The Effect of soil-flexibility on seismic response of a typical Steel Plate Shear Wall subjected to Duzce Earthquake

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Abstract: - Steel Plate Shear Wall is commonly employed as a principal system to resist lateral loads due to wind or earthquake forces. An accurate model for SPSW needs to consider the effect of all components for analysis such as foundation and subsoil. One of the most important aspects of structural analysis is soil-structure interaction (SSI). Such interaction may alter the dynamic characteristics of structures and consequently may be beneficial or detrimental to the performance of structures. This investigation is aimed to evaluate the effect of soil-structure interaction on seismic response of a typical multi-story SPSW designed according to AISC requirements. In this procedure, a time-direct method is used in which the unbounded soil is modeled by couple finite-infinite elements. To investigate the effects of SSI the following types of analysis are performed: in the first type, the structure is analyzed without subsoil (fixed base) and in the second type, analysis is carried out for the same structure with consideration of soil-structure interaction (flexible-base). Finally, the results of analysis with and without SSI effects are compared.

Key-Words: - Steel Plate Shear Wall, Soil Structure Interaction, seismic response, dynamic analysis

1 Introduction
Steel Plate Shear Wall is commonly employed as a principal system to resist lateral loads due to wind or earthquake forces. An accurate model for SPSW needs to consider the effect of all components for analysis such as foundation and subsoil. For example the deformation at the base of a major shear wall in a building structure will significantly affect the displacements and force distribution in the upper stories of a building for both static and dynamic loads [1]. Therefore, one of the most important aspects of structural analysis is soil-structure interaction (SSI). Such interaction may alter the dynamic characteristics of structures and consequently may be beneficial or detrimental to the performance of structures. In classical method for the structural analysis, it’s 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 constructed on rock or very stiff soil. For the structures constructed on soft soil, foundation motion is usually different from the free motion and a rocking component caused by support flexibility on horizontal motion of foundation is added [2]. For buildings with high periods, the effect of foundation movements may not be very significant.

But for relatively stiffer structural systems, such as medium-height shear walls and braced frames, the foundation movements can cause significant flexibility in the system, and may result in an inaccurate estimation of seismic demands [3]. Also, the strength and stiffness characteristics of the underlying soil control the foundation movements and SSI effects on the structure significantly [4-5]. On the other hand past researches indicate that in tall rigid structures on softer soil, the SSI generally tends to large increases in natural period of the structure, leading to much larger relative displacements [6-7].

This study focuses on the effect of soil-structure interaction on structural response of Steel Plate Shear Wall in terms of story shear, story displacements and story drift. In this paper a time-direct method is used in which the numerical modeling of system is carried out with finite element method (FEM) using the software Abaqus [8].

2 Details of structure, foundation and soil condition
2.1 Steel Plate Shear Wall
As the objective of this paper is to study SSI effects on seismic response of SPSW, a typical multi-story SPSW designed [9] according to AISC 341 [10] for the lateral earthquake forces specified by ASCE 7 [11], is considered for this study. The SPSW is a 9-story 3-bay frame with infill plates in the second bay’s panels. The geometry and section properties of the SPSW structure in this investigation are presented in Fig. 1. The x-translation inertia due to floor masses is 5,440 kips (2468 ton) in total, distributed equally between the first to ninth floors. Ref. [12-13] present more relevant information about structural characteristics of SPSW.

2.2 Radiation condition, geometry and element selection of foundation and infinite soil medium

Modeling of infinite soil medium in soil-structure interaction plays a vital roll. The unbounded nature of the soil medium requires special Boundary Condition (BC) that does not reflect seismic waves into the soil-structure domain. Various models of Boundary Condition exist that enable the energy transmission (Lysmer, Kuhlmeyer 1969 [14]), the most commonly used in finite element method are of the viscous type [15]. Another approach is to use infinite element, Abaqus provides infinite element that are based on work of Lysmer, Kuhlmeyer 1969 [14] for dynamic response. The elements are used in conjunction with standard finite element, which model the area around the region of interest, with the infinite elements modeling the far-field region. Infinite elements provide quiet boundary to the finite element model in dynamic analysis [16]. In this study three dimensional eight noded solid continuum element have been used for finite element modeling of foundation and soil (light gray in Fig. 2) and three dimensional eight noded solid continuum infinite element have been utilized to simulate far-field region (dark gray in Fig. 2). As can be seen in Fig. 2 the mesh density of the infinite element is much coarser than that of the internal soil. The local viscous boundaries should be placed far away from the structure in order to obtain realistic results. Therefore, horizontal distances between soil boundary and center of structure are assumed to be 160’ (equal to 2.5 times of foundation radius) from each side, with 10’ width. Bed rock depth is assumed to be 100’ for all soil types.

