



SEISMIC SOIL-STRUCTURE INTERACTION (SSI) EFFECTS FOR A DIFFERENT TYPE OF BUILDINGS IN DENSE URBAN AREA

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ABSTRACT

The paper presents the results of a project of the new research center in earthquake engineering entitled “*Dan Ghiocel International Research Center*” at TUCEB, Romania.

The paper investigates the seismic soil-structure interaction effects for different type of buildings, such as a multistory residential building, an old church and a metro subway station in the Bucharest city. The site soil profile corresponds to the INCERC site soil layering in Bucharest. This is a relatively soft and deep soil deposit. Two seismic inputs are considered: i) the 1977 Vrancea Earthquake acceleration records NS, EW and Vertical at the INCERC site and ii) a set of 3-directional spectrum compatible acceleration input histories simulated based on the Romanian seismic code design spectrum. The seismic SSI analysis was performed using the state-of-the-art ACS SASSI software (Ghiocel, 2013). The Flexible Volume (FV) substructuring method was used to perform accurate SSI analyses.

SITE SOIL PROFILE AND SEISMIC INPUTS

The INCERC site is located in the eastern part of Bucharest and is characterised by a relatively soft soil deposit, with shear wave velocity at the surface of 260 m/s to 440 m/s at the maximum depth. Bucharest is located on sedimentary deposits of 1000 to 1500 m thickness, represented mostly by gravel, sands and clays, on the north of the Danube’s Moesian Platform.

On the 4th of March 1977 a severe earthquake occurred in Vrancea, with a moment magnitude $M_w=7.5$ and a focal depth of 109 km, seriously affecting Bucharest and other cities. Most of the damage and victims were in Bucharest. Only one recorded motion was obtained in Bucharest, at the INCERC site. The motion shows peak amplification at low frequencies around 0.75 Hz and a quite large overall amplification in the 0.5 to 1.0 Hz range (Fig. 1).

The seismicity in Romania is characterised mostly by the Vrancea seismic source. Vrancea source is located on the corner of the Carpathian Mountains, at intermediate depth (60 km to 170 km) and is characterised by strong earthquakes produced in a small volume. The seismic activity is generated by interaction of two subducting plates, one old, one new, or, by some researchers, by a sinking gravitationally old subducting plate.

The second set of seismic inputs is obtained by using the Romanian seismic design code P100-2006 elastic spectrum (Fig. 2).

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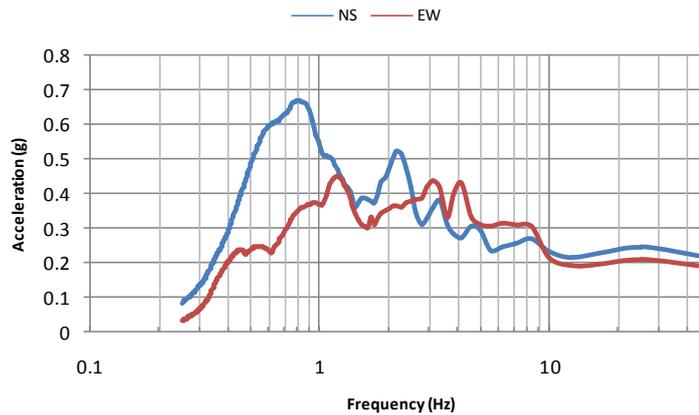


Figure 1. Acceleration Response Spectrum for INCERC site 1977 March 4 Earthquake (5% damping)

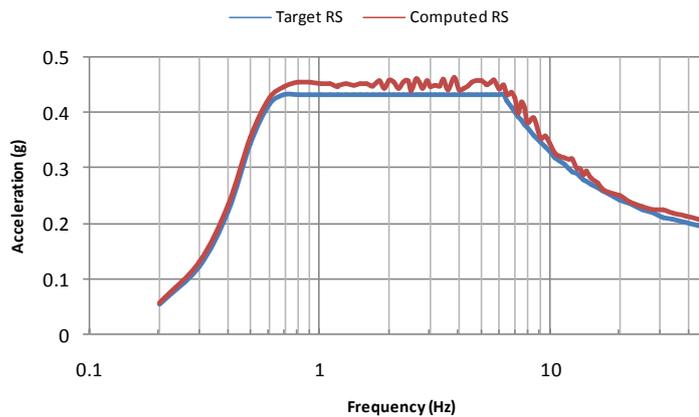


Figure 2. Computed and Target Seismic Design Spectra for EW Horizontal Direction

CONSIDERED STRUCTURES DESCRIPTION

The first seismic design rules were implemented in Romania in 1940 following the Italian seismic code. The old structures designed before 1940 are therefore poorly seismically designed. They are old structures, many historical masonry made buildings, with one or two stories located mostly outside city centre, or multistory masonry and concrete buildings located in the city centre. Most of the build areas in Bucharest are now represented by residential apartment concrete buildings made in the communist regime before 1990, with heights starting from 4 to 25 stories. They are shear walls, or mixed shear walls and moment frames structures, erected after 1960 and designed based on the new implemented seismic codes.

The subway network was started in 1979 in Bucharest and in the present time has a number of 51 stations in use and 69.2 km of tunnels and railways.

