Seismic response of steel plate shear walls considering soil-structure interaction

P. Memarzadeh, J. Mirlohi and F. Behnamfar

Abstract—Due to structural efficiency, Steel Plate Shear Wall (SPSW) is widely employed in buildings as a principal system for resisting lateral loads due to wind and earthquakes. An accurate model of seismic demand for SPSW requires consideration the effect of all components for analysis such as structural, foundation, subsoil elements and the interaction between them. Such interaction may alter the dynamic characteristics of structures and consequently may be beneficial or detrimental to the performance of structures. This investigation considers two typical SPSW designed according to AISC requirements. The effects of soil-flexibility on seismic demands of such frames resting on two soil types subjected to two different earthquake ground motion is investigated using the time direct method and a comparison is presented with the results obtained from fixed-base. It is observed that soil–structure interaction affect the seismic performance of SPSW and the effect of soil-flexibility must be taken into account in dynamic analyses of SPSW.

Keywords—Steel Plate Shear Wall, Soil Structure Interaction, seismic response, dynamic analysis

I. INTRODUCTION

Due to structural efficiency, Steel Plate Shear Wall (SPSW) is widely employed in buildings as a principal system for resisting lateral loads due to wind and earthquakes. An accurate model of seismic demand for SPSW requires consideration the effect of all components for analysis such as structural, foundation, subsoil elements and the interaction between them. In the conventional design, buildings are generally considered to be fixed at their bases. In reality, flexibility of the supporting soil medium allows movement of the foundation resulting in a decrease in global stiffness of the structural system [1]-[3]. In addition, a part of the structure’s vibration energy will transmit to the soil layer and can be dissipated because of the radiation damping resulted from the wave propagation and hysteresis damping of the soil materials. However, in classical methods for the rigid base structures, this energy dissipation is not considered [4]. Consequently the response of the structure is altered that may be beneficial or detrimental to the performance of building.

The effects of soil-structure interaction (SSI) on the response of a structure subjected to earthquake ground motions depend on the stiffness of the structure relative to the supporting soil stiffness, and the dominant periods of the input ground motions. Structures resting on soft soil are likely to experience larger SSI effects than those supported by stiff soil [5]. 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, neglecting SSI effects may result in an inaccurate estimation of seismic demands [6]. Moreover, it has also been suggested that for structures with the fundamental periods between 0.3 and 1.0 sec. may be more sensitive to the SSI effects than those with the fundamental periods outside the above-mentioned range [7]. Thus, the effect of SSI on the structural response of SPSWs may be of major concern that current study is intended to contribute towards achieving this goal. In this procedure, a time-direct method is adopted in which the numerical modeling of system is carried out with finite element method (FEM) using the software Abaqus [8].

II. DESCRIPTION OF STRUCTURAL SYSTEM, FOUNDATION AND SOIL MODELLING

A. Steel Plate Shear Wall

As the objective of this paper is to study SSI effects on seismic response of SPSW, two typical multi-story SPSW, consisting of 6 and 9 story models, designed [9] according to AISC 341 [10] for the lateral earthquake forces specified by ASCE 7 [11], are selected for this study. The SPSW models are 3-bay frames 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. Reference [12], [13] present more relevant information about structural characteristics of the SPSWs.
B. Radiation condition, geometry and element selection of foundation and infinite soil medium

Modeling of infinite soil medium in SSI plays a vital role. The unbounded nature of the soil medium requires special Boundary Condition (BC) that does not reflect seismic waves into the soil-structure domain. The non-reflecting viscous boundaries developed by Lysmer and Kuhlemeyer [14] and White et al. [15] have been widely used for various dynamic soil–structure interaction problems. In this study the radiation condition was treated by the infinite elements implemented in ABAQUS [8]. In this regard, three dimensional eight noded solid continuum elements [16] have been used for finite element modeling of foundation and soil (light gray in Fig. 2) and three dimensional eight noded solid continuum infinite elements [16] 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 57.60 m (192 ft) (equal to 3 times of foundation width) from each side.

Bed rock depth is assumed to be 30 m (100 ft) for all considered soil types. The frames are assumed to be found on shallow foundation which size is 19.2 m×1 m (768 in ×40 in) in plan, while a depth of embedment of 0.75 m (30 in) is provided. These dimensions were first determined on the basis of Terzaghi’s bearing capacity formula for strip footings with an ultimate bearing capacity of 334 KPa with a factor of safety equal to 3 and 5 for 9-story SPSW and 6-story SPSW, respectively [17].
III. 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 [18] are selected in this research. Characteristics of utilized soils are shown in Table I. 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 [19].

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

IV. INPUT MOTIONS CONSIDERED FOR ANALYSES

Two different ground motions are selected in this study for dynamic analysis. The seismic signals are recorded on the ground surface. In reality, the motion of the base, to which the soil-structure system will be subjected, has to be obtained by deconvolution. In this regard, the program SHAKE 2000 [19] was used to perform a deconvolution analysis to obtain the base motion corresponding to each ground motion for both soil types. Details of the selected ground motions are listed in Table II while Fig. 3 provides some relevant information for the records. In addition the acceleration response spectra of the ground motions are presented in Fig. 4.