![Fig. 2. Dimensions and properties of SPSW building](adapted from [12]).

<table>
<thead>
<tr>
<th>Imperial</th>
<th>SI</th>
</tr>
</thead>
<tbody>
<tr>
<td>W27*94</td>
<td>W690*140</td>
</tr>
<tr>
<td>W30*108</td>
<td>W760*161</td>
</tr>
<tr>
<td>W30*116</td>
<td>W760*173</td>
</tr>
<tr>
<td>W14*283</td>
<td>W360*421</td>
</tr>
<tr>
<td>W14*398</td>
<td>W360*592</td>
</tr>
<tr>
<td>W14*665</td>
<td>W360*990</td>
</tr>
</tbody>
</table>

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**Table 1.** Section properties of SPSW beams, plates, and columns.
3 Material properties
Two types of soil representing soil type II corresponding to stiff soil and soil type IV corresponding to soft soil according to classification of the Iranian Standard no. 2800-05 [17] are selected in this research. Analysis is carried out in this study only on these soil types in this category. Characteristics of utilized soils are shown in Table 1. The dynamic response of soils is nonlinear even at low to moderate deformation levels, during a seismic event. Therefore, soil nonlinearity must be appropriately taken into consideration. In this study equivalent-linear properties were used to take into account approximate soil nonlinearities. These properties were obtained throughout 1-D waves propagation analyses conducted with the program SHAKE [18]. The method used in this program is based on the assumption of horizontally layered deposits and vertically propagating shear waves.

<table>
<thead>
<tr>
<th>Soil type</th>
<th>Shear module $G_{\text{max}}$(MPa)</th>
<th>Shear wave velocity (m/s)</th>
<th>Poisson’s ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>II</td>
<td>536</td>
<td>518</td>
<td>0.40</td>
</tr>
<tr>
<td>IV</td>
<td>31</td>
<td>131</td>
<td>0.30</td>
</tr>
</tbody>
</table>

Table 1
Geotechnical characteristics of the utilized soils

4 Ground motion considered for analyses
One ground motion is selected in this study for dynamic analysis. Then the program SHAKE 2000 [18] was used to perform a deconvolution analysis to obtain the base motion corresponding to each ground motion for all soil types. Fig. 4 provides some relevant information for the record. In addition the acceleration response spectra of the ground motion are presented in Fig. 3.

<table>
<thead>
<tr>
<th>Earthquake</th>
<th>Station</th>
<th>$PGA$ (g)</th>
<th>$PGV$ (cm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duzce,Turkey 1999</td>
<td>Duzce</td>
<td>0.535</td>
<td>83.5</td>
</tr>
</tbody>
</table>

Table 2
Properties of seismic ground motion used in the analyses

5 results
The effect of soil-structure interaction on SPSW resting on different type of soil, viz., soft (soil type IV) and stiff (soil type II) is attempted to be studied in the present work. The outputs, obtained from two mentioned analysis types under the influence of Duzce earthquake with considering two soil types, have been compared with the aim of investigating SSI effects on seismic response of SPSW.
5.1 Natural frequency
Flexibility of soil medium below foundation decrease the overall stiffness of the building frames resulting in a subsequent increase in the natural periods of the system. It is well established that the seismic lateral response may considerably alter due to the change in lateral natural periods. The change in first four frequencies due to the effect of soil-structure interaction is studied on SPSW resting on each soil type. In Table 3 are indicated the four lowest natural frequencies of the frame over a range of soil type. Also included are the four natural frequencies when soil–structure interaction is not permitted. A maximum decrease of about 60% is observed for SPSW resting on soft soil. It is observed that first four frequencies decrease with increasing softness of soil.

