The effect of the number of adjacent buildings on the seismic response of structures

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Abstract This study explores the effects of structure-soil-structure interaction (SSSI) on a 10-story structure under earthquake excitations, while it is linked closely to one or two (shorter, taller and the same) adjacent building structure/s, conjunction with a type of soft soil media. Then it is compared with non-adjacent building structure as SSI model. Fully nonlinear dynamic analysis, under influence of three different earthquake records, are conducted in direct method using 3D OpenSees software; and maximum responses of relative acceleration, displacement, drift and shear force of the ten-story structure in the SSSI models are compared with that of the SSI model. The results indicate that the building structures are significantly affected by the presence of the adjacent building structure/s. The 10-story building structure's response amplifies in drift, 16% when flanked by a taller building structure (15-story) and 20% when flanked by two taller building structures, also increase in shear force to 16% is considered. Indeed, the responses reduce to 17% in drift and 68% in shear force by a shorter adjacent building structure (5-story). On the other hand, effects of SSSI can be more prominent when there is more than one building structures interacting.

1 Introduction

As in cities and urban areas, the building structures are built closely to each other, and there are more than one structure in the medium, because of interference of the structural responses through the soil, the soil-structure problem evolves to a cross-interaction problem between multiple structures [1] [2]. Under such circumstances, the dynamic interaction and dynamic coupling of adjacent buildings via the underlying soil shouldn't be ignored [3]. But available evidences show that interaction of adjacent structures has not been paid comprehensive attention to.

In addition, major researches in this field are subjected to simulate superstructures as lumped mass with a single degree of freedom [3] [4] [5] [6]. Also, tow-dimensional models with plain strain behavior [7] are applied. Soil is simulated by spring, mass, and damper, or an equivalent impedance function [8] or assumption as a homogeneous, isotropic and linear elastic half-space [9]. Because of this excessive simplification, the complex geometry of the cross-section as well as the wrapping and secondary torsion specially in complicated and massive structures, are ignored [1], that would be lead to obtain not so accurate and reliable seismic results rather than 3D models, so 2D simplification is potentially risky in the seismic analysis of soil structure interaction (SSI) [10].

The result of researches in this field have shown that the structure soil structure interaction (SSSI) effects are very dependent on adjacent structures height in two structures, three structures and a group of structures on shallow foundations or deep foundations [4] [5] [11] [12].

As mentioned above, the aim of this paper is study on the effects of the number of adjacent structures (according to Fig. 1, as a sample of models) on the seismic response of a structure conjunction with three different earthquake excitations.

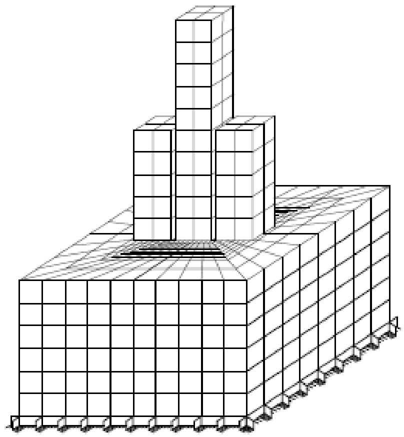


Fig. 1 Modelling of Structure-soil-structure interaction for a group of three structures in direct method

2 Structure-soil-structure system

2.1 Super structure model

In this study, in order to use a 3D model of a group of structures; five-, ten-, fifteen-story RC frame structures, two (5m) spans in X direction and two (4m) spans in Y direction with shallow foundations are employed. Primary analysis for designing of each single structure according to Iranian Concrete Code using ETABS software, without considering any effects of SSI or SSSI are conducted and gravity loads considering with National building regulations (section 6) and lateral loads considering with Iran’s 2800 standard (Iranian Seismic Code) [13], as well as gravity floor loads 600 and 200 (Kg/m^2) of dead and live load respectively are considered. In addition, the weight of beams and columns according to presented specific gravity to the software in the form of dead loads are added, automatically.