TABLE I
GEOTECHNICAL CHARACTERISTICS OF THE UTILIZED SOILS

TABLE II
PROPERTIES OF SEISMIC GROUND MOTIONS USED IN THE ANALYSES

<table>
<thead>
<tr>
<th>Earthquake</th>
<th>Station</th>
<th>PGA (g)</th>
<th>PGV (cm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tabas, Iran, 1978</td>
<td>9102 Dayhook</td>
<td>0.406</td>
<td>26.5</td>
</tr>
<tr>
<td>Loma Prieta, 1989</td>
<td>16 LGPC</td>
<td>0.563</td>
<td>94.8</td>
</tr>
</tbody>
</table>

This investigation is aimed to better understand the seismic performance of a typical SPSW incorporating soil-structure effect. The seismic response of the structure in terms of the story shear as well as, internal forces over the height of the structural elements and ductility demand are selected as response parameters of interest as these are generally considered the most important response parameters in seismic design practice. The results of SSI models will be compared to those obtained from fixed base model denoted as the Reference SPSW from here on.

Fig. 3 accelearograms of earthquakes used in time-history analysis

Fig. 4 acceleration response spectra of the earthquakes used in the analyses
A. Story shear

Story shear is an important parameter from the structural designer's point of view. In the current effect variation of change in story shear due to the incorporation of soil-flexibility as compared to the same obtained at fixed-base condition expressed as a ratio of such response of SSI models to Ref. SPSW has been plotted in Fig. 5. We can observe that story shear of structure modeled with soil as flexible base are almost less than the story shear of structure modeled as fixed base. These results are in agreement with common assumption, postulated by almost all the design codes such as NEHRP-97 [20].

B. Internal forces

Internal forces are considered to be significant to describe the possible damage of the structural elements. Fig. 6 shows percentage distribution of story shear between vertical elements viz., steel plate, perimeter columns and Vertical Boundary Elements (VBEs), over the height of 9-story SPSW considering all base conditions (flexible and fixed-base condition). The figure shows that SSI decreases the share of shear forces of steel plates in resisting the story shear in most the stories of 9-story SPSW founded on both soil types.

Consequently an increase in the contribution of shear forces of columns in resisting the shear story is observed as a consequence of soil flexibility. The figures clearly indicate that the change is largest for soil type IV. The contribution of the story plates to story shear is about 48% to 75% when the structure is assumed as fixed-base while such quantity is observed to be around 35% to 73% for the building frame resting on soil type IV. As it is shown, the contribution of the perimeter columns to the story shear is about (6-27)% in Ref. SPSW dependent on the story level, while the contribution ranges from 9% to 37% and 7% to 48% for soil type II and IV, respectively. Also a comparison of contribution of the story VBEs to story shear due to incorporation of soil-flexibility relative to that in Ref. SPSW in absence of sub-soil, is illustrated in Fig. 6c. Comparing the results obtained from both base conditions, it can be seen that inclusion of soil-flexibility slightly influences contribution of the story VBE to the story shear increasing it, for most of the stories. Fig. 7 presents percentage contribution of shear forces of structural elements over the height of the 6-story SPSW. Similarly variation curves for the frame resting on different soil types are marked with the corresponding soil type. It can be seen that SSI generally produces an increase in share of steel plates in resisting the story shear for SPSW.
founded on soil type II, while it undergoes significant variations in the case of soil type IV dependent on story level. Remarkable change in contribution of shear forces due to SSI effect can be seen in second and last story in the case of soil type IV. In addition another consequence of soil-flexibility is a reduction in contribution of shear forces of VBEs to the story shear observed in most of the stories with respect to the Ref. SPSW. On the other hand a minor influence on distribution of shear forces in perimeter columns is observed for middle stories when the base condition is changed from fixed to flexible.

C. Ductility demand

Ductility demand is crucial parameters to measure the inelastic range response of the structural element. Memarzadeh et al. [12] recommend using an effective relationship for the energy ductility, \( \mu_c \), which is convenient to use for the case of dynamic response of SPSWs as follow:

\[
\mu_c = \frac{\max(E_p + E_s)}{\max(E_s)}
\]

(1)

Where \( E_p \) and \( E_s \) are the hysteretic and recoverable strain energy, respectively. Fig. 8 summarizes average ductility demand calculated according to the mentioned equation, for the story plates and their distribution over the height of the structure for SSI models and Ref. SPSW. We can see that the ductility demand reduces when foundation flexibility, is introduced to the fixed-base system. The figures clearly indicate that the effect of SSI produces a reduction in ductility demand that becomes significant in the case of soft soil.
VI. CONCLUSION

The study as a whole may prove useful in formulating design guidelines for seismic design of building frames incorporating the effect of soil-flexibility. For this purpose a time direct method was used considering nonlinear behavior of SPSW and using an equivalent-linear model for underneath soil deposit during time history analyses. The analyses consist a complete 3-D model for both soil and structure. The outputs obtained from all mentioned base conditions under influence of two accelerograms with considering two soil types, was obtained and compared with the aim of investigating SSI effects on seismic response of SPSW in terms of story shear, distribution of shear forces between structural elements and ductility demand. The following specific observations are drawn from the analyses:

The results showed that the incorporation of SSI tends to decrease story shear of all SPSW models by reducing the shear wave velocity of the soil deposits.

SSI decreases the share of shear forces of steel plates in resisting the story shear in most the stories for 9-story SPSW founded on both soil types. Consequently an increase in the contribution of shear forces of columns (VBEs and perimeter columns) in resisting the shear story is observed as a consequence of soil flexibility.

SSI generally produces an increase in share of shear forces of steel plates in resisting the story shear for 6-story SPSW founded on soil type II.

With reference to the Ref. SPSW, SSI caused reduction in contribution of shear forces of VBEs to the story shear in most of the stories in 6-story SPSW.

Ductility demand is another parameter evaluated in this study. The ductility demand was observed to reduce when the base condition changes from fixed to flexible.

References