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One-Side Seismic Structure-Soil-Structure Interaction Analysis Using SASSI Approach

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ABSTRACT

An approximate approach to the seismic structure-soil-structure interaction (SSSI) analysis is developed for the case when one of the neighboring buildings is far greater than the others. The goal is to replace the single analysis of several structures by a set of analyses of smaller systems. Only the influence of the main building on the adjacent ones is considered; the back influence and cross-influence of the adjacent structures is neglected (that is why the analysis is called one-sided).

At first the main building is treated separately. Then each of the adjacent buildings is treated with the nearest part of the main building's basement moving as prescribed by the former solution. Special technique is developed to incorporate this second excitation from the basement of the main building (the first excitation is from seismic wave) into the SASSI approach, i.e. into the complex response analysis. The problem is that transfer functions are calculated from the one-component soil motion representing certain seismic environment, and in our case there appear at least six new excitation components.

ASCE4-98 code allows neglecting the SSSI effects if the foundation stiffness is varied. This statement is checked for the NPP vent stack located near the auxiliary reactor building and found to be non-conservative in some frequency ranges.

KEY WORDS: seismic analysis, soil-structure interaction, adjacent buildings, nuclear power plant, complex response analysis, frequency domain, transfer functions.

INTRODUCTION

Nuclear power plants are always composed of number of adjacent structures. Generally speaking, seismic analysis must account not only for soil-structure interaction (SSI) but for structure-soil-structure interaction (SSSI) as well. However, the size of such problem treated properly (i.e. with all limitations to the size of 3D finite elements modeling soil) is unbearable for common computers even now. Thus, the approximate approaches are used. For example, ASCE4-98 [1] code states that the SSSI effects are covered with a variation of soil stiffness 1.5 times up and down used to account for the uncertainties in SSI. It sounds doubtful, because the SSSI effects obviously depend on range of parameters not referred to the soil stiffness (e.g., geometry, masses and stiffness of structures).

Fortunately, in many cases one of the adjacent structures is greater than the others (considering mass and stiffness properties). Thus, the SSSI problem can be treated as "one-side", i.e. the main building is not significantly influenced by the adjacent buildings and may be treated separately. The adjacent building is then excited not only by seismic waves, but also by the movement of the main building. The problem for the adjacent building is smaller than the initial problem because the main building can be represented only by rigid basement (in fact, only by the part of it nearest to the adjacent building) moving as prescribed by the former solution (the main building treated alone).

However, this simple idea is not so easy to incorporate into the complex response analysis because transfer functions are calculated from a single component of the motion of the soil. The purpose of this report is to present a special technique to do this using the well-known SASSI [2] approach.

The second goal is to check the above-mentioned statement of ASCE4-98 using the particular example of the NPP vent stack (as adjacent structure) located near the reactor auxiliary building (as main building).

The third goal is to estimate the influence of the portion the main building's basement included in SSSI model.

THEORETICAL BACKGROUND

A model of structure-soil-structure (SSS) system includes the whole model of the adjacent structure and some portion of the main building's basement, nearest to the adjacent building. This portion is considered rigid and moves together with some "control node", as prescribed by the analysis of the main building staying alone. Useful feature of SASSI approach is that the intermediate soil between two basements needs not to be modeled by FEM.

Seismic environment according to the SASSI approach is controlled by one-component motion of some soil point. Usually vertical wave in horizontally layered soil is adopted and the soil point is taken on the surface of the soil. In this case three components of seismic excitation are treated separately as three different seismic environments.

Let the full solution in the frequency domain for a single seismic environment $u(x,y,z,\omega)$ be composed of seven partial solutions $u_j(x,y,z,\omega)$ with coefficients $A_j(\omega)$ (j=0,...,6):

$$u(x,y,z,\omega) = A_0(\omega)u_0(x,y,z,\omega) + \sum_{i=1}^{6} A_i(\omega)u_i(x,y,z,\omega) \qquad (1)$$

Partial solutions $u_j(x,y,z,\omega)$ (j=0,...,6) are defined as solutions for the model with fixed control point at the basement of the main building. The difference between solutions is only in fixed DOFs of this control point: for j=0 all DOFs are fixed; for j=1,...,6 all DOFs but one DOF number j are fixed.