Table 3
Natural frequencies of SPSW

<table>
<thead>
<tr>
<th>Mode number</th>
<th>Soil type</th>
<th>Soft (soil type IV)</th>
<th>Stiff (soil type II)</th>
<th>Fixed base</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>0.3497</td>
<td>0.5489</td>
<td>0.904</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>2.4771</td>
<td>2.5698</td>
<td>2.776</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>3.5004</td>
<td>4.2523</td>
<td>4.912</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>4.4889</td>
<td>4.8311</td>
<td>5.158</td>
</tr>
</tbody>
</table>

The seismic response of the structure in terms of the story shear, story deflection and story drift are selected as response parameters of interest, as these are generally considered the most important response parameters to evaluate the seismic vulnerability of a structure in seismic design practice. Fig. 5 to 7 show the effect of SSI on SPSW for each type of soil, using the ratio of response parameters in flexible-base to that of fixed base model.

5.2 Story shear
Fig. 5 summarizes the effect of SSI on the peak story shear of SPSW. The above results indicate that when nonlinear SSI is incorporated, the story shear of SPSW reduces significantly. It can be observed that the ratios of story shear incorporating SSI to that of fixed base is less than one in all stories for each type of soil. Therefore, story shear of structure modeled with soil as flexible base are always less than the story shear of structure modeled as fixed base. These results have good conformity to the NEHRP-1997 [19] regulations. This indicates that in the absence of consideration of SSI, over prediction in story shear demand may result, considering the fact that story shear increased when the soil stiffness is changed from soft (soil type IV) to stiff (soil type II).

5.3 Story displacement
Fig. 6 shows the effect of soil-flexibility on the story deflection considering stiff and soft soil. The ratio of story deflection at flexible base to story deflection at fixed base is plotted against to story levels. As it is shown, story displacement increases when base condition is changed from fixed to flexible. As it is expected the increase is larger for soil type IV ($\nu_s$=131 m/s). The results show that SSI effect increases story deflection as much as 50% and 150% for SPSW founded on soft and stiff soil, respectively.

![Fig. 5 Ratio of story shear of flexible-base to fixed base on soil type II and IV](image1)

![Fig. 6 Ratio of story deflection of flexible-base to fixed base on soil type II and IV](image2)
5.4 Story drift
Since the inter-story drift demand is an important parameter for the design of structural members, story drift is also selected as a parameter of SSI effects on SPSW behavior. According to the results shown in Fig.7 the story drifts of flexible-base structure are more than that of SPSW modeled as fixed base in almost all of stories. The inter-story drift demand with flexible based is observed to increase that ranged from 40% to 230% for soft soil. Such a big difference in story displacement and drift ratio is not negligible; thus, the effect of soil-structure interaction must be taken into account in dynamic analyses.

The increase in story displacement is occurring due to the overall reduction in the global stiffness and natural frequency resulting from the induced foundation movement. In fact, by decreasing the rigidity of soil, the difference between period of vibrations in two cases (structure modeled on flexible soils and structure modeled as fixed base) will be increased; consequently, the effect of soil-structure interaction for soil type IV is considerable. It should be noted that the above mentioned results have been derived based on the nonlinear behavior of the SPSW and equivalent-linear model of underneath soil deposits during time history analyses.

The following specific observations are obtained from the analyses.

The peak story shear of SPSW reduces significantly when nonlinear SSI is incorporated.

The results show that SSI effect increases story deflection for SPSW founded on soft and stiff soil. The inter-story drift demand is observed to increase in almost all of stories due to soil-flexibility compared to the fixed-base.

The effect of soil-structure interaction must be taken into account in dynamic analyses of SPSW. Modeling nonlinear SSI, shows that the SSI effect may play an important role in altering the force, indicating the necessity for consideration of soil-flexibility behavior in the modern design codes to accomplish a more economic yet safe structural design.

References:


