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Structure-to-Soil-Structure Interaction Analysis: A Case Study

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STRUCTURE-TO-SOIL-STRUCTURE INTERACTION ANALYSIS: A CASE STUDY

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ABSTRACT

Current industry codes, such as ASCE 4-98 recommend consideration of Structure-to-Soil-Structure Interaction (SSSI) only when it is determined to have a significant effect on local results. In some cases, it is not computationally feasible, or too costly, to analyze an explicit model including a complex of all contributing structures.

The significance of SSSI is dependent upon several variables, namely the characteristics of the soil, structures, and ground motion, as well as the spatial distance between structures. The SSSI effect is most significant for lighter structures adjacent to more massive structures that are founded on soil sites.

The Hanford Waste Treatment Plant Pretreatment Facility Complex is comprised of two small surface-founded structures adjacent to one large partially embedded structure, separated by a seismic gap of less than one foot. The effects of SSSI are evaluated using explicit modeling of each building on the Complex. A case study, showing the importance of explicit modeling for SSSI analysis of the Hanford Waste Treatment Plant Pretreatment Facility Complex, is presented in this paper. The SSSI effect is illustrated through comparison of seismic member forces and acceleration response spectra. Overall observations are summarized and recommendations for future research are presented.

INTRODUCTION

The Hanford Waste Treatment Plant is a Department of Energy Facility that will vitrify radioactive and chemical tank waste stored at the Hanford site. The Pretreatment Facility will house the first step in the vitrification process.

The Pretreatment Facility and all important adjacent structures must be designed to Seismic Category I standards and must meet the criteria of U.S. Department of Energy Standard 1020 [2002].

The Hanford Waste Treatment Plant Pretreatment Facility Complex (PTC), shown in Figure 1, is comprised of two small surface-founded structures, the Pretreatment Facility Annex (PTFA) and the Pretreatment Facility Control Building (PTCB), adjacent to one large partially embedded structure, the Pretreatment Facility (PTF).

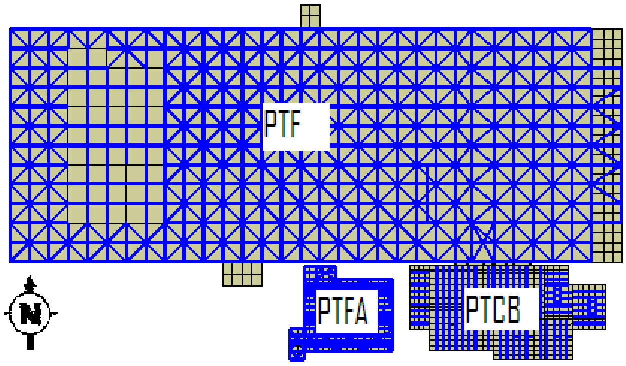

Fig. 1. Pretreatment Facility Complex

The PTFA and PTCB are separated from the PTF in the north-south direction by a seismic gap of less than one foot, as shown in Fig. 2.

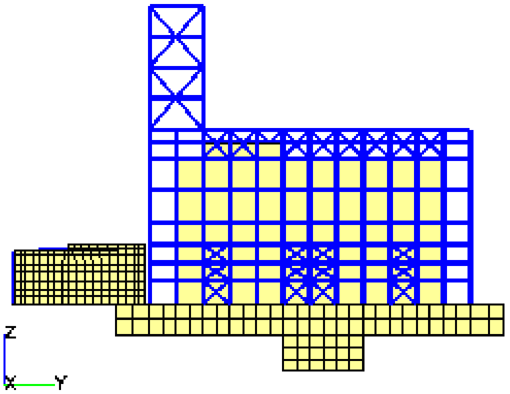

Fig. 2. Pretreatment Facility Complex (West View)

INDIVIDUAL BUILDING CHARACTERISTICS

The PTF consists of a core system of concrete shear walls that extend to Elevation (EL) 98’-0”. This portion of the structure resists lateral loads through relatively rigid composite slab diaphragms and concrete shear walls. The roof and perimeter of the structure consists of steel framing that are laterally supported by vertical steel bracing or the concrete shear walls below EL 98’-0”. Above EL 98’-0”, lateral loads applied to the roof steel are resisted by vertical steel bracing, as distributed by a horizontal roof bracing system. The PTF exhibits a complex response particularly due to the interaction between the steel and concrete lateral resisting systems.

Lateral loads applied to the PTA are resisted by a steel framing system, distributed by an intermediate composite slab diaphragm and a flexible roof diaphragm. The PTA exhibits a relatively flexible response.

Lateral loads applied to the PTCB are resisted by a concrete shear wall system as distributed by composite slab floor and roof diaphragms. The PTCB exhibits a relatively rigid response.

The soil and ground motion characteristics are most critical in the low frequency range at the Hanford site. As will be shown in this paper, the incorporation of Soil-Structure Interaction (SSI) and Structure-to-Soil-Structure Interaction (SSSI) shifts the relatively rigid response of the PTCB into this critical frequency range. Hence, the incorporation of SSSI effects is most significant in the analysis of the PTCB and is the focus of this paper.

STRUCTURAL RESPONSE OF THE PTCB

Structural Characteristics

The PTCB is a concrete shear wall structure with 1’-6” thick shear walls extending floor to roof and a 4’-0” thick mat with areas of 1’-0” recessing. Contributing shear walls are shown highlighted in Figure 3.