Coefficients $A_j(\omega)$ (j=1,...,6) provide the prescribed movement of the control point at the basement:

$$A_j(\omega) = F_j(\omega) / U_j(\omega) \qquad (j=1,...,6) \qquad (2)$$

Here $F_j(\omega)$ (j=1,...,6) - transfer functions to the control point at the basement in the former solution (main building alone) for the same seismic environment; $U_j(\omega)$ are just values of $u_j(x,y,z,\omega)$ in the control point at the basement.

The last coefficient $A_0(\omega)$ makes the composite seismic environment equal to the initial one:

$$A_0(\omega) = 1 - \sum_{i=1}^{6} A_i(\omega) \qquad (3)$$

Thus, the solution Eq.1 provides the fulfillment of three principal conditions:

1) Equilibrium equations are satisfied everywhere except the control point at the basement due to the origin of partial solutions.
2) Control point at the basement of the main building moves as prescribed by the former solution due to Eq.2 and number of fixed DOFs in partial solution.
3) Seismic environment remains the same as for the former solution due to Eq.3 .

In fact, one solution for the coupled system is replaced by eight solutions for uncoupled systems. This may be justified in cases when the solution for the coupled system is not available.

SAMPLE PROBLEM

Vent stack of NPP standing near the auxiliary reactor building was considered as a sample problem. The stack of 100 meters height is embedded to 10.6 m. Basement slab of the stack is 10 meters in diameter. The axis of the stack is 16 meters apart from the basement of the auxiliary reactor building, which is embedded to 8.6 m. Soil foundation has 25 layers resting on flexible halfspace.

Three-component seismic excitation was applied at the free surface of the soil. Statistically independent components were generated to match standard RG1.60 spectra. Horizontal acceleration amplitudes were taken as 0.4g, vertical amplitude 0.267g.

To investigate the influence of the portion of the main building’s basement included in the SSSI model two SSSI models were used. In the model no.1 the part of the bottom was included together with four vertical walls (two of them - partly). The underground part of this model is shown on Fig.1. Basement of the stack was modeled by 3D volume elements; only their bottom surfaces are shown. Basement of the building was modeled by set of nodes connected with rigid weightless beams.

In the model no.2 the stack was the same; in the basement of the main building only two vertical walls facing the stack were included in the SSSI model.

The control point at the basement was selected in the corner of the basement slab. The motion of this node was obtained through the solution of the SSI problem for an auxiliary reactor building standing alone.

DISCUSSION OF NUMERICAL RESULTS

Overall SSSI Effect

The first question considering SSSI is the overall effect and the necessity to go in for complex calculations to account for it. To estimate the overall effect the solution for stack standing alone is compared to the solutions for model no.1 and model no.2.

