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EFFECT OF SOIL IMPROVEMENT ON SEISMIC RESPONSE

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ABSTRACT

In seismic design of heavy structures in soil sites they often use “soil pillows” under the base mat. Inside the volume of the “pillow” the initial soil is either removed and substituted by another soil, or upgraded by various technologies. Generally the main goal of such a design is to control settlements and provide stability of soil foundation, including special care to the potential soil liquefaction during seismic events. However, this “pillow” also impacts structural seismic response. In the paper the author considers three variants of the pillow depth in seismic analysis. It is demonstrated that structural seismic response can be considerably decreased as compared to the initial seismic excitation. The author demonstrates crucial role of the kinematical interaction in the considered effect. Two main parameters controlling the degree of seismic protection are: 1) the relative thickness of the pillow as compared to the wavelength in the initial soil; and 2) the ratio of the acoustic stiffness of the initial and upgraded soils. As wavelength is frequency-dependent, the protective effect is frequency-dependent too. Simple 1D models (analytical or SHAKE-type ones) provide useful insight.

INTRODUCTION

Sometimes they create a “soil pillow” under the base mat: in a certain finite volume the initial soil is either substituted with another soil, or upgraded without outcropping. Different technologies are available nowadays, but the result in mechanical terms is always one and the same – upgraded soil inside the “pillow” has properties substantially different from the initial soil. Upgrade can go in both directions: soft pillow in the hard surrounding soil and hard pillow in the soft surrounding soil. The first direction was studied for rock site and proved to be ineffective, because the wave damping proved to be switched off. The second direction – i.e. a hard pillow in soft surrounding soil – is studied in this paper.

Usually the main goal for such a decision is to withdraw the soil with unacceptable properties (e.g., liquefaction potential) or to decrease the settlement. However, the upgrade of the soil properties inevitably changes seismic response. In this paper the effect of the depth of the “soil pillow” on structural seismic response is studied.

First this effect is demonstrated using sample soil site and sample structure. Then the nature of the protective effect is studied closely. It turns out, that kinematical soil-structure interaction plays a crucial role. Fortunately, soil pillow without structure may be often modeled by infinite surface layer, enabling SHAKE calculations for layered sites and analytical solution for homogeneous sites. The results are compared to the SASSI results obtained for finite (in horizontal directions) soil pillow. Good matching makes the seismo- protective effect trustable. Analytical solution enables good understanding of the governing parameters.

DEMONSTRATION OF THE PROTECTIVE EFFECT

Here is the description of the sample structure considered. Rigid base mat 80.0 x 76.8 meters is resting on the surface of the soil. “Soil pillow” in each horizontal direction extends 2.5 meters beyond the base mat, so it is 85.0 x 81.8 meters. For the convenience it is assumed that the whole pillow is covered with a rigid base mat (actual inertia of the mat is preserved when structural model is involved).

Initial soil is modeled by a set of 18 horizontal layers resting on a homogeneous half-space. Total thickness of the package is 90 meters. Soil density is 2.0 t/m^3, material damping in the soil is 4%. Shear wave velocity Vs has non-monotonous profile in the range from 499 to 585 m/s; primary wave velocities Vp are in the range from 1897 to 2145 m/s.

Upgraded soil in the “pillow” has properties considerably different from the initial soil. Shear wave velocity Vs is 1300 m/s, primary wave velocity Vp is 2400 m/s; mass density is 2.3 t/m^3; material damping falls to 2%.

Three variants of the pillow thickness are considered in this paper. In the first variant (hereinafter it is called “medium”) the thickness is 14.7 m. In the second variant (called “deep”) the thickness is 18.7 m. In the third variant (called “shallow”) the depth is 10.7 m. Soil pillow starts from the surface.

Seismic response is calculated using the first option of the combined asymptotic method (see Tyapin (2007) and Tyapin (2010)). The first step – SRA – is skipped in this case: soil degradation is not considered, time-history from the surface is not modified. Time-history is given with time step 0.004 sec; duration is 30 sec. Spectra will be shown below.

Impedances for rigid base mat resting on the flexible soil pillow are calculated by SASSI using methodology of the “complex soil environment” (see Tyapin (2015)). The upper structure is set by “rigid” inertia (mass is 374866 tones, center of gravity is 26.7858 m above the ground surface), and also by a set of natural frequencies and natural modes (presented by their participation factors) calculated for the fixed-base detailed model in ABAQUS. The first natural fixed-base frequency is about 4.0 Hz. Modal damping coefficients calculated by ABAQUS are around 7%.

Having transfer functions and free-field motion one can use FFT to get the response of the base mat in the time domain. Figure 1 shows the comparison of the response spectra along Ox axis with 5% oscillator damping for different soils.