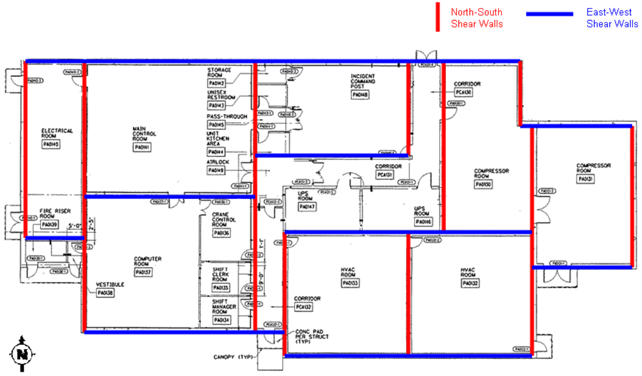

Fig. 3. PTCB Shear Walls

The roof and floor slabs consist of composite steel girders and concrete slabs. The slabs are constructed of 1’-0” thick concrete poured on steel decking connected with shear studs to the steel girders.

There are two mezzanine slabs at EL 15’-0” as shown in Fig. 4. While the ICP mezzanine is supported on all four sides, the HVAC mezzanine slab is cantilevered on the North end.

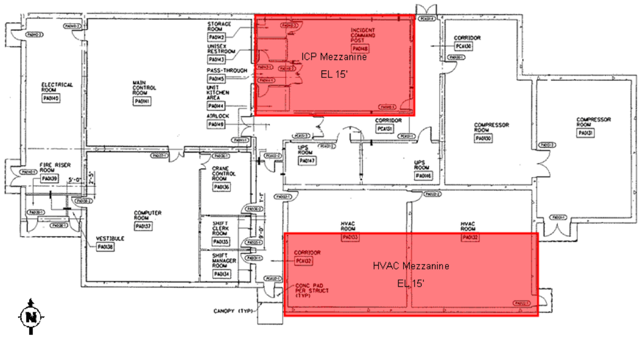

Fig. 4. PTCB Mezzanine Slabs at EL 15’

There are four roof elevations that range from EL 22’-6” to EL 37’-6” as shown in Fig. 5.

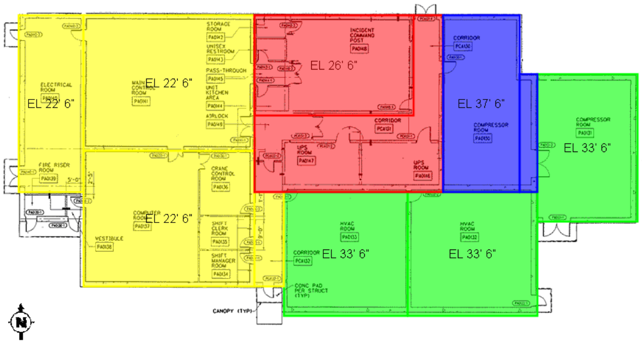

Fig. 5. PTCB Roof Slabs

Modal Analysis

The modal analysis of the PTCB is completed using SAP2000 (Computers & Structures, 2000), after incorporating all appropriate loads (i.e. equipment load, collateral load, and 25% of live load) as prescribed by DOE Standard 1020 [2002]. Shown in Table 1, are the results of PTCB modal analysis.

Table 1. PTCB Modal Results

East-West (X)			North-South (Y)		
Mode	Mass Participation	Frequency (Hz)	Mode	Mass Participation	Frequency (Hz)
41	12.2%	21.6	26	15.4%	18.7
69	9.5%	28.2	43	15.0%	22.2
37	8.9%	21.0	28	6.9%	19.5
40	7.3%	21.5	51	5.8%	24.2

The PTCB modal analysis results indicate that excitation in the East-West (EW) direction of the structure results in one dominant mode at a frequency of 21.6 Hz. The North-South (NS) excitation of the PTCB results in 2 dominant modes in the 18 Hz to 22 Hz range.

The SSI and SSSI analyses are conducted using the computer program SASSI2000 (Lysmer et al. 1972, and Lysmer et al. 1999) which provides a linear solution in the frequency domain.

Hard Rock Analysis

In order to validate the PTCB Finite Element Models and check the response of the PTCB structure, a hard rock analysis is completed using SASSI 2000. Transfer functions can be computed as the ratio of the Fourier amplitude of the seismic response as a function of frequency at the considered node to that of a control point node at the free field where the input seismic motion is applied.

A Hard Rock (HR) soil case is created, with high shear wave velocities and low damping ratios, to emulate the fixed base condition. Transfer functions are computed for the HR case. These transfer functions quantify the response characteristics of the structural models. The HR transfer functions for the EW (x) direction and the NS (y) direction, are shown in Fig. 7 and Fig. 8, respectively.