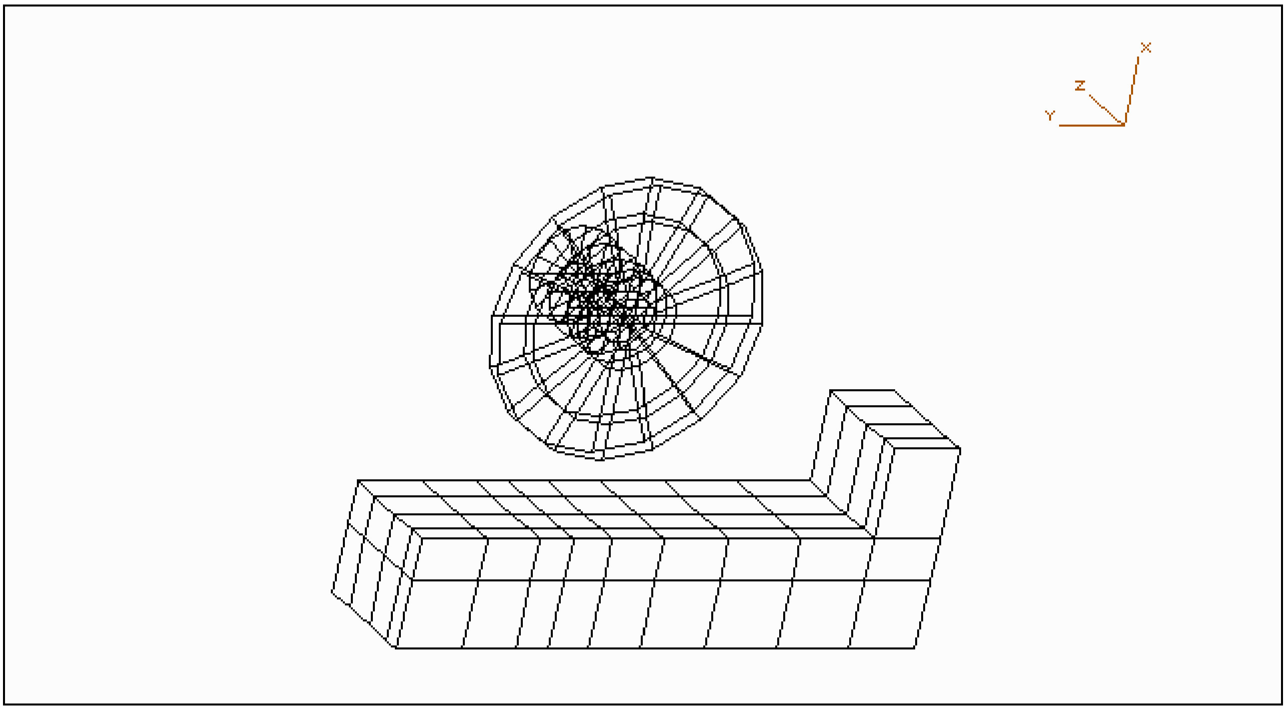

Fig.1 Underground part of model no.1: stack and portion of the basement of the auxiliary reactor building

First, SSSI changes transfer functions in the direction of excitation. Second, SSSI changes "cross-responses" in other directions. For example, stack itself is axisymmetrical, so cross-responses are zero. However, SSSI models are not axisymmetrical, so cross-responses appear.

The example of the overall SSSI effect is shown on the Fig.2. The absolute values of the transfer functions from the displacements of the free soil surface in all three directions to the vertical displacements of stack's axis at the level z=0.0 m are compared in the frequency domain.

For stack standing alone only one transfer function is non-zero: vertical response to vertical excitation. For both SSSI models such transfer functions are just slightly different from this (in fact, for the frequencies below 2.5 Hz they are practically the same). However, in SSSI models the cross-responses appear from both horizontal excitation components. One should keep in mind that horizontal accelerations of seismic excitation are usually about twice vertical ones in amplitude, so the cross-response transfer functions from horizontal soil displacement to the vertical response displacement are "of double importance" compared to the transfer functions from vertical excitation to the vertical response. Interesting to mention that in our case the cross-response from excitation in the direction X proved to be much less than that from the excitation in Y-direction.

The first peak in Y cross-response near 3.5 Hz is caused by the first resonance of the auxiliary reactor building standing alone. This resonance is of sway-rocking type, but due to the rocking the corner part of the basement slab gets vertical displacements leading to the peak in vertical displacements of the stack.

The second peak in Y cross-response near 9 Hz corresponds to the resonance of the stack itself. At the same frequency there is the main Z response resonance.

The level z=0.0 m is suitable for studying SSSI effects because stack itself is a low-frequency structure; three first eigenfrequencies are so low, that for the top of the stack neither SSSI nor SSI effects occur.

The first conclusion is that the overall SSSI effect in our case proved to be significant for the frequencies above 2 Hz and mostly in cross-responses.