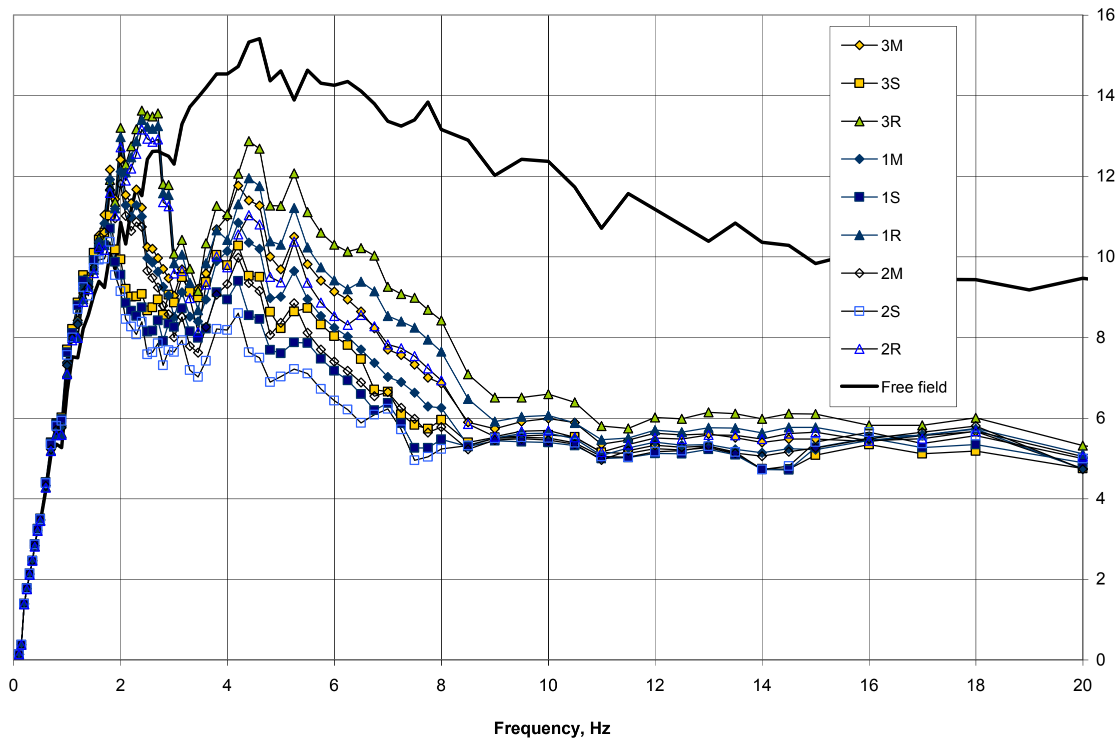

Figure 1. Comparison of RS along Ox axis.

Soil moduli were scaled two times as compared to the medium soil. Each curve in Figure 1 (except the last one corresponding to the initial free-field motion) is marked by a number (this is a number of thickness variant) and letter (M – medium soil, S – soft soil, R – hard soil). In the first peaks the pillow thickness does not affect the response, but in the second peaks this effect is more pronounced. The worst variant in terms of the second spectral peaks is hard soil and shallow pillow. The best variant – soft soil and deep pillow.

As compared to the free-field spectrum, the response of the base mat is considerably less at the frequencies above 2.5 Hz. Near the frequency 5 Hz the decrease in spectral accelerations is doubled when the pillow thickness is changed from the shallow to the deep variant.

Figure 2 shows the response spectra along Oz axis.