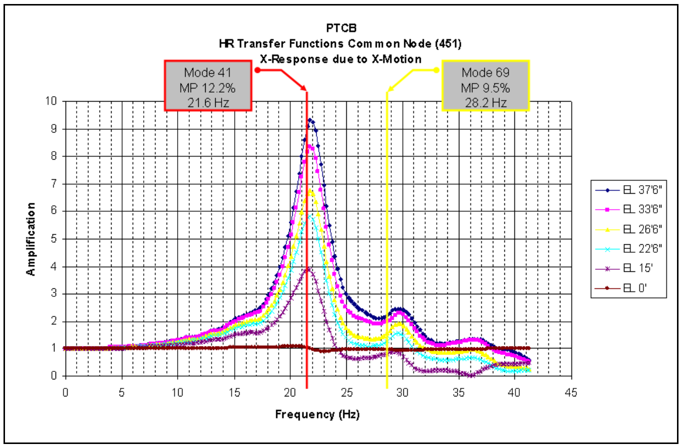

Fig. 7. PTCB HR EW Transfer Functions

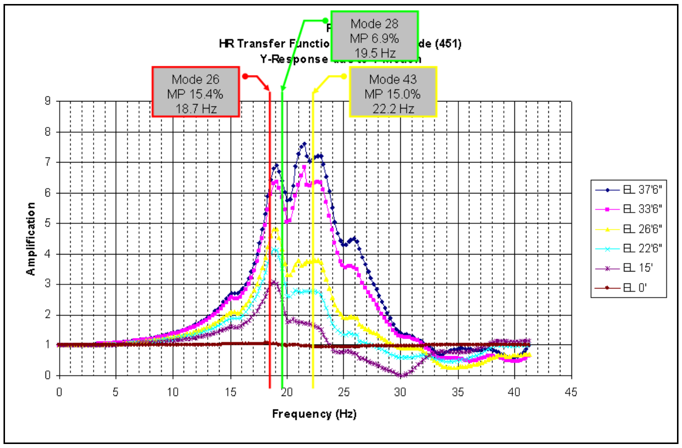

Fig. 8. PTCB HR NS Transfer Functions

The peak amplifications of the HR transfer functions correspond to the dominant frequencies resulting from the fixed base modal analysis. This serves as a check on the validity of the finite element models and also helps to visually clarify the modal response of the structure.

It is evident both in the fixed based modal analysis and the hard rock analysis, that the EW response exhibits one significant dominant mode, while the NS response exhibits at least two dominant modes. A further study is completed to ensure that this multi-modal response is appropriate for the structural characteristics. A closer look at the transfer functions for each wall in-plane to the NS direction indicates that the overall response is reflected in each individual wall response. However, each wall has a different dominant frequency. This is characteristic of the PTCB structural layout. As shown in Fig. 3 there are uniformly rigid shear walls in the EW direction, while in the NS direction, the shear walls vary in position and length.

SSI RESPONSE OF THE PTCB

Three strain compatible soil profiles, Upper Bound (UB), Mean (M), and Lower Bound (LB), are generated through free-field deconvolution analysis based on the soil site characteristics. SSI analysis of the PTCB is completed for each profile in each of the three orthogonal directions.

Transfer Functions

Transfer functions are computed for each soil case at the highest roof elevation. Shown in Fig. 9 and Fig. 10 are the SSI transfer functions compared for response parallel to the direction of excitation, for the EW and NS directions, respectively.

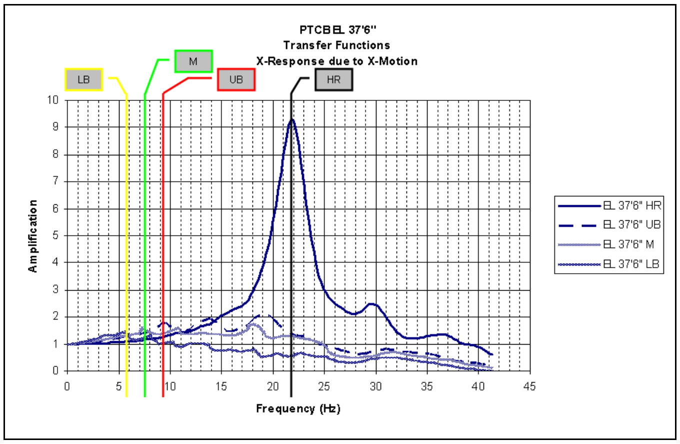

Fig. 9. PTCB SSI EW Transfer Functions

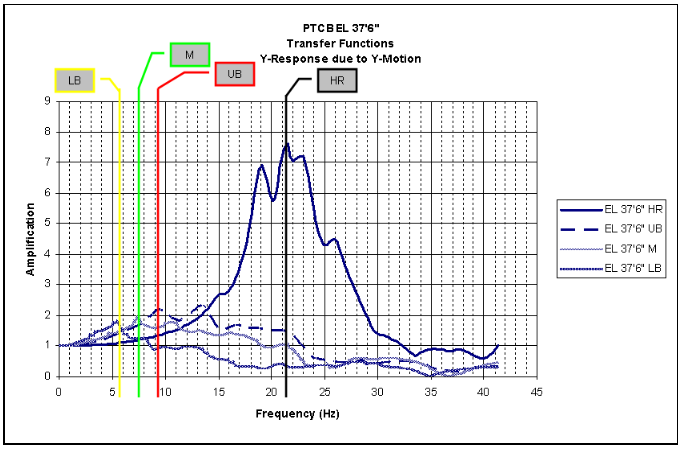

Fig. 10. PTCB SSI NS Transfer Functions

As demonstrated in the figures above, incorporation of SSI effects shift the characteristic frequencies of the PTCB into a much lower frequency range.

