SEISMIC EVALUATION OF REINFORCED CONCRETE SHEAR WALLS CONSIDERING SOIL-STRUCTURE INTERACTION

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ABSTRACT

The use of concrete shear wall is quite common in a number of seismic countries as a result of their successful seismic behavior during past severe earthquakes. As the Iranian seismic code does not address the soil–structure interaction (SSI) explicitly, the effects of SSI on reinforced concrete shear walls are studied using the sub-structure method. Two types of slender (H/L>2) and squat (H/L<2) walls on three types of soil, with and without the soil interaction, are modelled and subjected to different earthquake records. The walls and supports are modelled using finite element method (FEM). The FEM calculations are carried out using the program ABAQUS. The results showed that soil-structure interaction has negligible effect on maximum displacement of both squat and slender walls; however, considering SSI for seismic design of the squat wall is essential.

1. INTRODUCTION

The estimation of earthquake motions at the site of a structure is the most important phase of seismic design of a structure. In classical methods used in structural analysis, it is assumed that, the motion in the foundation level of structure is equal to ground free field motion. This assumption is correct only for the structures resting on rock or very stiff soils. For the structures constructed on soft soils, foundation motion is usually different from the free field motion and a rocking component caused by the support flexibility on horizontal motion of foundation has been added (Tabatabaiefar and Massumi, 2010). However, the destruction of numerous buildings in 1985 Mexico earthquake made researchers focus on soil–structure interaction effects on the response behavior of structures. There are numerous studies which have shown correlation between damage and local geology and site condition (Ghosh and Madabhushi, 2003). Many researchers studied seismic analysis of soil-structure interaction for different types of structures (Dogangun et al., 2007; Mwafy et al., 2008).

The use of concrete-shear-wall buildings is quite common in some earthquake-prone countries such as Iran; their seismic behavior has been successful during past severe earthquakes, both, from a serviceability as well as a safety standpoint (Wood, 1991). Therefore, their use has been recommended in earthquake-resistant design as long as its true behavior is included in building modeling (Sozen, 1989).

In this investigation an attempt has been made to study the interaction effects of concrete shear wall-foundation-soil system. The parameters of the problem are constant and don't change during the computational process. The problem requires a sophisticated and robust modeling which in turn would yield desirable accuracy in the predicted behavior. The analysis involves a fully three-dimensional finite element formulation. SSI analysis is based on the sub-structure approach and ground motion corresponding to Kobe (1995) is used to excite the model. The aim of considering the entire system as one integral compatible unit is to estimate the deformation and stress pattern of concrete shear wall.

2. PROBLEM DEFINITION

In this investigation, models of concrete shear walls analyzed by Thorhallsson and Olafsson (2010), has been considered for analysis.

2.1. WALL MODELS

First case is the squat wall which is shown in Fig. 1. On the top of the wall is distributed load q= 24.5 KN/m to represent concrete roof or floor. Second case is the slender wall model which is three times higher than the squat one and the distributed load (q) reacts on every story (Fig. 2).

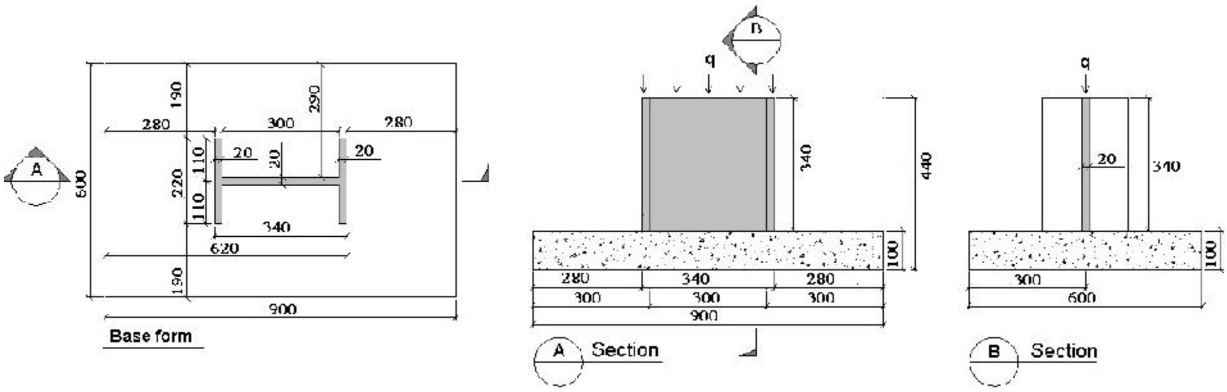

Figure 1. Geometry of squat wall and its foundation (Thorhallsson and Olafsson, 2010),
(All dimensions are in centimeter)