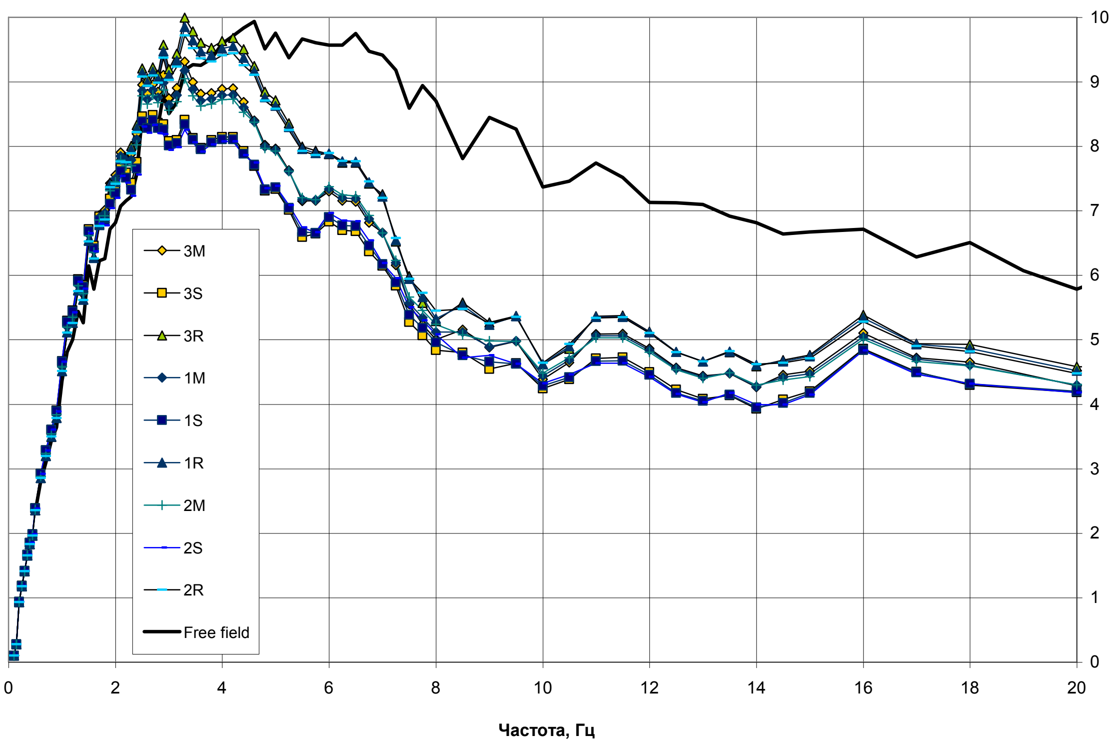

Figure 2. Comparison of RS along Oz axis.

There is a considerable difference in the seismic protective effect between horizontal and vertical directions. Pillow thickness does not affect the vertical response (unlike the soil moduli variation).

This was a demonstration of the protective effect of hard "soil pillow" in the soft initial soil on the structural seismic response. The discovered effect enables the treatment of the "soil pillow" as an alternative kind of seismic isolation. As compared to the conventional seismic base isolation this solution is much cheaper. Physical likeness with the mechanism of the conventional seismic isolation is obvious: the first natural frequencies fall into the frequency range of the small spectral accelerations of seismic excitation. Besides, the effective damping increases (due to the wave damping in the soil). The relative displacements of the base mat increase, but unlike the conventional seismic isolation they are not localized in the isolators, but instead they are distributed in the vicinity of the base. This may be favorable for the communications attached to the upper structure.

ROLE OF KINEMATICAL INTERACTION IN THE SEISMIC PROTECTIVE EFFECT OF THE SOIL PILLOW

It is well-known that SSI problem may be presented as a sequence of two separate problems: a) kinematical interaction, and b) inertial interaction. The decrease in the seismic response noted above may be caused either by kinematical interaction, or by inertial interaction, or by both of them.

Without the “soil pillow” under the base mat, the response of the weightless surface rigid base mat to the vertically traveling waves in the horizontally-layered soil would be similar to the free-field motion at the surface. Thus, kinematical interaction would not affect seismic response at all. However, the upgrade of the soil in the “soil pillow” changes the situation. One should clarify how seismic response changes after the soil upgrade, and how close is the resulting response of the weightless base mat to the resulting seismic response of the massive base mat under the massive upper structure obtained above. After this clarification one can conclude whether the seismic protection effect of the soil pillow should be expected for relatively light structures (typical for civil engineering), or this effect should be expected only for heavy structures like the one considered above.

Figures 3 and 4 present the response spectra (5% damping in oscillators) in vertical and horizontal translational directions for massive and weightless base mats as compared to the free-field motion. Variant 2 from previous section is considered (“deep soil pillow”): thickness of the “pillow” is 18.7 m. Free-field RS and RS for massive base mat are taken from Figures 1 and 2. RS for the weightless base mat were calculated specially for this paper.

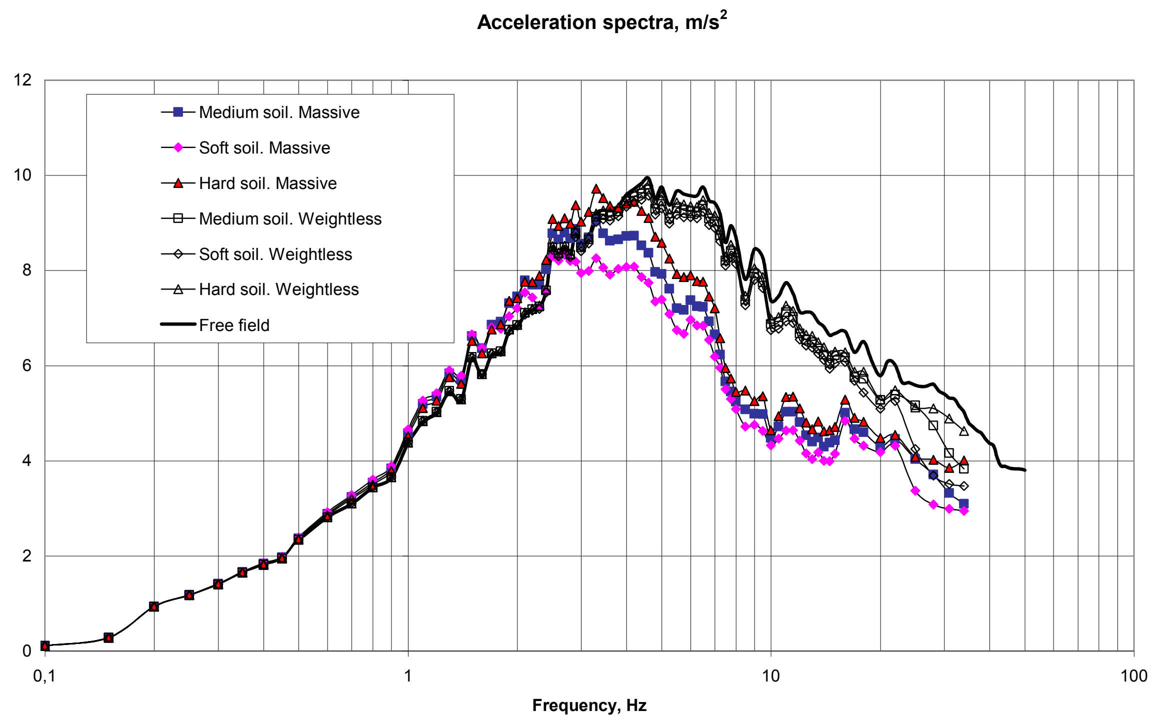

Figure 3. RS with 5% damping in oscillators: comparison of the free-field with the response in the center of the base mat along vertical axis Z.

Response spectra in Figure 3 for weightless base mat for all three soil profiles are only slightly lower than the free-field RS. It means that designer should not expect seismic protective effect from the “soil pillow” for the light structures in vertical direction. Actual decrease in the seismic response for our sample structure in the frequency range above 3 Hz obtained above and shown in Figure 3 is explained in full by the great weight of the sample structure and not by kinematical interaction. One should expect that the response of a structure with smaller weight resting on the same base mat will be somewhere between RS for our sample structure and RS for weightless base mat (i.e. practically the free-field RS).

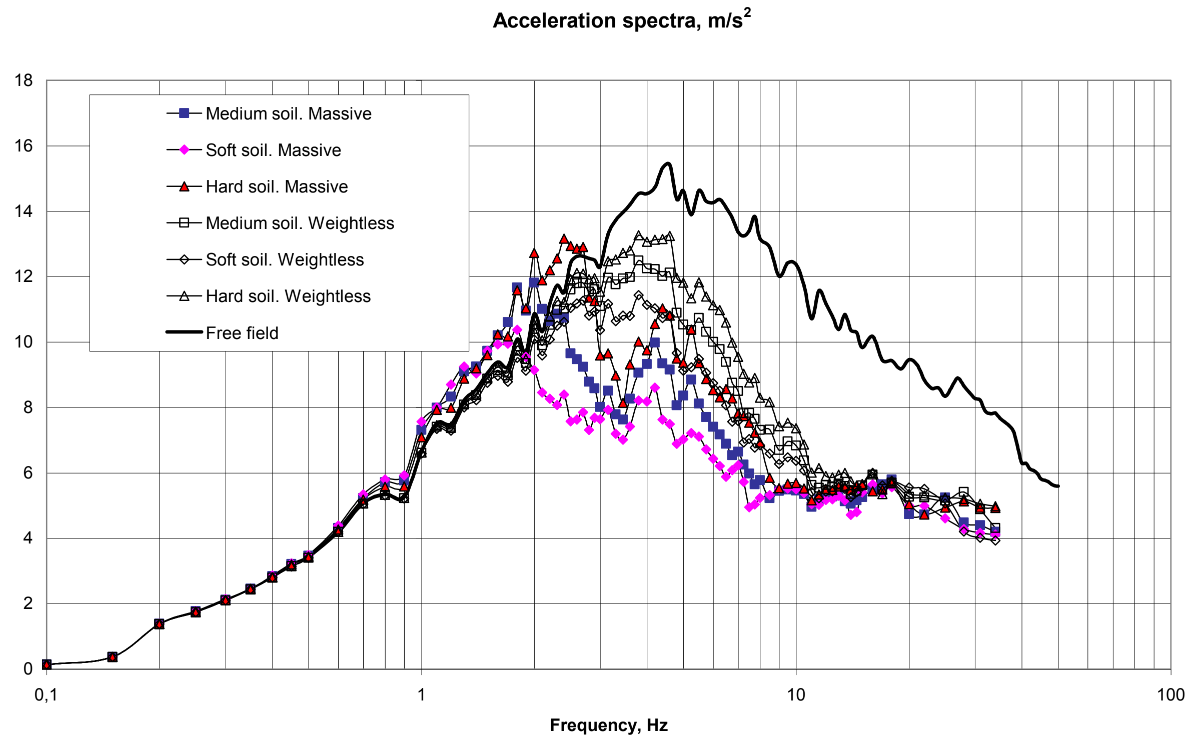

Figure 4. RS with 5% damping in oscillators: comparison of free field with response in the center of the base mat along horizontal axis X

However, in Figure 4 one can see completely different comparison. In the frequency range below about 2.5 Hz the response spectra for the weightless base mat are almost similar to the free-field like we saw in Figure 3 for vertical accelerations. However, for higher frequencies (especially above 4 Hz) the response spectra for horizontal accelerations go down from the free-field RS. They are still somewhat greater than the RS for the massive base mats under massive upper structure, but closer to these spectra than to the free-field ones. It means that one should expect considerable seismic protective effect from our "soil pillow" even for the light civil structures on the same base mat in horizontal direction. Roughly speaking, in the frequency range from 1 to 6 Hz about half of actual decrease in spectral accelerations as compared to the free-field goes from kinematical interaction; another half goes from inertial interaction; for higher frequencies about 70-80% of the total decrease goes from kinematical interaction.