The scope of the paper is to study the seismic soil-structure interaction for three representative structures for Bucharest: an apartment concrete multistory building, a masonry historical, single story church and a typical subway station. This paper is followed by a second one where the seismic structure-soil-structure interaction (SSSI) is studied for different combinations and relative positions of the three considered structures.

The multistory concrete structure has 15 stories above ground and 3 stories below, with a story height of 3.0 m. The structure has 3 spans of 6.0 m and 9 bays of 8.0 m. On the transversal direction the lateral loads are transferred to foundation by 10 shear walls with 35 cm thickness and on the longitudinal direction, the lateral loads are transferred by 2 shear walls with 35 cm thickness and 28 columns having 160 cm by 70 cm rectangular cross section. On the centre and on the lateral bays (including structure corners) 12 columns with 70 by 70 cm square cross section are placed. The slabs are 16 cm thickness. The foundation is made by 3 underground stories with 35 cm thickness shear walls. The concrete material is characterised by an elastic modulus of 30 GPa.

The historical masonry church has 3 bays of 2.0 m, 5.0 m and 2.0 m and 4 spans of 5.0 m, 5.0 m, 15 m and 5.0 m. The middle bay is no shear walls inside on both transversal and longitudinal directions. The tower is located on top of the second span and middle bay and has a height of 8.0 m. The total height of the structure is 20.0 m. The shear walls, the tower walls and the slabs are all 1.0 m thickness. The base slab is concrete made and has 35 cm thickness. The masonry material is characterised by an elastic modulus of 0.925 GPa.

The subway station is located below ground level and has 2 bays of 9.9 m and 17 spans of 8.0 m. The total height is 22.8 m and is comprised by 7.7 m height of the tunnel and 15.1 m height of the longitudinal lateral diaphragm walls. The thicknesses of the slabs are 1.0 m for the top and 2.2 m for the bottom slab. The lateral longitudinal walls thicknesses are 1.4 m for the tunnel and 0.8 for the diaphragm walls. On the middle of the tunnel and longitudinal direction, 16 columns with 60 cm by 100 cm rectangular cross section are placed. All the structural elements are made by concrete with 29 GPa elastic modulus.

Fig. 3 shows the three structural models considered. It should be noted that the multistory building has three levels of embedment, the church has no embedment, and the subway station is fully embedded below ground surface.

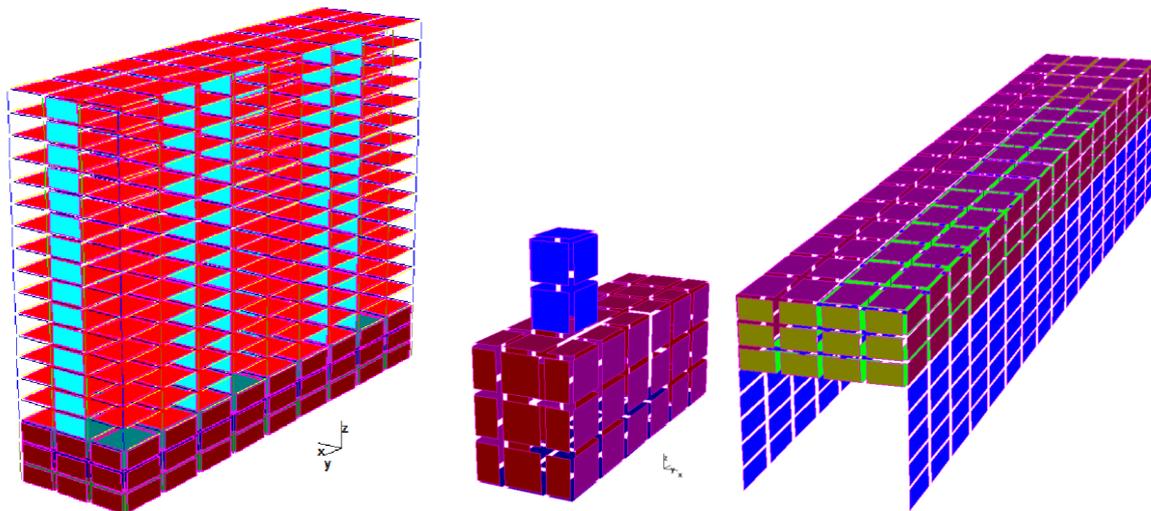


Figure 3. Structural Models, Block, Church and Subway Station, Used for the SSI Analysis Study

The SSI model results were compared with the fixed-base model results. To understand the dynamic behaviour changes produced by SSI effects, the acceleration response spectra (ARS) for 5% damping were compared for different locations within the structure. For the Multistory Building, that is the main focus of the study, structural forces and bending moments were computed in the corner columns and transversal shearwalls.

BLOCK MODEL SSI RESULTS

The 5% damping ARS and ATF were determined for points located on the corner column, at the Foundation Bottom Level (Elevation -9m), Structure Base (Elevation 0m), Middle Story (Elevation 21m) and Rooftop (Elevation 45m).

The below figures indicates for the **1977 seismic input motion** similar trends for the Foundation Bottom and Structure Base Levels, and also for the Middle Story and Rooftop Levels. The horizontal directions ARS for the Substructure shows a reduction in inertial acceleration response for the SSI model with significant frequency pattern modification on high frequency domain (Fig. 4).

The horizontal 5% damping ARS amplitudes at different structure locations (middle and top) are significantly reduced due to SSI, especially, in the transversal direction due to the important SSI rocking motion. As a consequence, there is a similar reduction of the corresponding horizontal seismic loads for the SSI model. Also, the natural frequency suffers a significant reduction for the transversal direction due to the rocking effects (Fig. 5). In the longitudinal direction, the SSI model is indicating

an increase of the response accelerations in the low frequency domain. The lateral displacements are larger in the transversal direction than in longitudinal direction due to the SSI induced rocking motion effects.

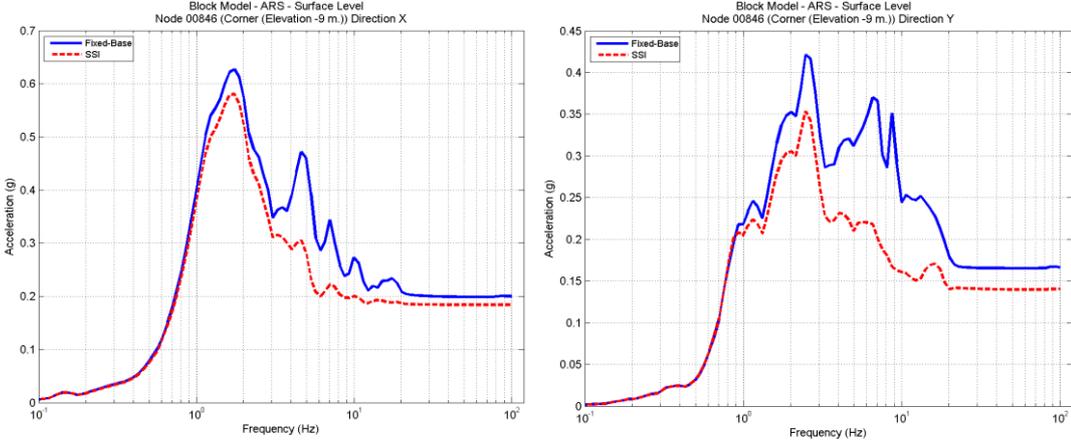


Figure 4. Foundation-Bottom Level (Elevation -9.0 m) ARS for Multistory Building in X and Y Horizontal Directions

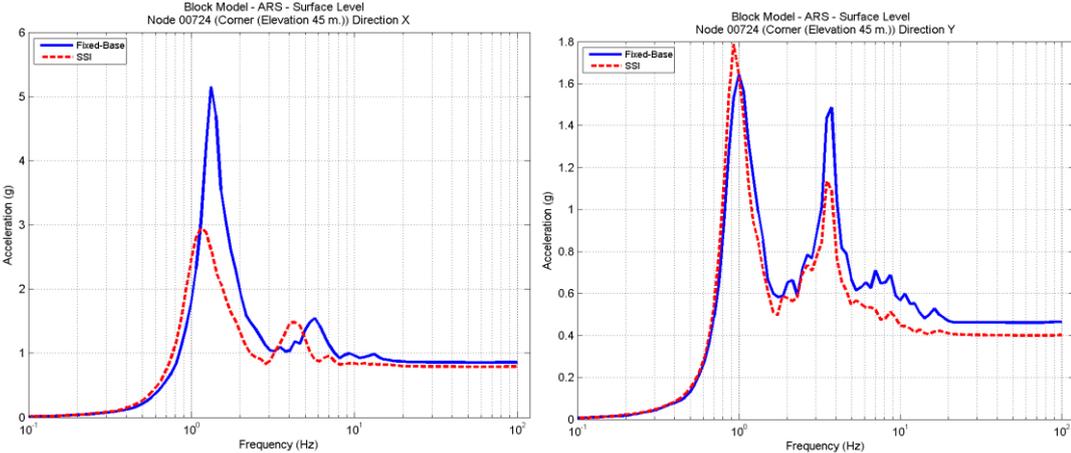


Figure 5. Roof-Level (Elevation 45m) ARS for Multistory Building in X and Y Horizontal Directions

For the vertical components of the acceleration response, a reduction in the high frequency domain appears above 8-10Hz, for all the levels in the structure. The computed ARS at the foundation and roof level are shown in Fig. 6.

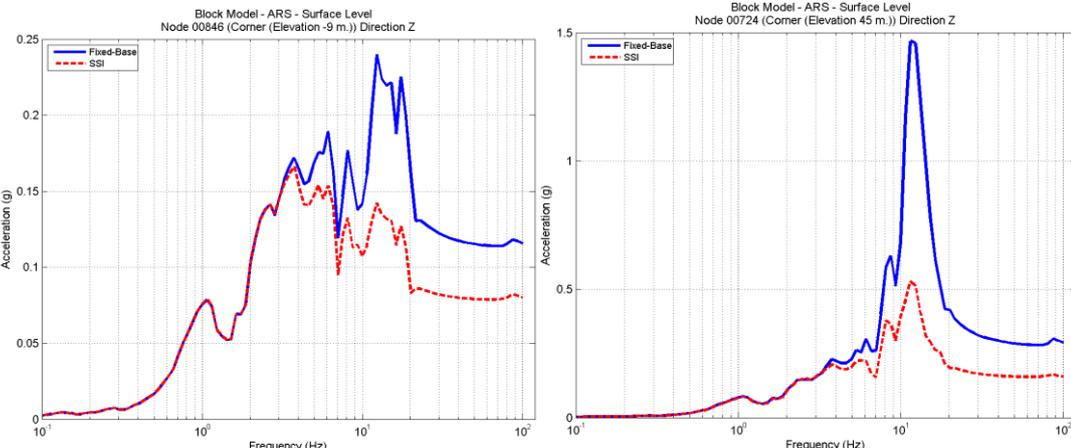


Figure 6. Foundation-Bottom and Roof-Level (Elevations -9.0 m and 45m) ARS for Multistory Building in Vertical Directions

It should be noted that the seismic SSI results computed based on the Romanian **seismic code design ARS** and the 1977 earthquake ARS are quite similar. For both seismic inputs, there is a significant reduction of the acceleration responses that is much more important for the transversal horizontal direction, due to the rocking phenomenon. For the middle and roof top level, the horizontal loads are significantly decreased for the transversal direction and negligibly reduced for the longitudinal direction. In the transversal direction, the rocking SSI frequency of the building shifts to a lower frequency and has lower amplitude due to SSI effects expressed through the rocking response motion (Fig. 7).

The vertical acceleration responses, in high frequencies have large reductions at the structure roof level and the middle height level. At the ground level, the accelerations reductions are less significant (Fig. 8).

The ATF for the rooftop column nodes and horizontal accelerations are indicating a significant reduction on the transversal direction and a left shift of the natural frequencies. On the longitudinal direction, the ATF shows less reduction and negligible frequency shift for the SSI model (Fig. 9).

Fig. 10 and 11 show the computed structural shear stresses and out of plane bending moments obtained for the **1977 seismic input motion**, in two transverse shearwalls located lateral (wall 10) and inside the structure (wall 6). The element numbers are counting shear wall elements starting from bottom to the top of the structure. The out of plane bending moment for the bottom of the shear wall is slightly decreasing for outer shear wall and increasing for the inner shear wall due to the SSI effects. On the height of the shear wall, the bending moments are increasing up to the middle stories and decreasing to the top, in case of SSI. The shear stresses are dramatically decreasing for the inner walls if SSI is considered, so the corresponding shear damage of the walls is expected to reduce.

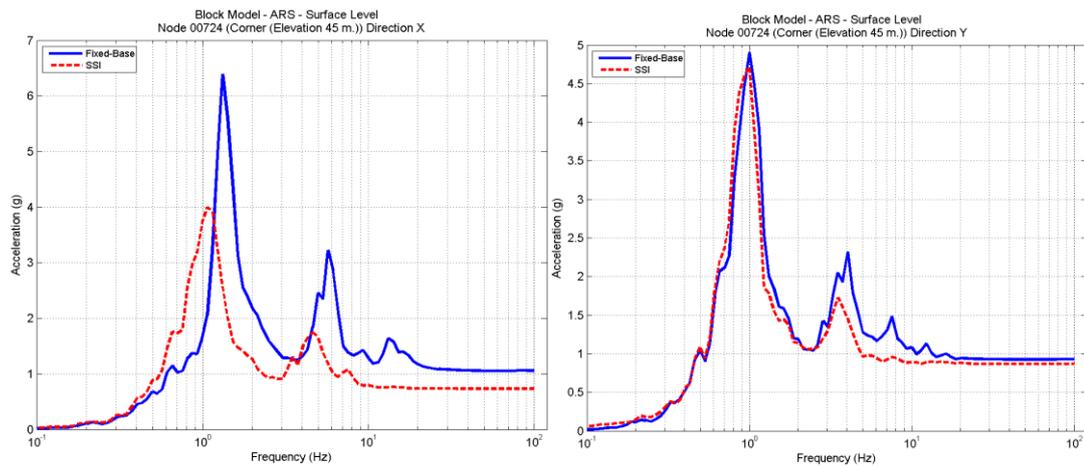


Figure 7. Roof-Level (Elevation 45m) ARS for Multistory Building in X and Y Horizontal Directions

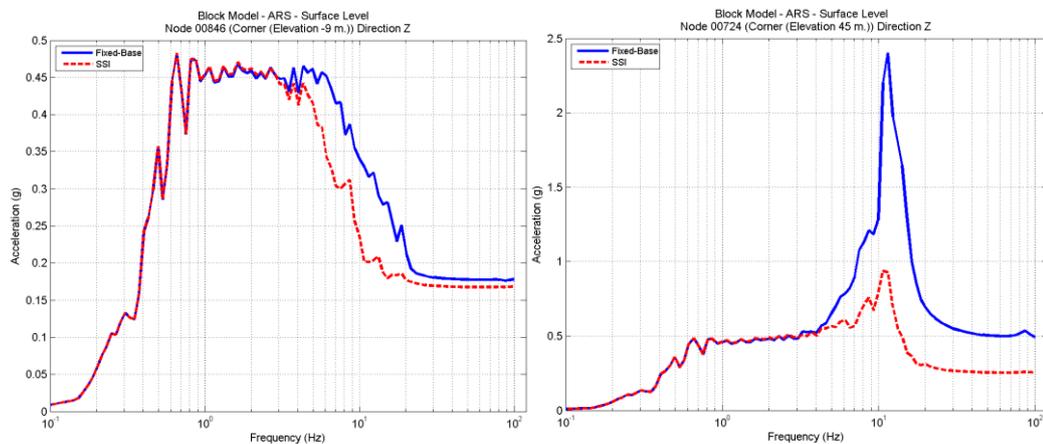


Figure 8. Foundation-Bottom and Roof-Level (Elevations -9.0 m and 45m) ARS for Multistory Building in Vertical Directions

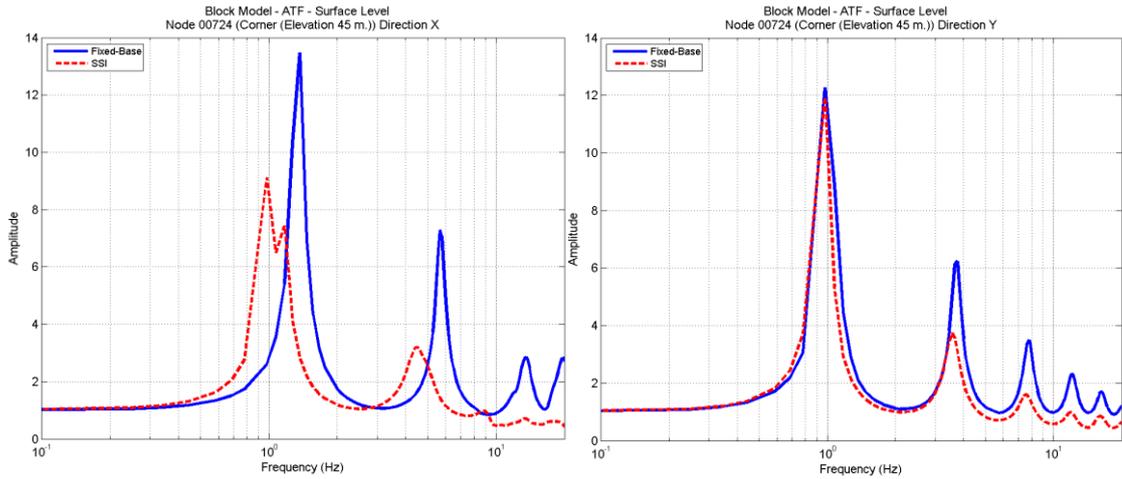


Figure 9. Roof-Level (Elevation 45m) ATF for Multistory Building in X and Y Horizontal Directions

In case of the outer shear walls, the shear stress is increasing at the ground level if SSI is considered (Fig. 11, left plot), due to the larger deformation of the three-level embedment that for the fixed base structure is completely neglected, since the basement is considered infinitely rigid.

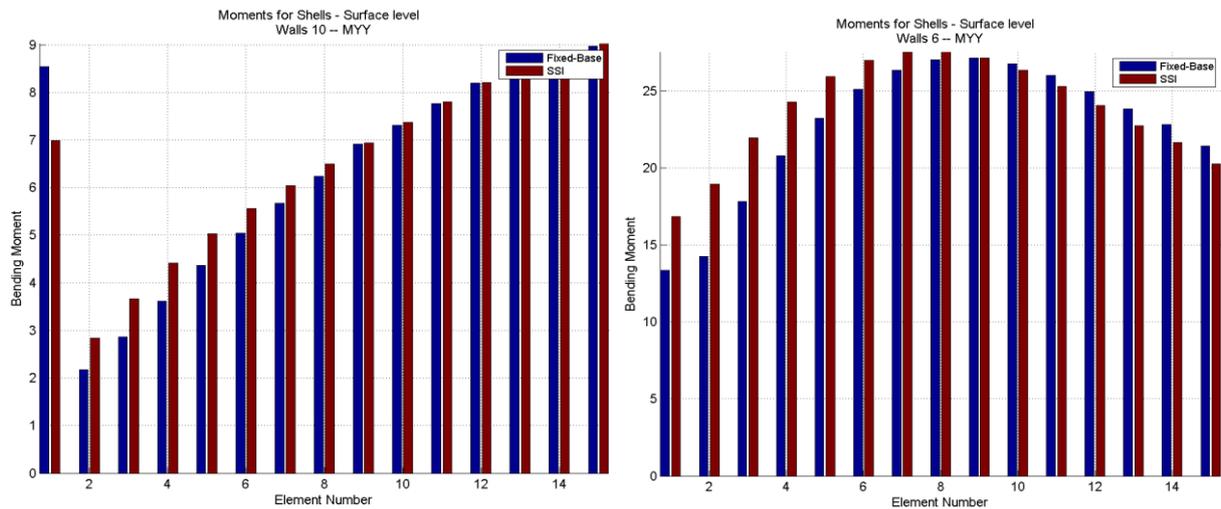


Figure 10. Multistory Building Out-of-Plane Bending (kNm/m)

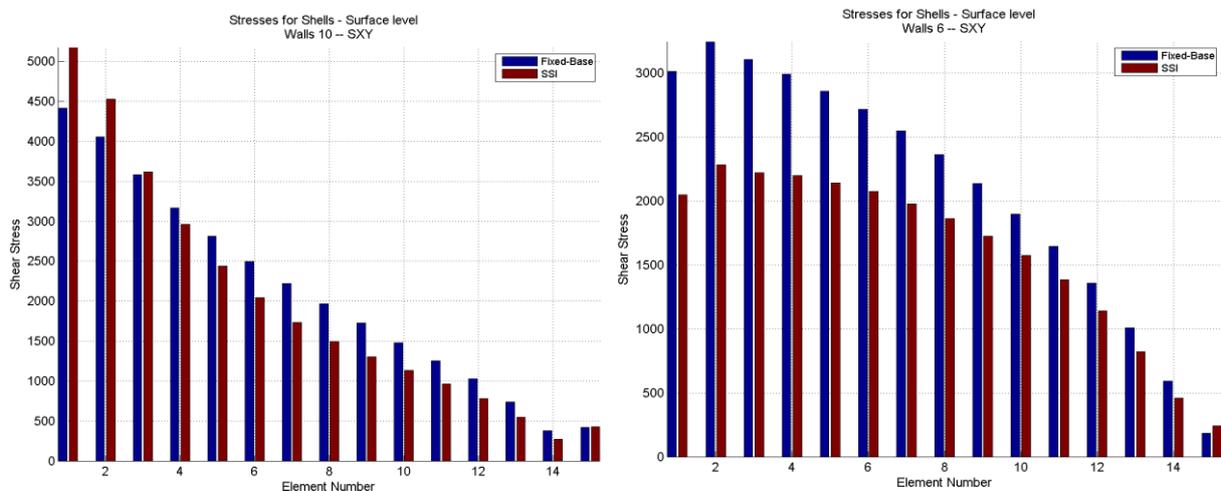


Figure 11. Multistory Building Shearwall Shear Stresses (kN/m²)

The shear forces of the corner columns (Fig. 12), located in the vicinity of the outer transversal shear wall presented above, at the bottom level, shows very large increase if the SSI effects

are considered, due to the torsion induced effects. On the height of the column, the shear forces are decreasing compared with the fixed base structure. The axial force has less change on the entire height of the column. The bending moment for the considered column indicate an increase if the SSI effects are considered (dramatically for the base column) and decreases above the middle height of the structure.

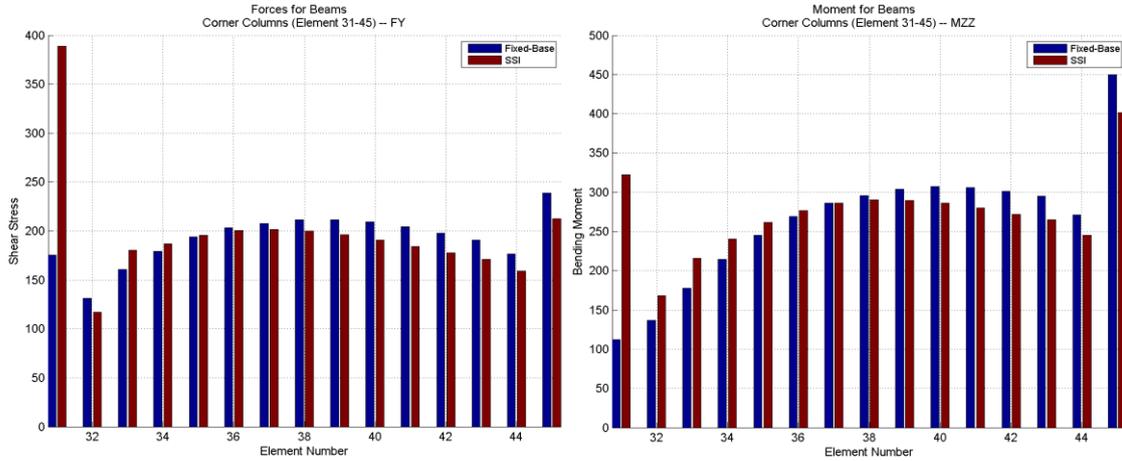


Figure 12. Multistory Corner Column Shear Force (kN) and Bending Moment (kNm)

CHURCH MODEL SSI RESULTS

Fig. 13 and 14 show the 5% damping computed horizontal directions ARS for corner points, at the foundation-level and tower-bottom level of the Church Building. The computed ARS are shown for the 1977 seismic motion case only. On the transversal direction of the building (left figures) the horizontal loads are increasing, if SSI is considered. The transversal vibration modes frequencies are not influenced by the SSI effects.

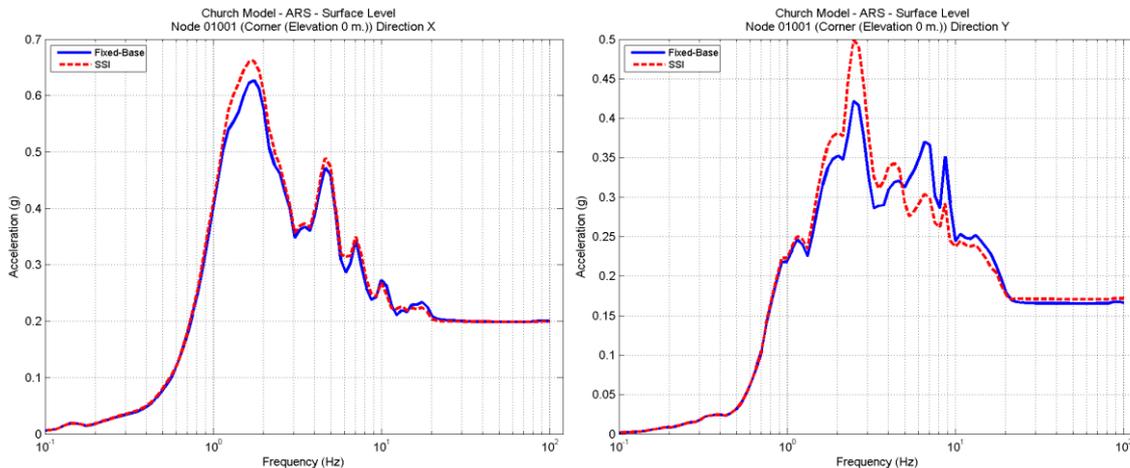


Figure 13. Foundation-Level (Elevation 0m) ARS for Church Building in X and Y Horizontal Directions

On the longitudinal direction (right figures) the horizontal loads are increasing for fundamental vibration mode, but decreasing for the superior modes. As for the vertical loads, the SSI produces a significant reduction of ARS at the top of the corner shear walls and less reduction at the bottom and top of the corners of the tower shear walls.

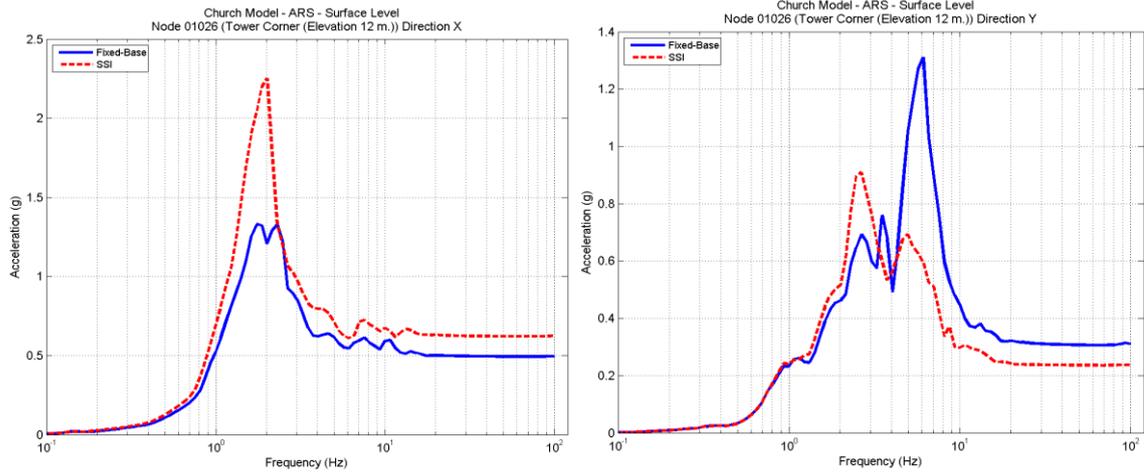


Figure 14. Tower Bottom-Level (Elevation 12m) ARS for Church Building in X and Y Horizontal Directions

SUBWAY STATION MODEL SSI RESULTS

The buried Subway Station is studied using the 5% damping ARS curves presented below. The points where these functions were considered are placed on the lateral longitudinal wall, close to the corner of the station tunnel. The plots are shown for locations on the top and bottom of the station tunnel and at the bottom of the lateral shearwalls.

Fig. 15 shows the computed ARS for transversal direction on the top and bottom levels of the Subway Station. The large reduction (around 50%) in response acceleration if SSI is considered is describing also an important decrease in out-of-plane bending moments. For the Subway Station, the ARS reduction is mainly due to spatial variation of the seismic soil motion with depth.

Fig. 16 is describing the longitudinal ARS indicating an increase at the tunnel bottom level, for first vibration mode, and a decrease for superior modes if SSI is considered. These reductions are produced by the fact that the soil motion is larger at ground surface than at foundation level. Due to this soil motion reduction with depth, at the ARS amplitudes at the foundation level decrease significantly.

It should be noted that the ARS results do not include the SSI effects produced by the soil foundation deformation during the earthquake which are reflected in the relative displacements of the foundation. These soil foundation deformation or kinematic SSI effects impact severely on the buried Subway Station structure stresses in the walls.

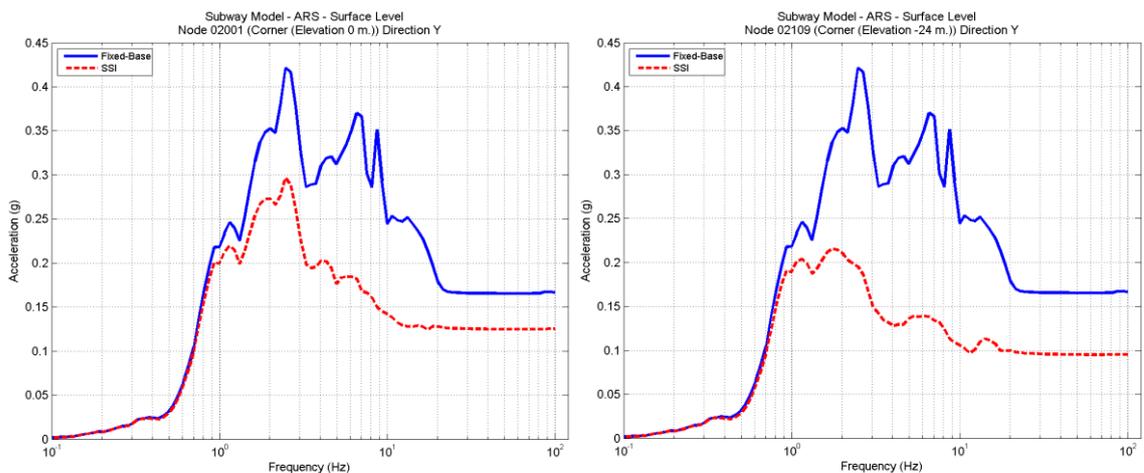


Figure 15. Top-Level (Elevation 0m) and Bottom-Level (Elevation -24m) ARS for Subway Station in X (transversal) Horizontal Direction

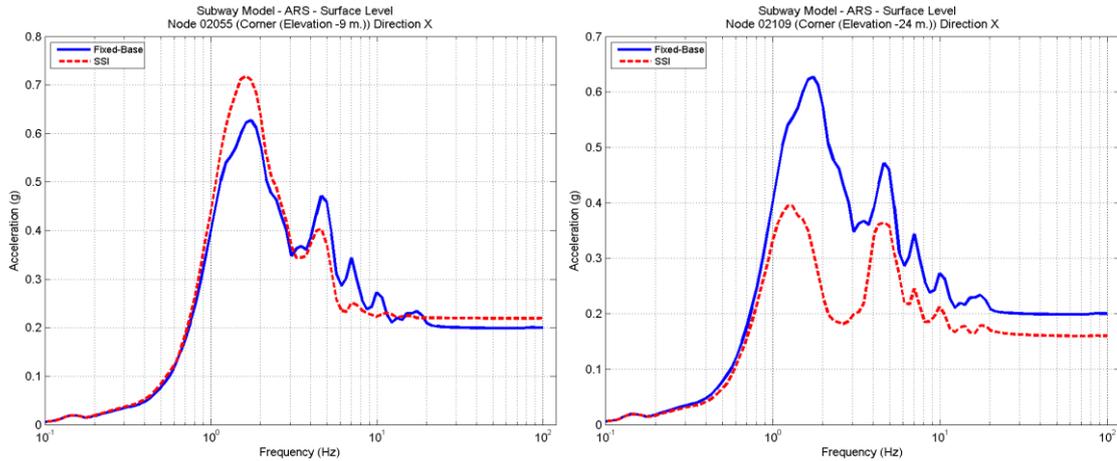


Figure 16. Tunnel Bottom - Level (Elevation -9m) and Bottom-Level (Elevation -24m) ARS for Subway Station in Y (longitudinal) Horizontal Direction

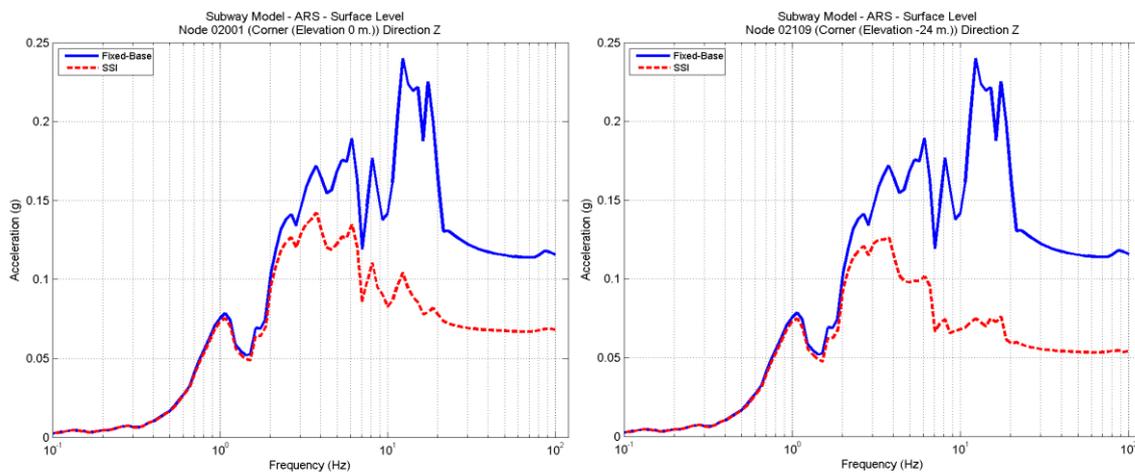


Figure 17. Top-Level (Elevation 0m) and Bottom-Level (Elevation -24m) ARS for Subway Station in Z Vertical Direction

The vertical ARS, for all the locations within the Subway Station Model, are showing a significant reduction. As a consequence, the axial forces in the shear walls have important decrease if SSI is considered, due to the deformation of the soil.

CONCLUSIONS

The three case study results illustrate that SSI effects are quite significant, not negligible, except for the Church surface structure. It should be noted that this contradicts the previous believe of some researchers in the past, that SSI effects are essentially favourable, and they always produce a decrease of the forces in structures. If the foundation deformation is neglected, as considered in the past using simplified SSI models with rigid foundation models, then, the SSI effects will be exclusively described by the changes in the structural acceleration responses. However, for embedded structures, on a case-by-case basis, the role of the foundation deformation could be important. As shown in the paper, the foundation deformation plays a dominant role for the buried Subway Station structure.

The paper results show that the solely judgement of the SSI effects based on the structural acceleration response computed for simplistic, rigid-base SSI models, as done in the often in the past, is insufficient.

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