SSSI effects vs variation of soil properties

To check the statement of ASCE4-98 about the conservatism of the variation of soil properties compared to the accounting for the SSSI effects one need to compare response spectra. Three problems for the vent stack standing alone were solved: in addition to the best estimate soil properties (referred to as "real" soil) shear modulus G for all soil layers was multiplied by 1.5 (referred to as "hard" soil) and divided by 1.5 (referred to as "soft" soil). Response spectra for 2% damping were obtained in three directions in the above-mentioned node (on the axis of the stack at the level z=0.0 m). All spectra were broadened in the frequency domain by 15% (in fact, ASCE4-98 does not demand broadening of spectra for soft and hard soils, but here the additional conservatism was introduced).

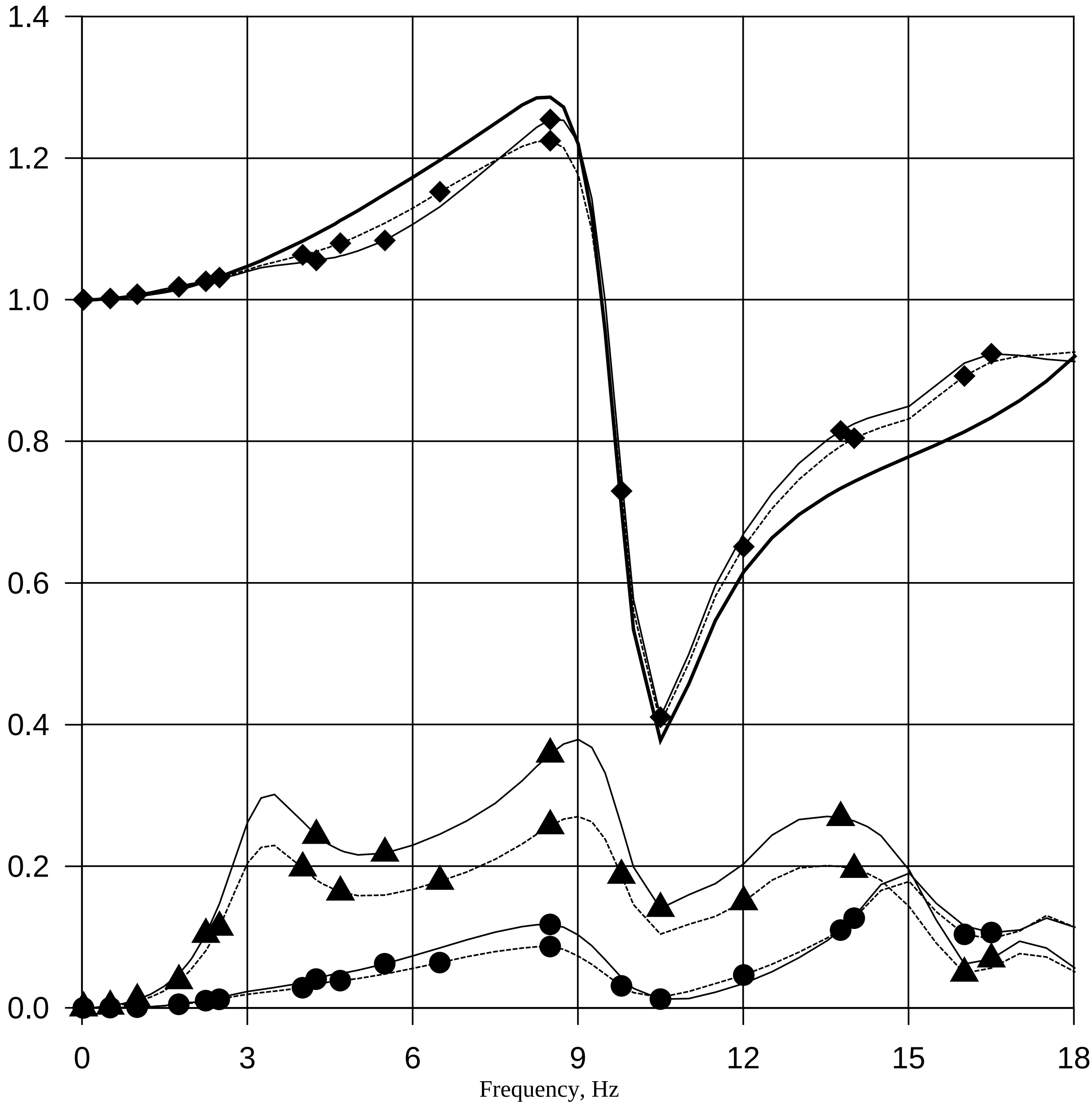

Fig.2 Absolute values of the transfer functions from the displacements on the free surface of the soil to the vertical displacements on the axis of the stack at the level z=0.0 m. Unmarked curve - the stack standing alone. Marked solid lines - SSSI model no.1, marked dashed lines - SSSI model no.2. Directions of excitation: circles - along X, triangles - along Y, rhombus - along Z

The comparison of vertical response spectra is shown on Fig.3 . All three soils give almost the same results up to 5 Hz (the main peak is about 8 Hz). As stated above, at the frequencies below 2 Hz there is practically no difference between all five curves (two for SSSI models and three for stack standing alone on different soils). Then there appears a frequency range around 3.5 Hz where both SSSI models give spectral acceleration greater (about 10% for model no.1) than all three models of the sole stack. This corresponds to the first resonance of the main building, as mentioned above, so the sole stack models just do not contain such information. Up to 9 Hz the results of the SSSI model no.1 exceed the greatest of the three sole stack results (broadened spectrum for hard soil). If one takes away broadening of the hard soil spectrum, the frequency range of the SSSI non-conservatism extends to 10.5 Hz, thus covering major part of seismic frequency range.