What is the reason for such a great difference between horizontal and vertical directions? The author believes that the main mechanism for the protective effect of the "soil pillow" on the seismic response of the weightless base mat is a certain constraint put on the wave field in the initial soil. Hard "pillow" is somehow averaging the initial wave displacements over the thickness of the pillow. The controlling parameter for such a "constraining" effect is a ratio of the thickness to the wave length. In the considered example shear wave velocity Vs near the surface for the medium soil is about 500 m/s. At the frequency 5 Hz wavelength in initial soil is 500/5=100 m and the thickness of the pillow (about 20 m) makes one fifth of this wavelength. Primary wave velocity Vp near the surface is about 2000 m/s – it is four times Vs; the same ratio of the thickness to the wavelength (one to five) will appear for Vp at the frequency four times greater than 5 Hz. And in fact at the frequency 20 Hz in Figure 3 we see greater deviation of the RS for the weightless base mat down from the free field RS.

The same logic explains the difference in the RS deviations from the free-field RS between different soil profiles in Figure 4. The softer is the soil, the less is the wavelength. Thickness of the pillow is one and the same for all cases; so, for the soft soil the same ratio of the pillow thickness to the wavelength is achieved at smaller frequencies. It corresponds to the results presented in Figure 4.

This is for sure only a part of the explanation – the deviation in Figure 3 at the frequency 20 Hz is still smaller than in Figure 4 at the frequency 5 Hz. What is the reason? Let us additionally consider the transfer functions from the free-field motion to the response of the weightless base mat. They are shown in Figure 5.

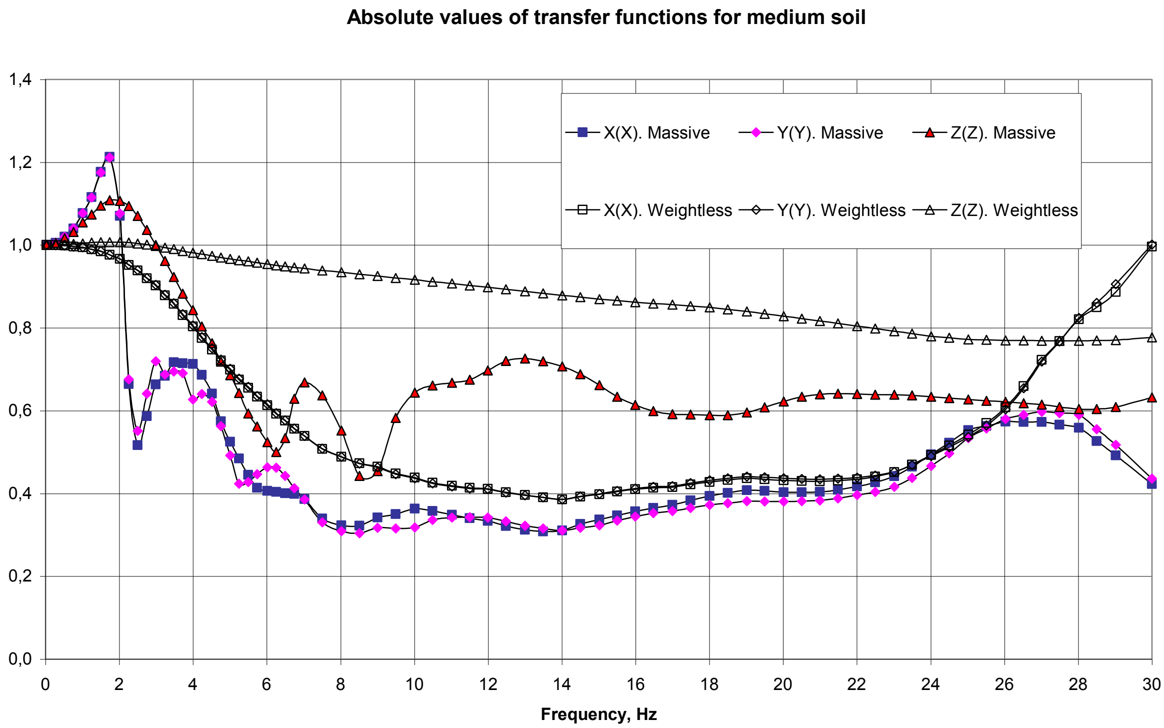

Figure 5. Absolute values of the transfer functions from the free-field motion to the response of the weightless base mat and massive base mat under massive upper structure.

We see the same difference: the absolute value of the transfer function Z(Z) at 20 Hz is greater than the absolute values of X(X) and Y(Y) at 5 Hz. The author explains it as follows. As compared to the initial Vs=500 m/s the "pillow" Vs=1300 m/s is much greater (i.e. 2.6 times); so the "pillow" behaves as almost rigid body. The same comparison for Vp gives different result: initial Vp=2000 m/s, and in the "pillow" Vp=2400 m/s (i.e., only 1.2 times greater). This hypothesis will be checked later on.

