standard No. 2800 must increase by at least 60%, for a 12-story structure against the 6-story the proposed spacing of Standard No. 2800 should be added by at least 90% and for a 12-story structure against 12-story built on type S3 soil and high seismic hazard level, this spacing is suitable.

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