Effect of Soil-Structure Interaction on Torsional Response of Asymmetric Wall Type Systems

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Abstract

Generally in the analysis of structures, the base of structures is assumed to be fixed. Whereas, the soil under the structures foundation modify earthquake loading and also change the structural properties. Therefore, considering the fixed base in the structure analysis is not realistic. On the other hand, recent studies have pointed out that for an important class of widely used structural elements such as reinforced concrete flexural walls; stiffness is a strength dependent parameter. This implies that the lateral stiffness distribution in an asymmetric wall-type system cannot be evaluated prior to the assignment of elements’ strength. Consequently, both stiffness and strength eccentricity are important parameters affecting the seismic response of asymmetric wall-type systems. In this study, for different position of stiffness and strength eccentricity, torsional response of asymmetric wall-type system is evaluated. In this evolution the effect of foundation flexibility, is assumed.

Keywords: Asymmetric-building; soil-structure interaction; torsional response; stiffness and strength eccentricity; wall-type system.

1. INTRODUCTION

Asymmetric buildings are more vulnerable to earthquake hazards compared to the buildings with symmetric configuration. The recognition of this sensitivity has led the researchers to concentrate their studies on earthquake characteristics, evaluation of the structural parameters and validity of the system models (such as: Kan and Chopra 1977).

In order to mitigate the effect of torsion during earthquakes, most seismic codes of the world provide design guidelines for strength distribution based on the traditional perception that element stiffness and strength is independent parameters. Recent studies have pointed out that for an important class of widely used structural elements such as reinforced concrete flexural walls, stiffness is a strength dependent
parameter (Priestley 1998). This implies that the lateral stiffness distribution in a wall-type system cannot be defined prior to the assignment of elements’ strength. Consequently, both stiffness and strength eccentricity are important parameters affecting the seismic response of asymmetric wall-type systems (Tso 2001).

Because of deformations within the soil immediately beneath a structure, the motion of the base of a building may differ from the motion of the ground at some distance away. Such a difference is indicative of soil-structure interaction. Interaction effects refer to the fact that the dynamic response of a structure built on site depends not only on the characteristics of the free-field ground motion but also on the inter-relationship of the dynamic structural properties and those of the underlying soil deposits. The importance of soil-structure interaction has long been recognized, and a number of techniques have been formulated for analyzing its effects on earthquake building response. In a commonly employed idealization, the effects of the foundation medium on the structural response are simulated by a series of springs and dashpots representing a theoretical half-space surrounding the base of the structure. Alternatively, the soil-structure system can be represented by a two or three-dimensional finite-element model (Shakib and Fuladgar 2004).

So far, several researchers have attempted to incorporate the flexibility of foundation in asymmetric system models. Among them, Balendra et al. (1982) used simple springs to represent frequency-independent values and to approximate the frequency-dependent foundation impedance functions in an asymmetric multistory building. Later, Tsicnias and Hutchinson (1984) extensively investigated the steady-state response of flexibility supported torsionally coupled buildings subjected to harmonic ground motions by using frequency-independent springs and dashpots. Using the same simple Single-storey structural model, Chandler and Hutchinson (1987) examined the seismic response to different types of earthquakes and considered approximate frequency-independent foundation impedance functions. Also, Sivakumaran et al (1992) and Sivakumaran and Balendra (1994) presented a method of analysis to determine the seismic response of three-dimensional asymmetric multi-storey Building-foundation systems using approximate frequency independent Foundation impedance functions. Wu et al. (2001) incorporated the frequency-dependent foundation impedance functions in the frequency domain to assess the combined soil–structure interaction and torsional coupling effects on the asymmetric buildings.

An accurate modeling of soil–structure interaction is expected to incorporate the major effects of the response of complex systems such as torsional coupled system. On the other hand, recent studies show that the location of CM and CR affect the dynamic response of asymmetric building significantly (such as: Myslimaj and Tso 2001). In this study an attempt has been made to consider the above effects by formulating soil–structure interaction system in order to evaluate the seismic response of asymmetric wall-type system. An accurate method of soil–structure interaction in time domain has been used by finite element method and also, different position of stiffness and strength eccentricity are assumed.