1D MODELING OF THE SOIL PILLOW

One can note that in Figure 5 the absolute values of the transfer functions X(X) and Y(Y) are practically similar though the two horizontal dimensions are slightly different (85 x 81.8 m). This fact causes the next question. In our case the upgraded "soil pillow" was finite in horizontal directions. What if it were infinite in horizontal directions? In this case we have just a different upper soil layer. The response of the surface rigid weightless base mat is equal to the response of the free surface of such "modified" soil profile. It can be obtained using conventional SHAKE approach for the horizontally-layered soil and vertically propagating waves - much faster and easier than the response of the finite "soil pillow" demanding SASSI. The comparison of the results for the infinite pillow (SHAKE) and the rigid weightless basement resting on the finite pillow (SASSI) with free-field RS is shown in Figures 6 and 7.

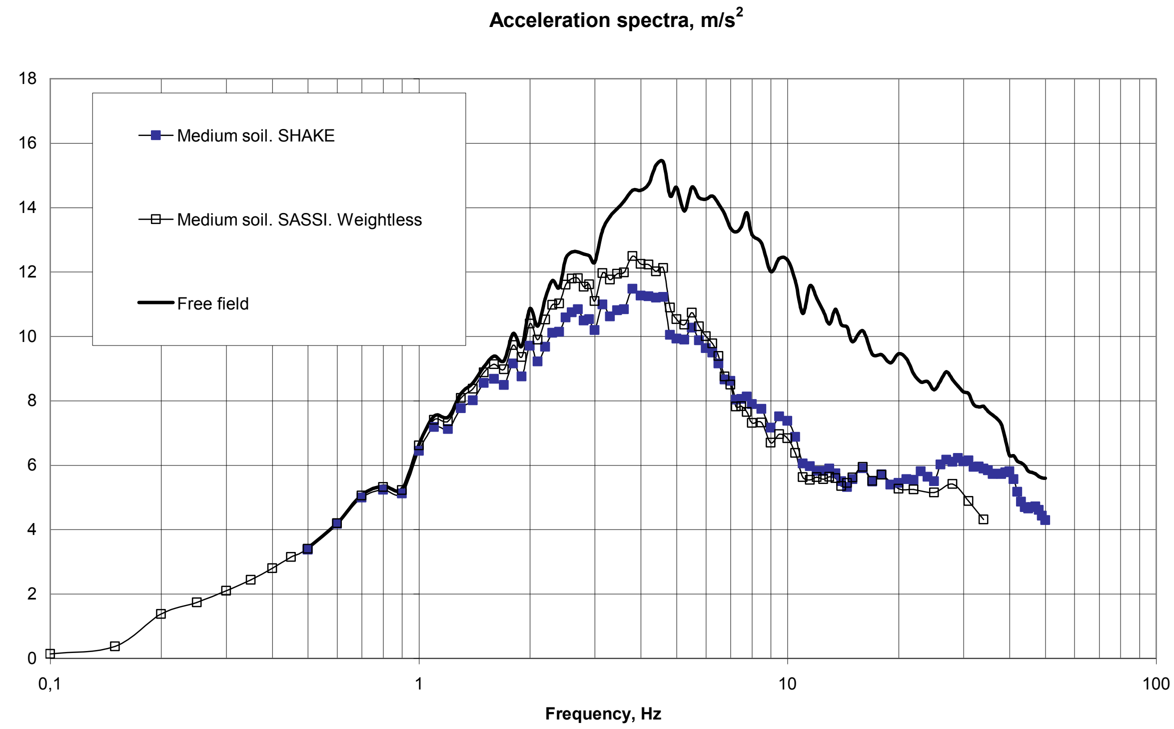

Figure 6. Comparison of RS (5% damping in oscillators) in the center of the weightless base mat resting on infinite and finite soil pillows with free field along X axis.