SSSI RESPONSE OF THE PTCB

Transfer Functions

In order to characterize the SSSI effect of the PTC on the structure and soil models, transfer functions are computed at 7 nodes in a NS section cut of the PTC, as shown in Fig. 11.

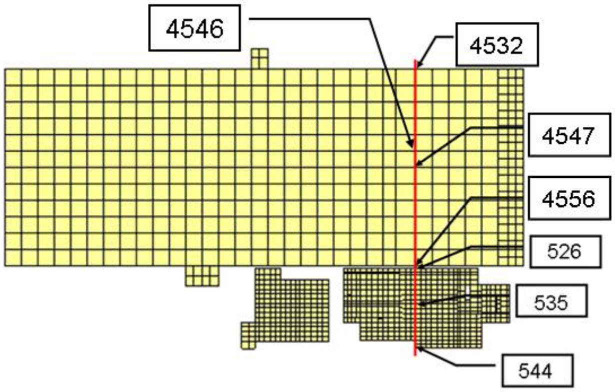

Fig. 11. PTC SSSI NS Section Cut

Transfer functions are shown for a common node (4547), in the center of the PTF mat, in both the individual (PTF) and combined (PTC) models, as shown in Fig. 12 through Fig. 14. For the purposes of this paper, only the UB soil case is shown.

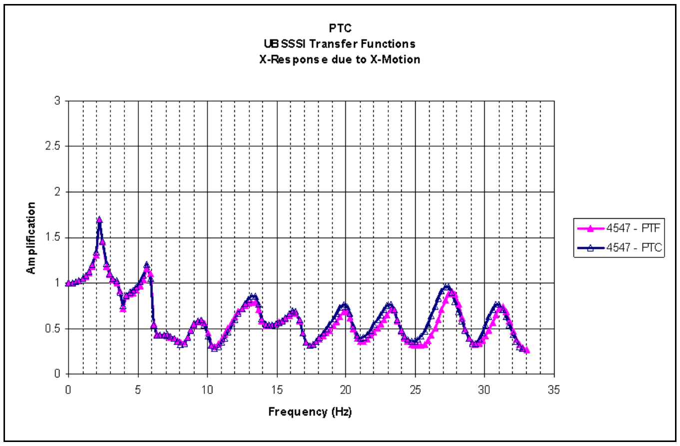

Fig. 12. PTF SSSI EW Transfer Functions

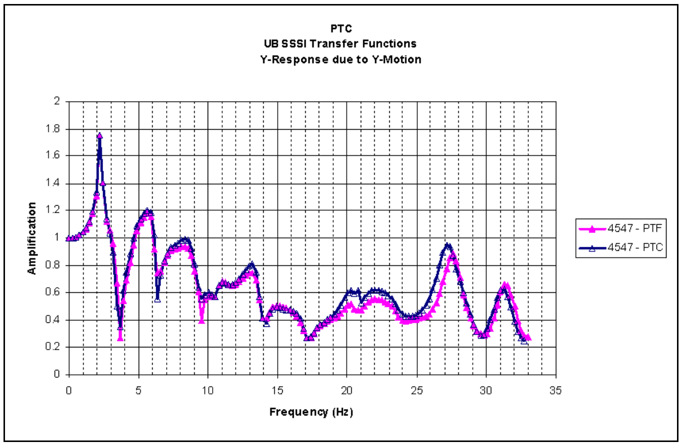

Fig. 13. PTF SSSI NS Transfer Functions

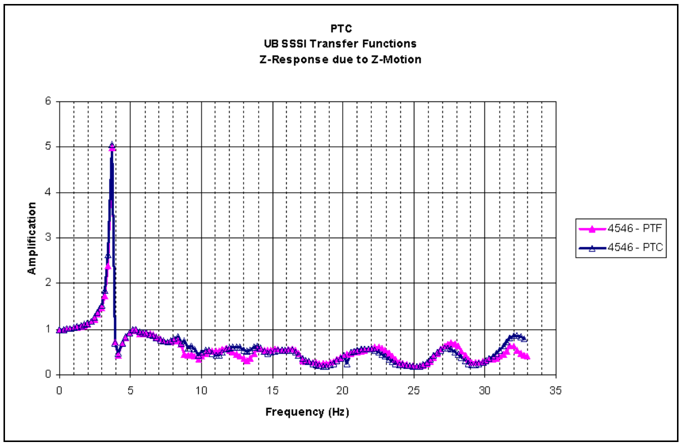

Fig. 14. PTF SSSI Vertical Transfer Functions

These comparisons show close agreement which indicates that the PTCB and PTA have little or no influence on the response of the PTF.

Transfer functions are shown for 6 nodes on the NS section cut from the combined model (PTC), in Fig. 15 through Fig. 17.