In this paper, the finite element method, is the used method with performing OpenSees 3D finite element analysis package [14]. Finite element modeling details of the RC frames and foundations are provided as:

Beam and columns are modeled as nonlinear force-based beam-column elements with distributed plasticity along the length of elements. Concrete behavior is modeled by a uniaxial material object with tensile strength and linear tension softening (Concrete02) [15]. Steel behavior is represented by a uniaxial Giuffre-Menegotto-Pinto model (Steel02).

Foundations are modeled as shallow foundations that made of eight-node mixed volume/pressure brick elements, which use trilinear isotropic formulation, and the material formulations for the elastic isotropic objects are three-dimensional, plane strain, plane stress, axisymmetric and plate fiber.

2.2 Sub structure model

Since the soil media plays a key role in SSI or SSSI models, then by using the finite element method based on direct method and applying 3D OpenSees software, a semi-infinite soil media is modeled conjunction with a group of building structures, as shown in Fig. 1. Table 1, shows the dynamic properties of the soil considered that is extracted of ref. [16] which categorized as type III according to the Iranian Seismic Code, with 30 (m) depth of soil and shear wave velocity of 270 (m/s^2), that includes eight-node brick elements, with three translational degrees of freedom along X, Y and Z coordinates and elastic-plastic behavior. In order to the numerous values of soil elements and to prevent excessive computation time, the element's size varied from 1m in each dimension around the buildings as well as near the surface in the soil to 5m far from the structures. And boundary conditions comprise fixed boundaries at the lowest level of soil, to model the bed rock and absorbent viscous boundaries, to avoid reflective waves produced by soil lateral boundaries. Absorbent boundaries are made of uniaxial and viscous material with non-linear elastic behavior that located as lateral boundaries in horizontal directions at a distance of 5 times the structure width [16].

Table 1 Major modelling properties of medium soft clay (Vs=270 m/s) (Rayhani and El Naggar, 2008)

Model parameters	value	Model parameters	Value
$\rho = \text{mass density}(\frac{kg}{m^3})$	1.595	$K = \text{bulk modulus(kpa)}$	9.37×10^4
$G = \text{shear modulus(kpa)}$	15.9×10^3	$\nu = \text{Poisson's ratio}$	0.42
$E = \text{elastic modulus(kpa)}$	4.5×10^4	$c = \text{cohesion intercept(kpa)}$	90
$\varphi = \text{friction angle(deg)}$	24	$c_{sb} = \text{interface cohesion(kpa)}$	50

k_n = normal stiffness($\frac{kpa}{m}$)	7.6×10[4]	k_s = shear stiffness($\frac{kpa}{m}$)	8×10[2]

2.3 Interface elements

Soil-structure interaction effects on seismic response of structures are examined employing interface elements. The interfaces between the foundation and soil are modeled as linear spring-slider systems and zero length contact 3D elements (Fig. 2) in the 3D OpenSees model, while interface shear strength is defined by the Mohr-Coulomb failure criterion. The relative interface movement is controlled by interface stiffness values in the normal (kn) and tangential (ks) directions, Based on recommended rule-of-thumb estimates for maximum interface stiffness values given by Itasca Consulting Group (2005) [17] and refining the magnitude of kn and ks to avoid intrusion of adjacent zones and to prevent excessive computation time.

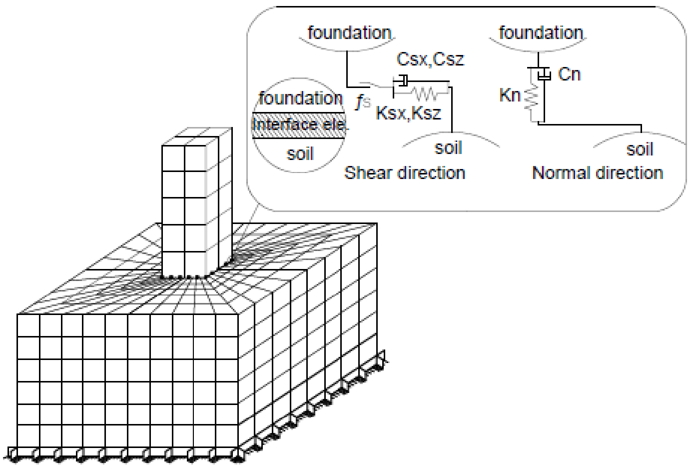


Fig. 2 Interface elements in SSI or SSSI models

3 Dynamic analysis of SSSI and SSI interaction

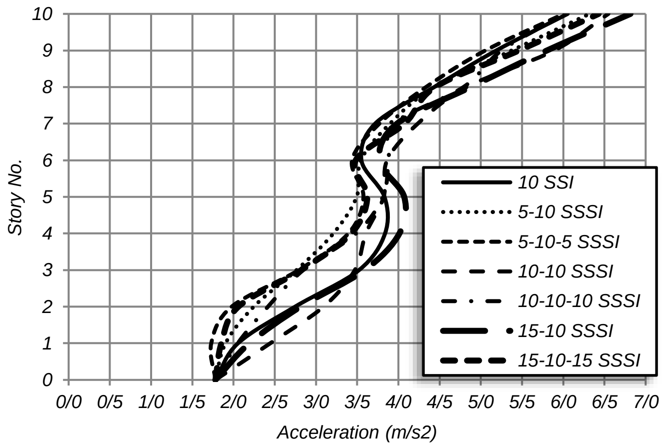
Fully nonlinear dynamic time history analysis by using of 3D OpenSees software under influence of three different ground motions (Iwait, Loma Prieta, Taiwan earthquakes) as shown in Table 1, that have been separately scaled according to the Iranian Seismic Code [13], are conducted for SSSI and SSI systems. All ground motions are recorded on high rigid soil in these regions that complies with the rigidity of soil type I of the Iranian Seismic Code [13]. We have used the scaled record displacements as bed rock records and applied to the models.

By using direct method, horizontal components of three different ground motion records have been applied to the lowest level of soil, representing the bed rock, in the combination of soil and structures, in three different models; i) a 10-story structure as a SSI model. ii) The 10-story structure flanked by one (shorter, taller and the same) adjacent building structure as a SSSI model with two structures. iii) The 10-story building structure flanked by two (shorter, taller and the same) adjacent building structures as a SSSI model with three structures (Fig. 3).

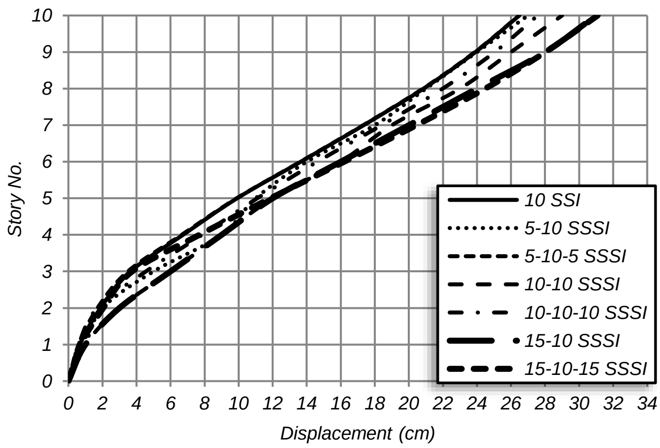
Table 1 Earthquake data for the parametric analysis obtained from the Pacific Earthquake Engineering Research (PEER) Centre Database

Earthquake	Station	Year	Soil shear velocity (m/s)	Magnitude (Mw)	Peak ground displacement (m)
Iwait	Minse Yuzawa	2008	655.45	6.90	0.043
Loma Prieta	Gilroy Array#6	1989	663.31	6.93	0.051
Taiwan SMART1(45)	SMART1 E02	1986	671.52	7.30	0.067