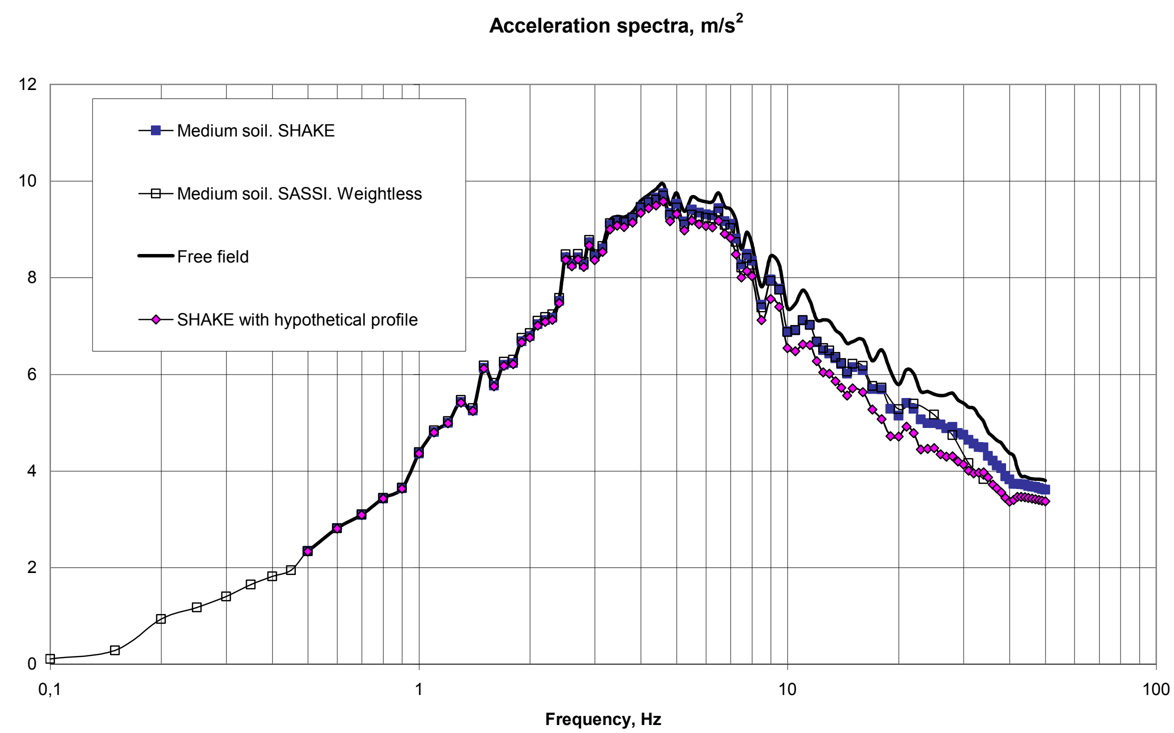

Figure 7. Comparison of RS (5% damping in oscillators) in the center of the weightless base mat resting on infinite and finite soil pillows with free field along Z axis.

We see in Figure 6 that the main part of the protective effect (especially above 6 Hz) is well represented in the SHAKE model, i.e. for the infinite soil pillow. Finite size has a limited effect only.

In Figure 7 for the vertical accelerations one more curve is added. It is calculated by SHAKE for hypothetic soil profiles with artificially increased Vp=5200 m/s in the "soil pillow".

As mentioned above, in terms of Vs the soil pillow is 1300 m/s and initial soil is 500 m/s, i.e. the ratio is 2.6. If we apply the same proportion to the initial Vp= 2000 m/s, we get hypothetical Vp for the soil pillow equal to 5200 m/s (and not 2400 m/s, as in our previous case). The resulting spectral reduction for the hypothetical soil profile at 20 Hz in vertical direction in Figure 7 proved to be much closer to that in the horizontal direction at 5 Hz in Figure 6.

Let us consider the same problem in terms of the transfer functions analytically comparing: a) homogeneous half-space, and b) the same half-space with the upper layer with upgraded properties.

In 1-D wave propagation problem the transfer function from the free surface of the homogeneous half-space to the free surface of the upgraded layer is given by

$$TF = \frac{\cos a_1 + i \sin a_1}{\cos a_2 + b\, i \sin a_2} \tag{1}$$

$$a_j = \omega H / V_j \ , \quad V_j = V_j^0 \left(\sqrt{1-\delta_j^2} + i\, \delta_j\right) \tag{2}$$

$$b = \frac{\rho_2}{\rho_1} \frac{V_2}{V_1} \tag{3}$$

Here i – imaginary unit, ω – circular frequency, H – layer thickness, V_j – complex wave velocity accounting for the material damping with coefficient δ_j (j=1 – for the half-space, j=2 – for the layer), ρ_j – soil mass density (j=1 – for the half-space, j=2 – for the layer). If the layer has the same properties as the half-space, coefficient b in (3) becomes unit, values a_1 and a_2 in (2) become similar, and the resulting transfer function (1) becomes unit, which is physically justified. One more physical check – for very small frequency ω both numerator and denominator in (1) become real units, and the transfer function becomes unit, which is again physically justified. Formulae (1…3) are valid both for shear waves and for primary waves (only wave velocities are different for them).

Figure 8 shows the results of calculations using formulae (1…3) as compared to the previous results from Figure 5. For each direction (X and Z) one curve is taken from Figure 5, another one is added using formulae (1…3). For the vertical direction one more curve is added using formulae (1…3) for the hypothetical soil profile with Vp=5200 m/s.

One can note a good agreement between analytical results (1…3) and previous results. As mentioned earlier, the substitution of the finite soil pillow by the infinite one in SHAKE caused some differences in curves below 6 Hz (remember Figure 6) for horizontal directions. One should additionally note that the initial soil in the first section was not completely homogeneous – the upper soil layer 5.7 m thick had Vs not 500, but 585 m/s. Below there was also some non-homogeneity in Vs not considered in formulae (1…3) – probably this is a reason for some deviations around 18 Hz.