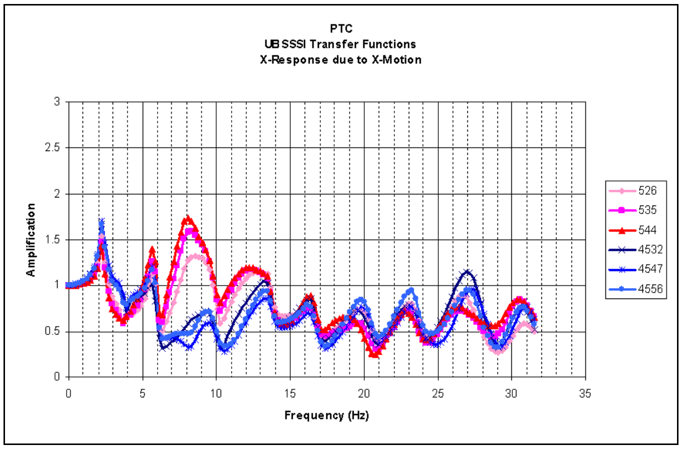

Fig. 15. PTC SSSI EW Transfer Functions

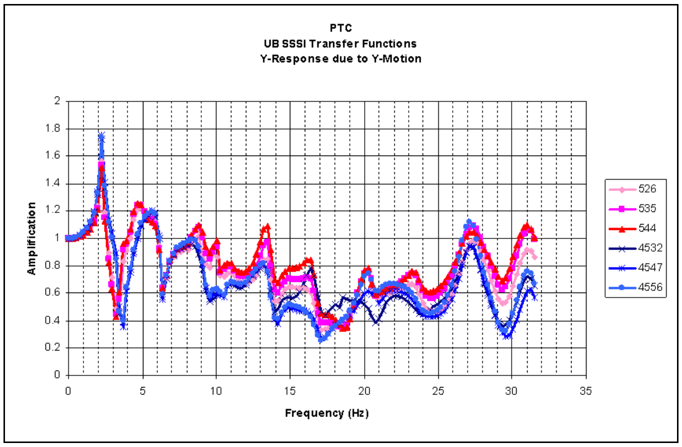

Fig. 16. PTC SSSI NS Transfer Functions

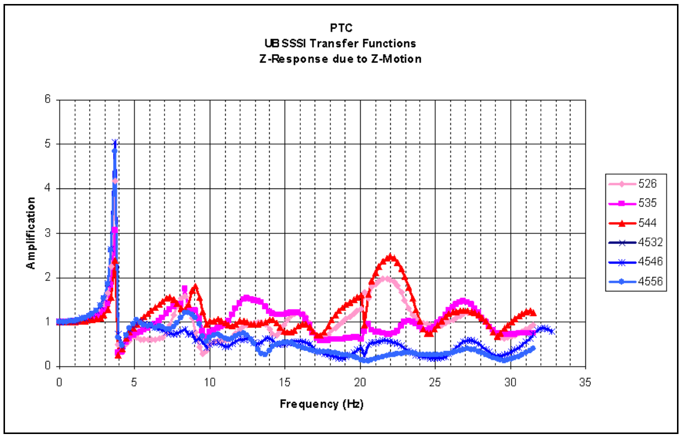

Fig. 17. PTC SSSI Vertical Transfer Functions

The transfer functions for the PTCB nodes follow the pattern of the response of the PTF nodes. The PTCB response approaches the pattern of the PTF response as the distance from the PTF decreases.

Transfer functions are shown for a common node, at the center of the PTCB mat, in both the individual (PTCB) and combined (PTC) models, in Fig. 18 through Fig. 20.