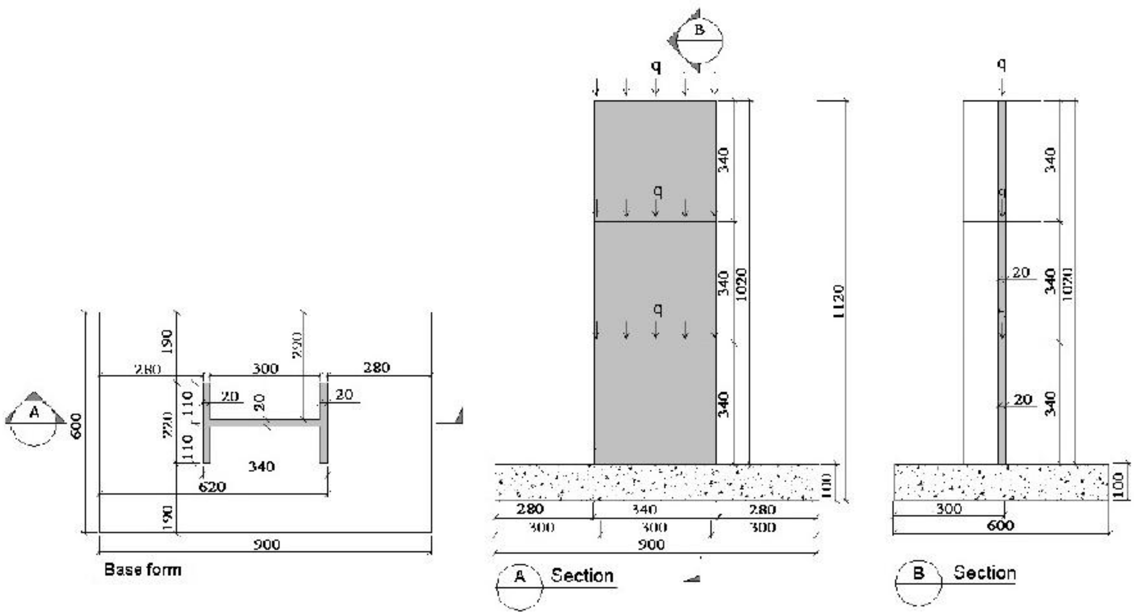

Figure 2. Geometry of slender wall and its foundation (Thorhallsson and Olafsson, 2010),
(All dimensions are in centimeter)

2.2. MATERIAL PROPERTIES

All the walls are made of concrete C25, which have compressive strength f_c = 25.0MPa and tensile strength f_t = 3.3MPa (Eurocode 2, 2004).

The reinforcement is B500, which have yield strength f_y = 500.0MPa. All the walls are reinforced in single layer in the middle of the wall in both directions with K10 c250, giving a:

Reinforcement ratio: $\frac{A_{bar}}{A_{wall}} = 0.0015 = 0.15\%$

Three types of soil representing type II, III and IV according to classification of the Iranian Standard no.2800-05 are selected in this study as presented in Table 1.

Table 1. Properties of the soil types considered in this study (Tabatabaiefar and Massumi, 2010)

Soil type	Shear wave velocity V_s(m/s)	Elastic modulus E(kg/cm^2)	Shear modulus G_{max}(kg/cm^2)	Density Ɣ(kg/m^3)	Poisson's ratio ν
II	600	16400	6480	1800	0.28
III	320	4945	1808	1750	0.39
IV	150	935	335	1500	0.40

2.3. TIME HISTORY ANALYSIS

The time history analysis of the integrated structure was carried out with ground motion corresponding to the longitudinal component of Kobe earthquake at Cue-Takatori station with peak ground acceleration of 0.611g. The total duration of the ground motion is taken as 18 sec. Acceleration time history of this ground motion is shown in Figure 3.