### 2. SYSTEM MODEL AND FORMULATION

Structural System consists of a single rectangular uniform slab of plan dimensions and weight W. The centre of mass CM is located at the geometric centre of the slab. It is supported at the edges by two mass less elasto-plastic elements E-1 and E-2(Figure 1). These two elements have three important parameters: yield displacements, nominal strengths and lateral stiffness. These parameter for element E-1, are assumed to be and for element E-2 is assumed to be , where is the yield displacement distribution parameter and is taken to be equal to or greater than unity. being greater than unity implies that the wall E-1 has a larger length than the wall E-2. is the strength distribution parameter and is taken to be equal to or greater than unity, this parameter relate strength of the two elements. The location of CV is governed by the strength distribution parameter . Also, is the stiffness distribution parameter which it is relate with and in the form .
For this system the strength and stiffness eccentricity can be evaluated according to the following relations:

\[ e_V = \frac{\beta - 1}{\beta + 1} \]  
(1)

\[ e_F = \frac{1 - \gamma}{\gamma + 1} \]  
(2)

Using a fixed value of \( \alpha \) equal to 1.4, five models were created, with \( \beta \) equal to 1.4, 1.2, 1.1, 1.0 and 0.8. They will be referred to as models 1, 2, 3, 4 and 5, respectively. Both elements in model 1 have the same stiffness, because \( \gamma = \beta / \alpha \) is equal to 1. With reference to CM as the origin, it has zero stiffness eccentricity and positive strength eccentricity. In models 2 and 3, \( \gamma > 1 \) and \( \beta < 1 \), consequently CR is located on the left while CV on the right of CM (balance condition). These models have negative \( e_V \), but positive \( e_F \). In model 4, \( \beta = 1 \) and \( \gamma < 1 \). Therefore, it has zero strength eccentricity and negative stiffness eccentricity. Finally, model 5 represents the situation when both the stiffness and strength eccentricities have the same (negative) sign. Details of the strength, stiffness eccentricity of the five models relative to CM, are given in Table 1.

Table 1: Detail of strength, stiffness eccentricity of the five models

| Models | \( \alpha \) | \( \beta \) | strength eccentricity | Stiffness eccentricity |
|--------|-------------|-------------|----------------------|------------------------|
| 1      | 1.4         | 1.4         | Right                | zero                   |
| 2      | 1.4         | 1.2         | left                 | Right                  |
| 3      | 1.4         | 1.1         | left                 | Right                  |
| 4      | 1.4         | 1           | zero                 | left                   |
| 5      | 1.4         | 0.8         | left                 | left                   |

Above five models resting on homogeneous soil surface, as shown in Figure 2, the walls of these models at the base are connected to a rigid foundation. Proportional viscous damping is assumed for the building such that the superstructure possesses classical normal modes. The supporting soil is characterized by its mass density, \( \rho \); shear wave velocity, \( V_s \) and Poisson’s ratio \( \nu \). In global co-ordinate system, the differential equation of motion of soil–structure interaction system can be written in the following form:

\[
[M][\ddot{U}] + ([C] + [C_{V2}] + [C_{V3}] + [C_{U3}])\{\dot{U}\} + \{P(U)\} = \{F(t)\}
\]  
(3)

Where \( \{F(t)\} \) can be written in the following form:
\[ F(t) = -[M][R_d]\{\ddot{u}_d\} + [C_{V_2}][\dot{u}_{V_2}] + [C_{V_3}][\dot{u}_{V_3}] + [C_{V_4}][\dot{u}_{V_4}] + [C_{V_2}][\ddot{u}_{V_2}] + [C_{V_3}][\ddot{u}_{V_3}] + [C_{V_4}][\ddot{u}_{V_4}] \]  

\( \{u_d\} \) is the vector of displacement in global co-ordinate system relative to the bedrock. \( \{\dot{u}\} \) and \( \{\ddot{u}\} \) are the vectors of velocity and acceleration in global co-ordinate system relative to the bedrock. \( [M] \) and \( [C] \) are the mass and damping of the whole system, which is derived by assembling the elements matrices. In this study, Rayleigh damping is used to construct the damping matrix \( [C] \). \( [C_{V_2}] \) to \( [C_{V_4}] \) are the viscous boundary matrices on the four sides of the free field elements. \( \{u_{V_2}\} \) to \( \{u_{V_4}\} \) are the vectors of free field velocity on the four sides. \( \{u_{d}\} \) is earthquake ground acceleration vector at the bedrock and \( [R_d] \) is the matrix of the ground motions influence. Then, the differential equation of motion of soil–structure interaction system (Eq. (3)) is solved in incremental form by employing the Newmark β-method assuming constant average acceleration over a short time interval.

![Diagram of the soil structure interaction system](image)

Figure 2: soil structure interaction system.

3. PARAMATRIC STUDY

To verify the effect of soil–structure interaction on the response of asymmetric buildings an idealized three dimensional single-storey system is studied. To provide a target for comparison, a symmetric model is created and will be referred to as model R. It has identical elements at the edges and the stiffness of each element is adjusted such that this system has the same lateral period and similar lateral strength as the other asymmetric models. Since there will be no torsional response, results obtained from this model represent translation response only. The influence of torsion on the other models can then be judged by comparison. The structural model consists of a single rectangular uniform slab of plan dimensions 12×9
m and weight $W=1265$ KN. One can design the above-described models so as to have a lateral period $T=0.69$ s and an overall nominal strength of $0.2W$, i.e. 253 KN. The centre of mass (CM) is located at the geometric centre of the slab. It is supported at the edges by two mass less elasto-plastic elements wall E1 and wall E2 in the y-direction, as shown in Figure 2. These elements may be identified as two reinforced concrete flexural Walls having different lengths. The walls yield displacements can be readily determined. The System is assumed to be mono symmetric. Such a model has been used to illustrate torsional phenomena in ductile systems. So, one can focus on the mechanism of the inelastic response process and obtain a physical understanding of the behavior of asymmetrical structural Systems. Rayleigh damping is assumed to be 5 per cent in each mode. According to table 1 and the above descriptions, six models are created and the details of these models are given in table 2.