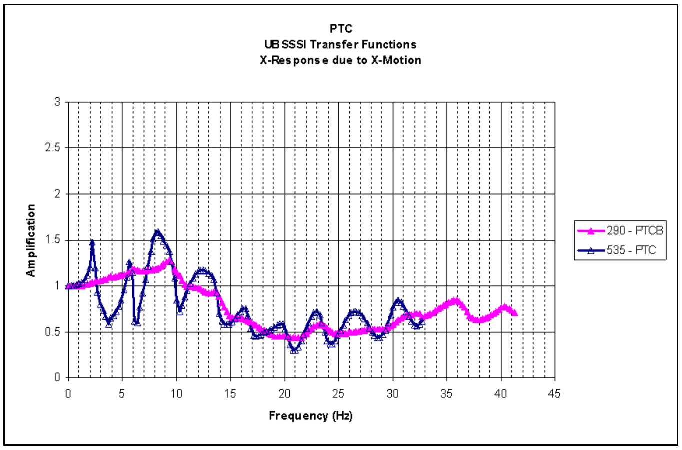

Fig. 18. PTCB SSSI EW Transfer Functions

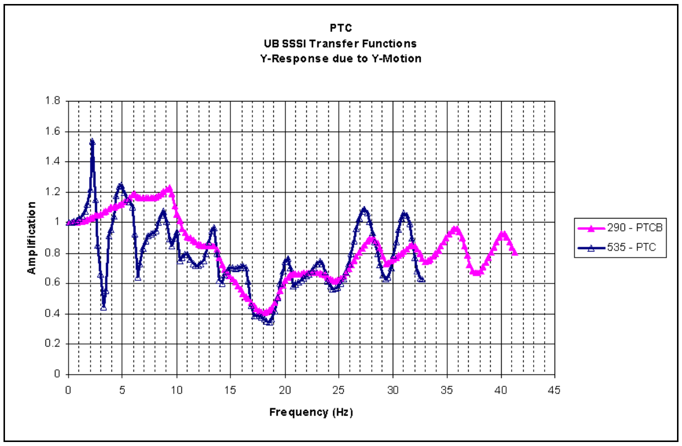

Fig. 19. PTCB SSSI NS Transfer Functions

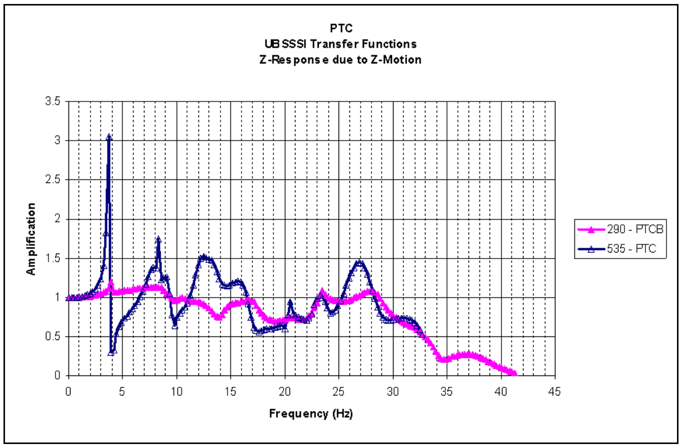

Fig. 20. PTCB SSSI Vertical Transfer Functions

It is observed that the response of the PTCB in the PTC model follows the pattern of the PTF response while oscillating about the individual PTCB response, at higher frequencies. The transfer functions shown for the PTCB indicate that the PTF response has a strong SSSI effect on the PTCB response.

<u>Maximum Nodal Accelerations</u>

The site specific input spectra at the free field for the PTC are shown in Fig. 21. H1, H2, and VT, correspond to the X, Y, and Z directions, respectively.

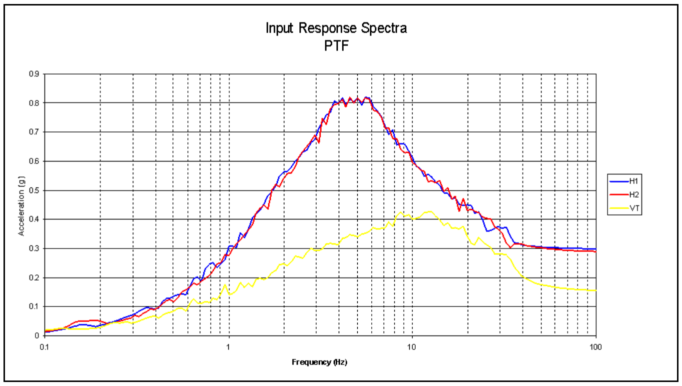

Fig. 21. PTC Site Specific Free Field Input Spectra

SSI analysis is completed applying the input motions shown in Fig. 21. Maximum accelerations at each node are extracted, in each response direction, due to seismic input in each of the three directions, for each of the three soil cases. For each node, the 100-40-40 rule (DOE-STD-1020 [2002]) is applied to combine the maximum accelerations (within each response direction) due to input seismic motion in all three directions. The combined maximum accelerations resulting from the three soil cases are enveloped. The result is one maximum acceleration, at each node of each model, for each orthogonal direction.

To quantify the effect of SSSI after incorporation of the seismic motion, a weighted average ratio is computed. First, the ratios of the maximum nodal accelerations from the results of the PTC analysis (including SSSI effects) to the results of the PTCB analysis (discounting the SSSI effects) are computed for each node. Second, the ratios are weighted by the characteristic nodal mass. Then, the weighted ratios are summed and divided by the total nodal mass of the PTCB.

The weighted average ratios for each orthogonal direction are shown in Table 2.

Table 2. SSSI Ratios

X	Y	Z
1.02	1.15	1.33

On average, the incorporation of SSSI effects amplifies the maximum nodal accelerations of the PTCB. When motion is in-plane with the interface of the PTF, the amplification when considering SSSI is only 2%. When motion is out-of-plane with the interface of the PTF, the amplification when considering SSSI is 15%. When motion is vertical, the amplification when considering SSSI is 33%.

As shown in the transfer function comparisons, incorporation of SSI shifts the characteristic frequency of the PTCB in a lower frequency range. This new frequency is much more critical, as it aligns with the peak of the horizontal input response spectra as shown in Figure 21.

The peak of the PTF transfer functions occurs at the frequency of the input response spectra peak. As shown in Figures 18, 19, and 20, the energy of the PTCB transfer functions are shifted to the range of the PTF critical response, when considering SSSI.

Acceleration Response Spectra

In order to further characterize the SSSI effect on the PTC, acceleration response spectra are computed at the same 7 nodes in the NS section cut shown in Fig. 11.

Acceleration response spectra are shown for a common node (4547), in the center of the PTF mat, in both the individual (PTF) and combined (PTC) models, as shown in Fig. 22 through Fig. 24. For the purposes of this paper, only the UB soil case is shown.