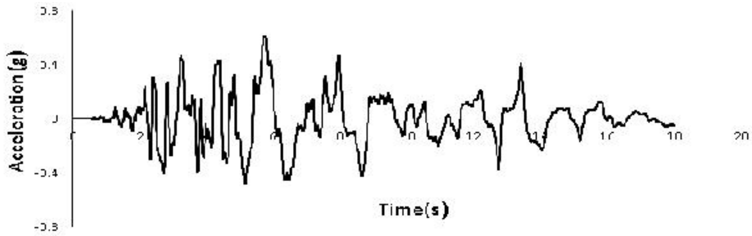

Figure 4. Time history plot of Kobe ground motion

3. SOIL–STRUCTURE SYSTEM

Dynamic soil-structure interaction (SSI) is a complex phenomenon for which research suggests solution by using two different methods: sub-structure method and the direct method. In the sub-structure method, the soil-structure system is divided into two sub-structures: (i) super-structure that may include a portion of soil in the neighborhood and (ii) the remaining unbounded soil. The unbounded half-space is usually represented by simple means using an impedance matrix, which may be directly added to the dynamic stiffness matrix of the structure. In the direct method, the structure and a fixed extent of half-space are modeled in an identical manner with only distinction in material properties. Sub-structure method operates in frequency domain while the scope of direct method is with time domain.

Sub-structure approach was adopted for modeling the soil. In the solution for a rigid disk on a half-space, terms in the impedance function are expressed in the form, (Stewart et al., 1998):

$$\bar{K}_j = K_j(a_0, \neg) + i\,\mu C_j(a_0, \neg) \qquad , \qquad a_0 = \frac{r\mu}{v_s} \tag{1}$$

Where j denotes either deformation mode u or ¯ , μ is angular frequency (rad/sec), a_0 is a dimensionless frequency, r = foundation radius, v_s = soil shear wave velocity, and ³ = soil poisson ratio.

Foundation radii are computed separately for translational and rotational deformation modes to match the area (A_f) and moment of inertia (I_f) of the actual foundation, as follows:

$$r_1 = \sqrt{\frac{A_f}{\Pi}} \quad , \quad r_2 = \sqrt[4]{\frac{4I_f}{\Pi}} \tag{2}$$

$$k_u = \alpha_u . K_u \quad , \quad c_u = \beta_u . \frac{K_u . r_1}{Vs} \tag{3}$$

$$k_\theta = \alpha_\theta . K_\theta \quad , \quad c_\theta = \beta_\theta . \frac{K_\theta . r_2}{Vs} \tag{4}$$

The quantities α_u, β_u, α_θ, β_θ are dimensionless parameters expressing the frequency dependence of the results, while K_u and K_θ represent the static stiffness of a disk on a half-space, defined by:

$$K_u = \frac{8}{2-\nu} G . r_1 \quad , \quad K_\theta = \frac{8}{3(1-\nu)} G . r_2^3 \tag{5}$$

Where G =soil shear modulus.

Presented in Figure 5 are the frequency-dependent values of α_u, β_u, α_θ, β_θ based on closed form expressions.