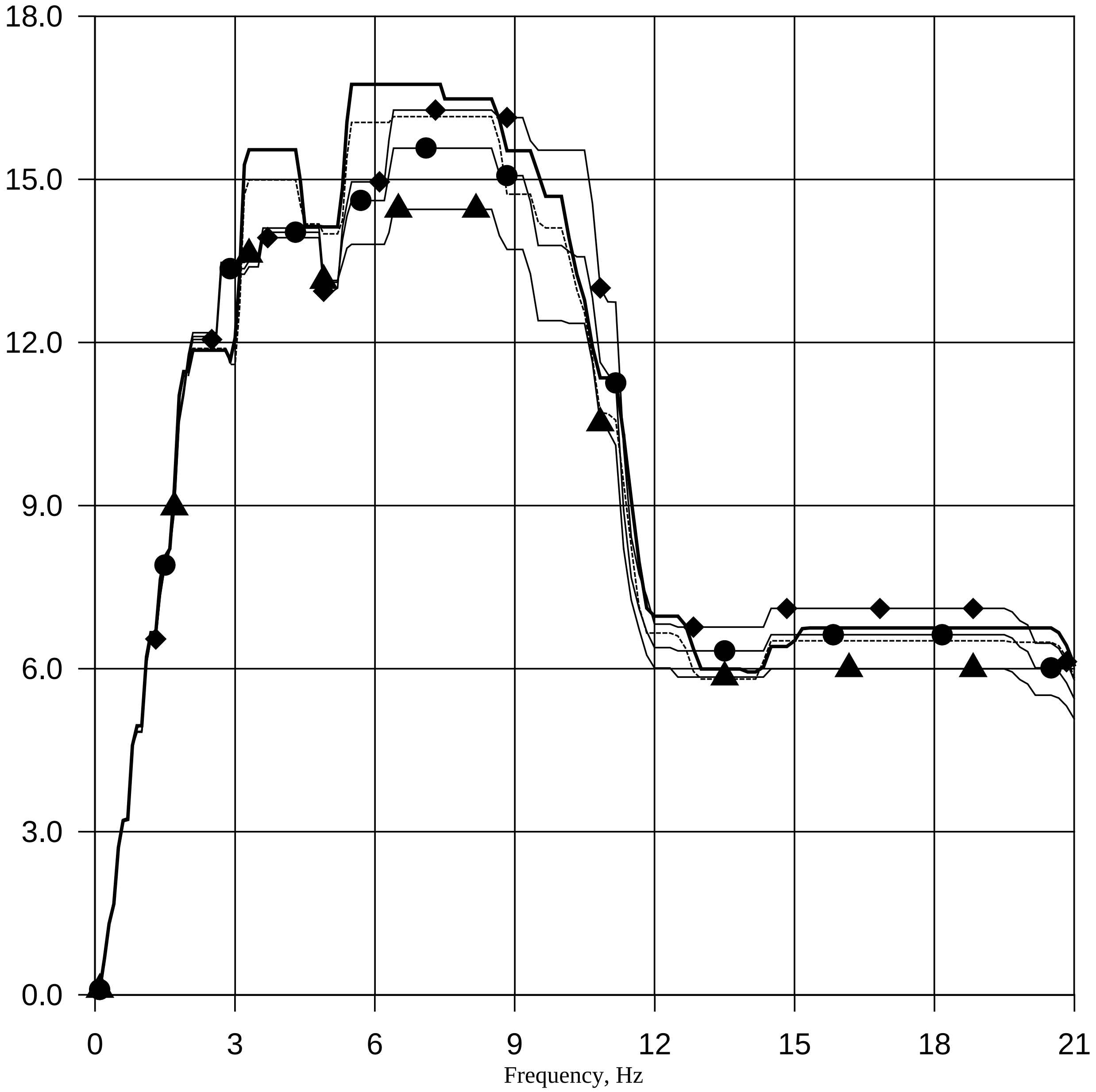

Fig.3 Vertical acceleration response spectra (m/s^2) for 2% damping broadened ±15% in the frequency range in the node on the axis of the stack at the level z=0.0 m. Unmarked solid line - SSSI model no.1, unmarked dashed line - SSSI model no.2. Marked lines: triangles - soft soil, circles - real soil, rhombus - hard soil

The comparison of horizontal response spectra in Y-direction is shown on Fig.4. Here the results of the sole stack models are conservative almost everywhere. However, even here there is a small frequency range around 8.5 Hz and high-frequency range above 16.5 Hz where the SSSI results proved to exceed those for the sole stack.

The second conclusion is the following: variation of the soil shear modulus 1.5 times up and down can not cover the SSSI effects completely. This is natural because such a procedure cannot take into account resonance properties of the main building, reflected in the adjacent building's response.

Influence of the portion of the main building's basement included in SSSI model

SSSI models no.1 and no.2 were used in parallel throughout all the studies described above. The comparison of results for these models on Figures 2...4 shows that the difference between them is visible, especially for vertical response (see Fig.2 and Fig.3). Moreover, the results for the expanded model no.1 almost always are higher than for the model no.2. However, the difference is not dramatic, so in our case one can hope that further expansion of the model will not lead to significant changes in results compared to the model no.2. The recommendation is to include into the SSSI model not only the vertical walls of the main building's basement facing the adjacent building but also the nearest fragments of the bottom and neighboring vertical walls. Computer used sets limitations.