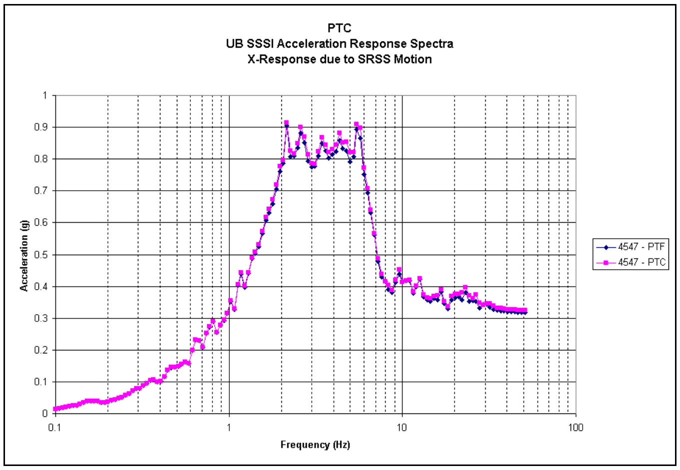

Fig. 22. PTF SSSI EW Acceleration Response Spectra

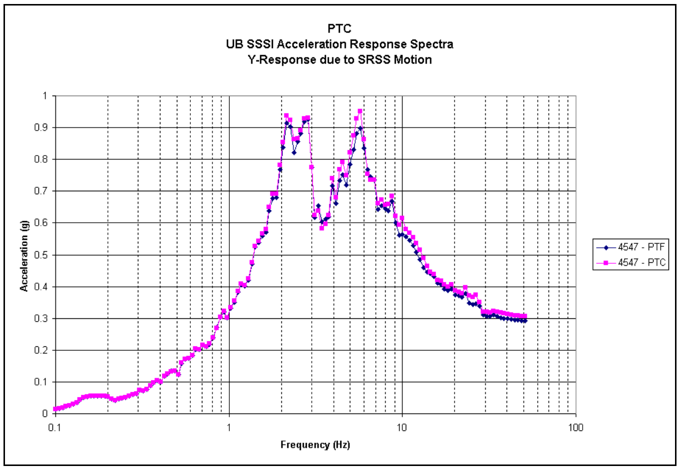

Fig. 23. PTF SSSI NS Acceleration Response Spectra

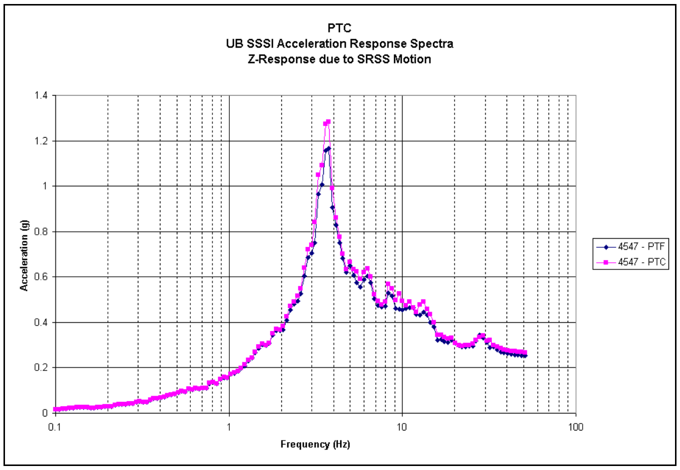

Fig. 24. PTF SSSI Vertical Acceleration Response Spectra

As with the transfer function comparisons, the acceleration response spectra compare well.

Acceleration response spectra are shown for a common node, at the center of the PTCB mat, in both the individual (PTCB) and combined (PTC) models, in Fig. 25 through Fig. 27.