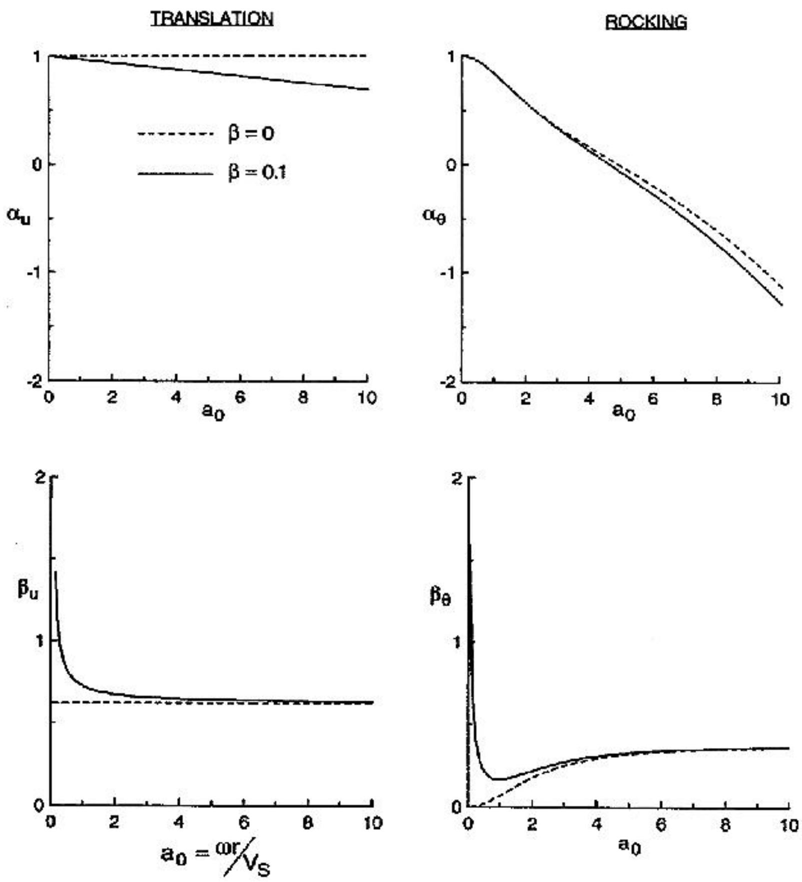

Figure 5. Foundation stiffness and damping factors for elastic and viscoelastic half-spaces (β=hysteretic damping)

4. FINITE ELEMENT MODELING

Three-dimensional finite element analysis of the entire system consisting of wall, foundation and the soil has been carried out in a single step considering linear elastic behavior of all components. Foundation has been modeled using three-dimensional continuum elements (C3D8) having three translational degrees of freedom at each node. Wall has been represented by shell element (S4R) which has both bending and axial tension/compression capabilities. Smeared layers of rebar in the wall have been modeled by isoparametric method. Fig. 6 represents the finite element model of squat and slender walls with two nodes; one at the top and other at the bottom of the wall to monitor the nodal translation both in the x and z direction over time in ABAQUS.

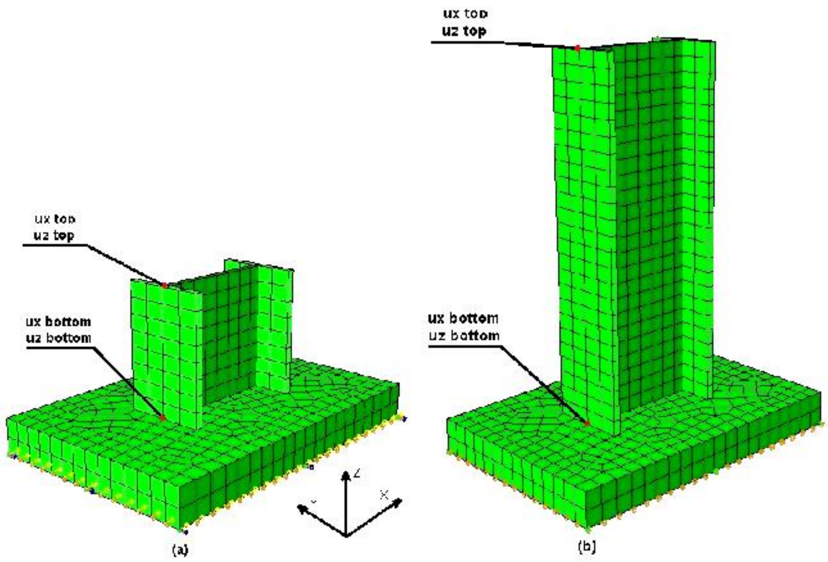

Figure 6. Finite element idealization of (a) squat wall, (b) slender wall with two chosen nodes

5. DISCUSSION OF RESULTS

The behavior of the wall-foundation-soil system under earthquake record considering SSI is discussed below. This behavior has been compared with that of the wall's foundation assuming fixity at the base, which will henceforth be referred to as Non-Interactive Analysis (NIA).