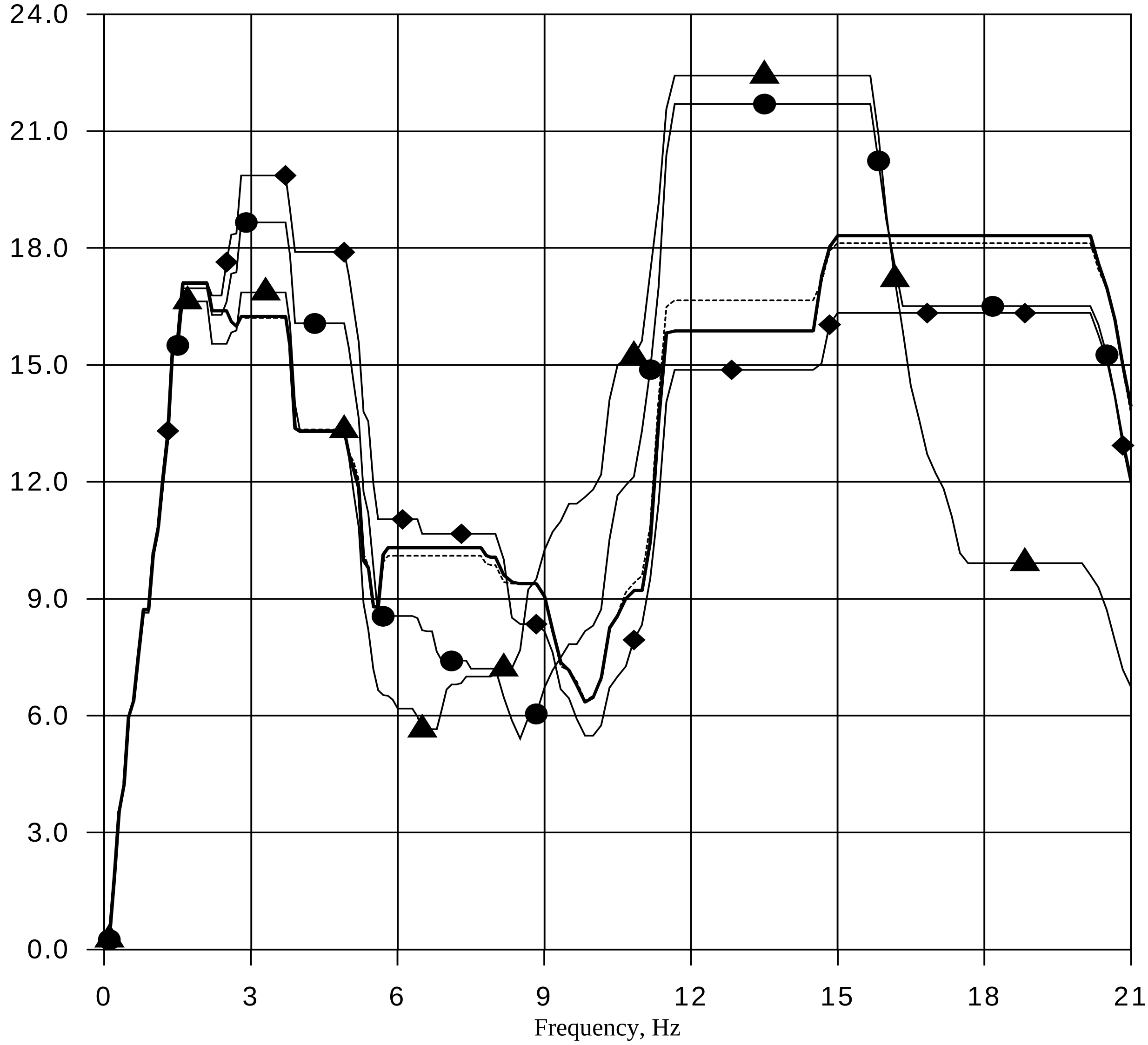

Fig.4 Horizontal (Y-direction) acceleration response spectra (m/s^2) for 2% damping broadened ±15% in the frequency range in the node on the axis of the stack at the level z=0.0 m. Legend - see Fig.3

GENERAL CONCLUSIONS

A new technique to account for the SSSI effects in the complex response analysis is developed. It allows replacing the analysis of several structures by a set of smaller analyses in cases when one of the structures is greater than the others. A sample problem for NPP stack was studied. The SSSI effects proved to appear mostly in cross-responses and above a certain frequency. It was demonstrated by the comparison of response spectra that the variation of soil shear modulus 1.5 times up and down in the sole stack model did not cover SSSI effects. The portion of the main building's basement in the SSSI model should include not only the vertical walls facing the adjacent structure, but also the nearest portions of the bottom and the neighboring walls.

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