Soil beneath the structure is modeled with solid elements. The solid element has eight nodes with three degrees of freedom at each node. The far field boundary is modeled by using “dashpot”. Height of the soil over the bedrock is assumed to be 30 m and the bounded soil is taken to be 150x90 m. In this study three type of soil are assumed and are given in table 3. Rayleigh damping equal to 7 per cent for each mode is included in the analyses. The seismic response computations are carried out using the OPENSEES program.

All models are excited along the y-direction by a widely used earthquake ground motion: the NS component of the 1940 El Centro earthquake record, amplified by a factor of 1.5. The earthquake is applied to the bedrock of models.

Table 2: Detail of strength and stiffness of six models

| Models | Strength(KN) | Stiffness(KN/m) | yield displacements(m) |
|--------|--------------|----------------|------------------------|
|        | Wall-1 | Wall-2 | Wall-1 | Wall-2 | Wall-2 | Wall-1 |
| R      | 126    | 126    | 5412   | 5412   | 0.0234 | 0.0234 |
| 1      | 105    | 147    | 5412   | 5412   | 0.0195 | 0.0273 |
| 2      | 113    | 136    | 5828   | 4995   | 0.0195 | 0.0273 |
| 3      | 118    | 129    | 6061   | 4762   | 0.0195 | 0.0273 |
| 4      | 123    | 123    | 6315   | 4508   | 0.0195 | 0.0273 |
| 5      | 134    | 107    | 6889   | 3934   | 0.0195 | 0.0273 |

Table 3: Properties of soil

| soil    | shear wave velocity | mass density (ton/m³) | Poisson’s ratio |
|---------|---------------------|-----------------------|-----------------|
| TYPE    | (m/sec)             |                       | ---             |
| I       | 800                 | 1.9                   | 0.4             |
| II      | 300                 | 1.8                   | 0.3             |
| III     | 100                 | 1.7                   | 0.3             |

To verify, the variation of time history responses of the symmetric building (model R), situated on three type of soil, figure 3 are represented by considering and ignoring soil–structure interaction (i.e. fix). Variations of response time histories are normalized to peak response of fix case. As it can be seen from the figure, the soil–structure interaction affects are increased the lateral displacements. Soil type III (soft soil), has maximum effect and the effect of soil type II (stiff soil) is less compared to soil type III. It is notable that in soil type I (very stiff soil), the variation time history for interaction and no-interaction are similar.

The variation of peak displacements of two edges (wall E1, wall E2), versus model number are shown in Figs. 4 for three type of soil respectively. As it can be seen from figure 4, for wall 1, in the two models 4 and 5 the effect of soil interaction is important so that for soil type I, peak displacements increase relative to soil type III. For wall 2, this pattern can be seen for model 1 and2. It is worth mentioning that
only for model 3, this effect is not important so that for three type of soil and for two walls peak displacements are equal.

Figure 3: Variation of displacement response time histories of the symmetric building

A clearer picture on how torsion affects the behavior of the models can be obtained by focusing on their rotational responses; one of these responses is slab rotation. Peak of slab rotation for five models are shown in figure 5. In each figure, base flexibility condition compare with fix condition. As it can be seen in Fig5 in each of five models (except model 3), the soil type I decrease the slab rotation. This effect in soil type II is less than the soil type I and in soil type III, is not noticeable. For model 3, similar to displacement response the effect of soil-structure condition on rotational response is not important. Also Figures 5, show that variation of rotational response of five models is independent of soil-structure interaction so that in all case model 3 has minimum rotation and model 5 has maximum rotation.

4. CONCLUSIONS

Three-dimensional soil–structure interaction behavior of wall-type asymmetric buildings with different condition of strength and stiffness, subjected to component of El Centro 1940 earthquake records is investigated. The study leads to the following conclusions:
The CV and CR positions have a significant effect on the response of soil–structure interaction system. In general flexibility condition increases the lateral displacement and decrease the rotational response. In balance condition, the effect of flexibility is not noticeable so that for any type soil (soft, stiff, very stiff) the lateral and rotational responses are almost similar compared to fix condition.
Figure 4: Variation of variation of peak displacements of two edges for five models
Figure 5: Peak of slab rotation for five models

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