Maximum displacements in x-direction for both squat and slender walls modeled with soil as flexible base does not differ much from that of structures modeled as fixed base, but for z-direction the results shown that wall with flexible base has rocking motion, especially for slender wall where displacements in z-direction are considerable (Table 2).

Table 2. Maximum displacement for squat and slender walls, (negative value in z-direction means down direction)

Wall type	Soil type	Maximum displacement in x-direction (m)		Maximum displacement in z-direction (m)	
		Top	Bottom	Top	Bottom
Squat	II	0.3481	0.3469	-0.0126	-0.0125
	III	0.3574	0.3551	-0.0078	-0.0076
	IV	0.3584	0.3579	-0.0104	-0.0102
	NIA	0.3578	0.3573	-0.0001	-0.0000
Slender	II	0.3697	0.3568	-0.0244	-0.0211
	III	0.3639	0.3555	-0.0268	-0.0240
	IV	0.3712	0.3654	-0.0490	-0.0476
	NIA	0.3666	0.3575	-0.0051	-0.0007

Table 3. Maximum stresses for squat and slender walls,(negative value is compression stress and positive value is tension stress)

Wall type	Soil type	Maximum stress in x-direction (MPa)		Maximum stress in z-direction (MPa)	
		Tension	Compression	Tension	Compression
Squat	II	3.76	-5.38	0	0
	III	1.80	-5.80	0	0
	IV	1.35	-6.59	0	0
	NIA	0.77	-2.17	0.40	-1.29
Slender	II	13.88	-20.00	0	0
	III	22.44	-28.53	0	0
	IV	6.61	-16.52	0	0
	NIA	18.05	-20.53	7.24	-11.99

Unexpectedly, considering SSI for squat wall caused considerable increase in stresses (Table 3). Squat wall with fixed base has both minimum tension and compression stresses and by loosening soil from type II to type IV compression stress has increased consequently; however, tension stress has a decreasing sequence. According to Table 3, unlike squat wall, maximum stresses in both tension and compression occurred in slender wall with fixed base and considering SSI caused reduction in stresses from stiff to loose soil. Stresses in z-direction for fixed-base slender wall have considerable amounts which due to rocking motion of flexible-base walls turn to zero.

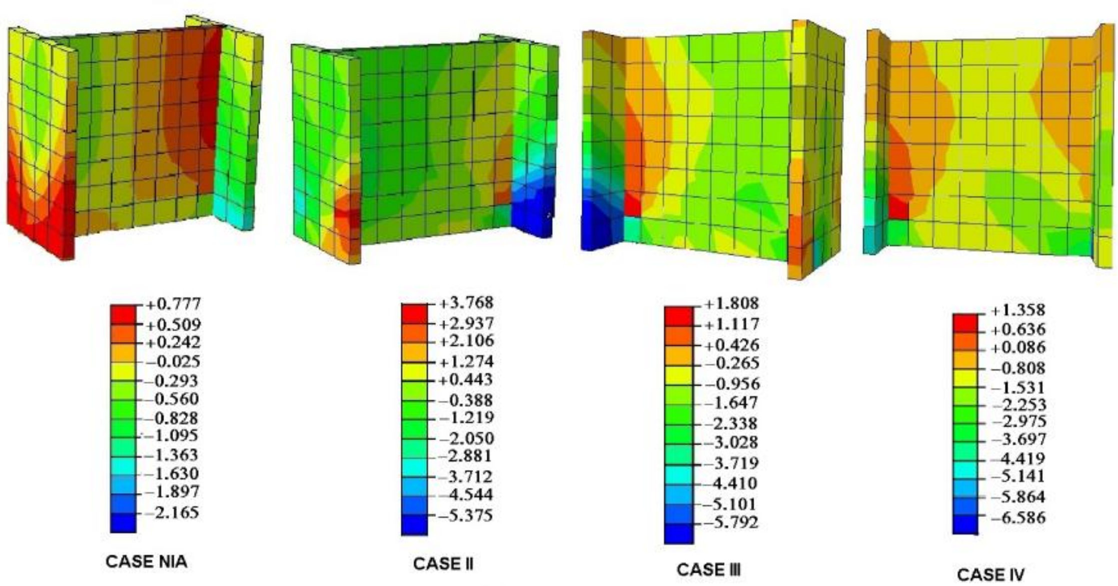

Figure 7. Contour of maximum stress (MPa) in squat wall with fixed base (case NIA) and flexible base on soil types II, III, IV, under Kobe ground motion, (negative value is compression stress and positive value is tension stress)