4 Results and discussions



a



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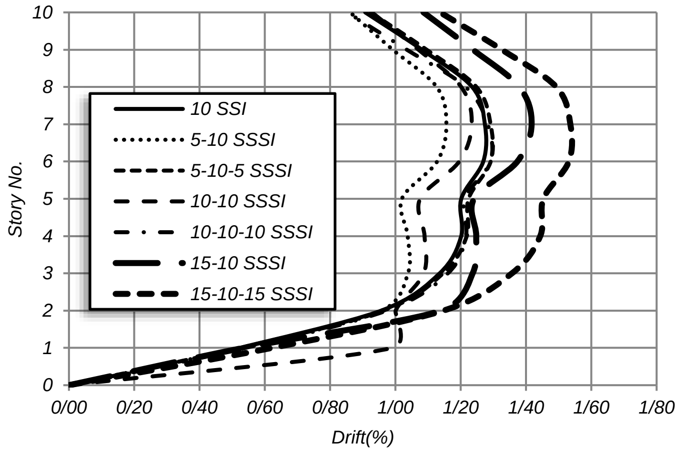

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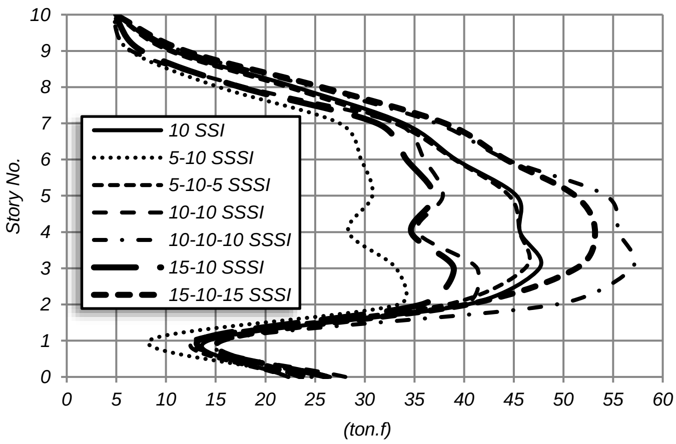

d

Fig. 3 – **a** Maximum responses of relative acceleration, **b** displacement, **c** drift and **d** shear force of a 10-story structure when it is alone in SSI model or linked with one or two other structure/s in SSSI models

The SSI and SSSI systems are analyzed with horizontal component ground motions from three earthquake records, and maximum responses of relative acceleration, displacement, drift and shear force of stories of the 10-story structure, have been considered when the 10-story structure as SSI model is i) alone, ii) in a group of two structures, flanked by one shorter, taller and the same adjacent structure or

iii) in a group of three structures flanked by two shorter, taller and the same adjacent structures.

Results of relative acceleration have been showed in Fig. 3– a. Comparing the SSSI with SSI response, the 10-story structure appears to be significantly affected, attenuated relative acceleration responses, -21% and -28%, by the presence of one and two 50% shorter structure/s respectively. While 12% amplified acceleration response is shown, by a 50% taller structure and 25% attenuated response by two 50% taller structures.

In Fig. 3–b, 10-story structure's displacement response amplifies up to 48% when adjoined by a 50% shorter structure and attenuates up to 11% when adjoined by two 50% shorter structures. 64% and 20% amplifications are seen when one and two 50% taller structure respectively is/are present in adjacency.

Responses of drift are shown in Fig. 3–c, 17% attenuation is seen when one 50% shorter structure is in adjacency; while adjoining with two 50% shorter structures has no significant attenuation or amplification in drift responses. Presence of one and two 50% taller structure/s, amplify drift responses up to16% and 20% respectively.

Responses of shear force in Fig. 3–d, indicate that, up to 68% and 9% attenuation of responses are occurred in adjacency with one and two 50% shorter structure/s respectively. Response attenuates up to 30% in adjacency with a 50% taller structure and amplifies up to 16%, when 10-story structure is linked by two 50% taller structures. Although linking with one identical building structure can attenuate response of shear force up to 39%. Two identical building structures can amplify response up to 22%.

5 Conclusions

Study of the response of relative acceleration, displacement, drift and shear force in the stories of the 10-story structure, indicate that effects of SSSI can be more prominent when there are more than one building structure interacting that depend on the number and height of adjacent structures, dynamic characteristics of buildings, and frequency content of seismic data. The results show that considering different adjacent structures lead to increase or decrease about 10 times of percent of responses.

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