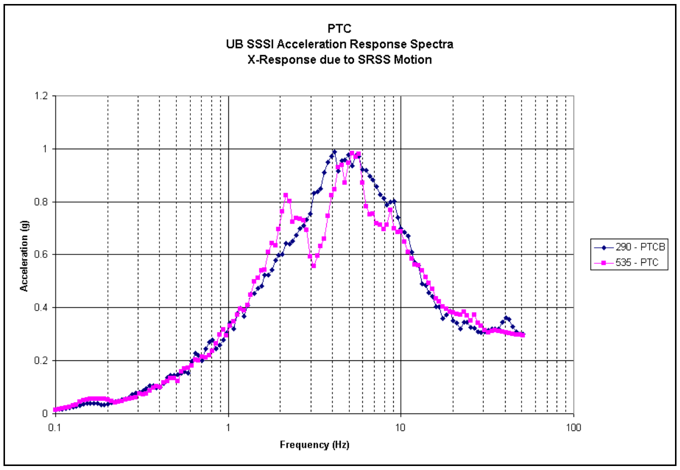

Fig. 25. PTCB SSSI EW Acceleration Response Spectra

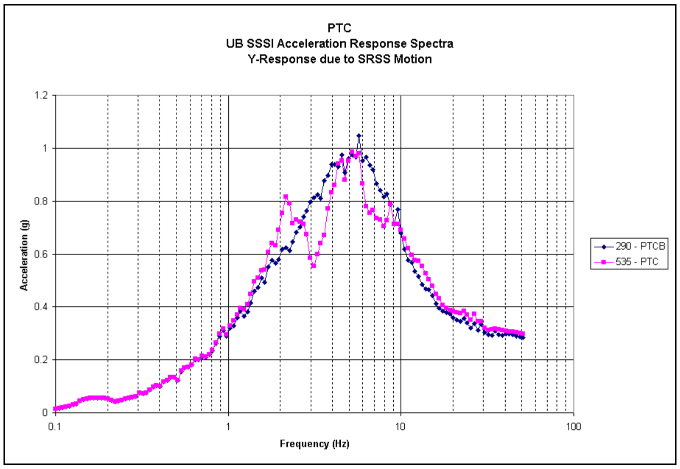

Fig. 26. PTCB SSSI NS Acceleration Response Spectra

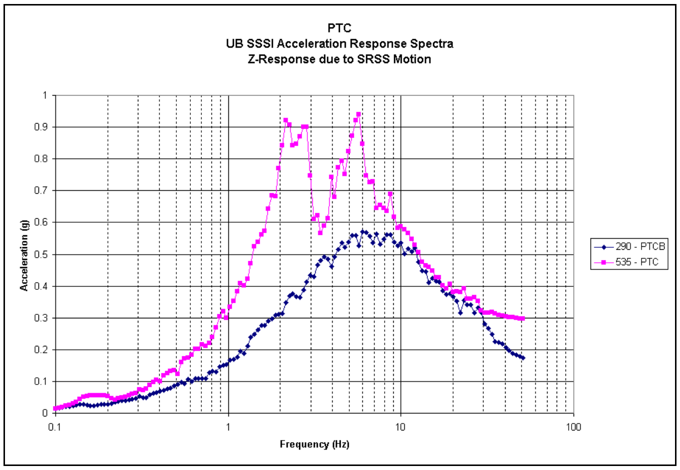

Fig. 27. PTCB SSSI Vertical Acceleration Response Spectra

The SSSI ratios given in Table 2 indicate the vertical direction is most effected by the incorporation of SSSI effects. This is clearly evidenced in Figure 27. At Elevation 0' the difference in SSSI amplifications between the x and y directions are not apparent. The larger SSSI ratio for the y-direction is predominantly due to the amplifications that occur in the structure portion of the PTCB as indicated by the transfer functions. Shown in Figure 28 and 29 are the same comparisons at a node with the same spatial coordinates at Elevation 26' 6".

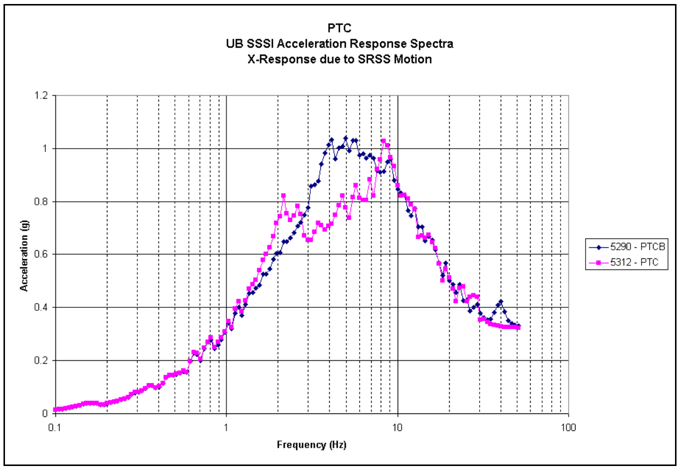

Fig. 28. PTCB SSSI EW Roof Acceleration Response Spectra

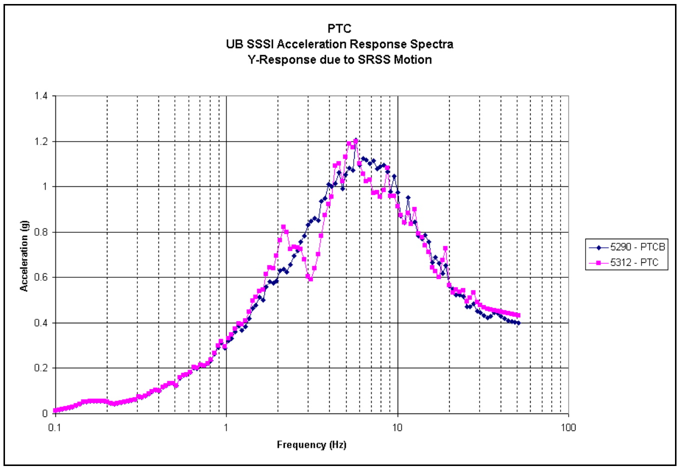

Fig. 29. PTCB SSSI NS Roof Acceleration Response Spectra

The difference in amplification between the x-direction and y-direction SSSI ratios is more apparent at the higher elevation.

CONCLUSION

This case study shows the importance of explicit modeling for SSSI analysis of the Hanford Waste Treatment Plant Pretreatment Facility Complex. The consideration of SSI and SSSI for the PTC drastically changed the PTCB demand loading resulting from the structural analysis. Weighted average ratios of zero-period accelerations indicate that the amplifications resulting from SSSI consideration are mostly apparent in the vertical direction, with a 33% increase in demand loads. The amplification in the response direction perpendicular to the buildings interface is also significant, with a 15% increase in demand loads. The amplification of the response direction parallel to the building interface is less significant, representing only a 2% increase in demand loads.

This is a result of the ground motion and soil-site response more closely aligning when the effect of the adjacent building is considered.

RECOMMENDATIONS

Industry codes should include more specific criteria for determining when SSSI should be taken into consideration. The importance of SSSI is dependent on a few quantifiable variables. Limits for applicability of SSSI incorporation can be set based on these parameters.

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