As it's shown in fig. 7, maximum field of tension in squat walls has developed in case NIA, nevertheless, has minimum amount of tension between four models. In three flexible models which SSI has considered, compression field is more than tension. It seems SSI effect caused compression field to overcome tension field as well as in amount; as compression is more than twice of tension in these flexible models. By loosening soil from case II to case IV, maximum tension has transmitted from the position of the flange to the web in the wall with a decreasing sequence in amount, however, in the whole models, maximum compression is concentrated in the wall's flange and has an increasing sequence in amount.

According to fig. 8, unlike squat wall, in all four slender models, maximum tension and compression concentrated in the wall's web. Maximum and minimum stress is gained for case IV. Sudden tension increase in case III which has disturbed the reduction sequence is notable; therefore, tension reduction sequence due to soil loosening is not seen in slender wall.

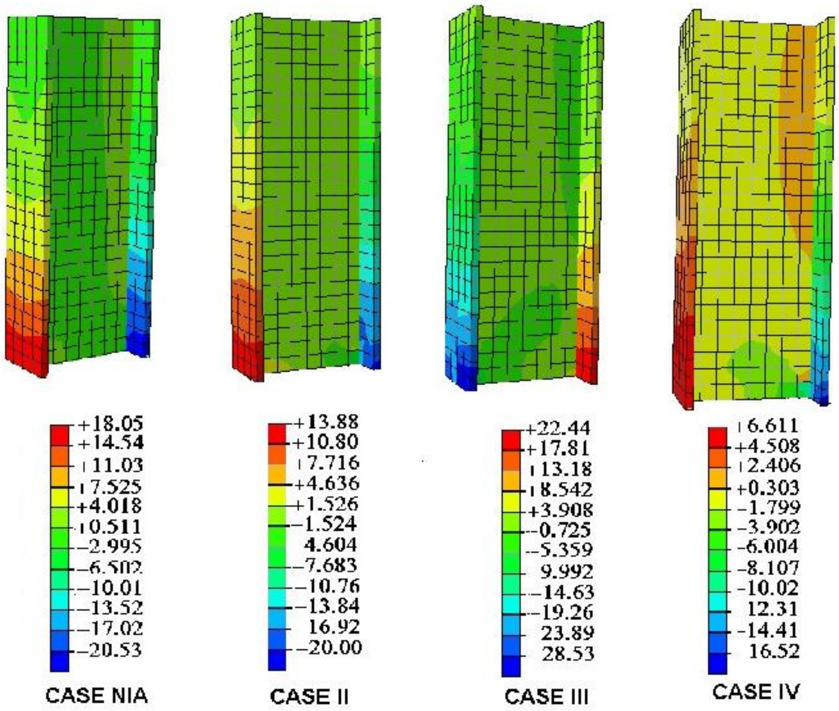

Figure 8. Contour of maximum stress (MPa) in slender wall with fixed base (case NIA) and flexible base on soil types II, III, IV, under Kobe ground motion,
(negative value is compression stress and positive value is tension stress)

6. CONCLUSIONS

The following conclusions may be drawn from the analytical investigation reported in this paper on the elastic response of the two types of squat and slender reinforced concrete shear wall modeled based on the Iranian Seismic Code (Standard no. 2800-05) with and without soil:

- Soli-structure interaction has negligible effect on maximum displacement of both squat and slender walls in x-direction.
- Maximum stresses in z-direction have significant amounts in slender wall with fixed base which in walls with flexible base is zero.
- Squat walls, unlike slender walls has different tension scattering and position of maximum tension changes due to soil-structure interaction.
- It is necessary to consider the effect of soil-structure interaction for seismic design of squat walls.
- It is essential to consider the effect of soil-structure interaction for seismic design of the slender wall founded on soil type III.

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