The important note is that the curve for the hypothetical profile Vp at 20 Hz gives the same value as the curve for horizontal direction at 5 Hz – this is a proof of the author's hypothesis about the ratio of thickness to the wavelength promised earlier.

Let us now further develop formulae (1…3). What if the stiffness of the soil pillow increases infinitely? From (2) one concludes that a_2 will go to zero. So, the first term in denominator in (1) will go to unit. What about the second term? Note that velocity ratio V_2/V_1, participating in (3), is equal to the ratio a_1/a_2. As a result, we see in denominator the ratio $\sin(a_2)/a_2$, going to the unit when a_2 goes to zero. Finally we come to the "limit" transfer function for the rigid layer:

$$TF_{\lim} = \frac{\cos a_1 + i \sin a_1}{1 + i\ a_1\ (\rho_2 / \rho_1)} \tag{4}$$

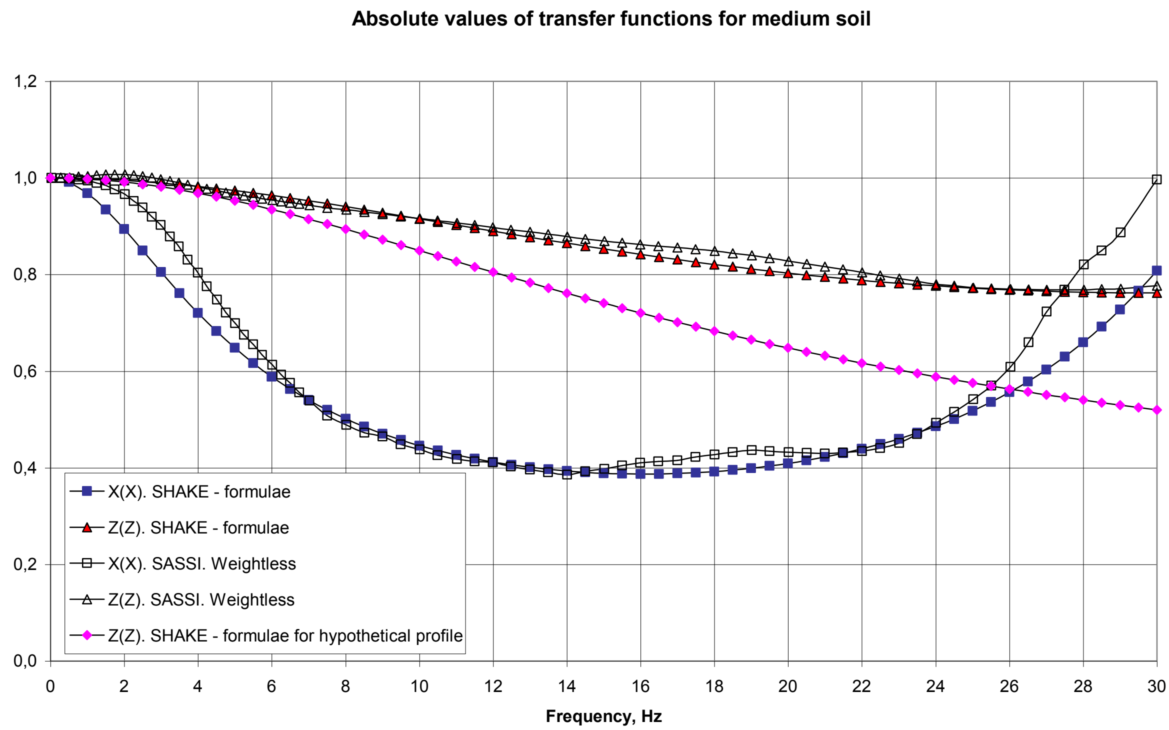

Figure 8. Absolute values of the transfer functions from free field motion to the response of the weightless base mat.

Thus, the unlimited increase in the stiffness of the “soil pillow” will lead to the decrease in the transfer function limited by a certain “limit curve” (4). Note, that (4) is a generalization of formula previously developed for rigid body resting on a homogeneous half-space.

And what will be the effect of increase in the thickness of the “soil pillow”? For the moderate material damping the absolute value of numerator in (4) will be around unit, and the absolute value of denominator will depend on the imaginary part. We get

$$\left| TF_{\lim} \right| \approx [1 + H^2 (\rho_2 / \rho_1)^2 (\omega / V_1)^2]^{-1/2} \tag{5}$$

Thus, the infinite increase in the thickness of the rigid “soil pillow” will lead to the infinite decrease in transfer function (it goes to zero). Note that the last term in (5) can be expressed using wavelength $L(\omega)=2\pi V_1/\omega$; then (5) can be modified to

$$\left| TF_{\lim} \right| \approx [1 + 4\pi^2 (H / L)^2 (\rho_2 / \rho_1)^2]^{-1/2} \tag{6}$$

Here one can clearly see the role of the ratio *H/L* - this very ratio was discussed above. Besides, one can estimate the “border” value of this ratio when it starts to play role (the second term in (6) is then comparable to the unit). This value in our case (similar densities) is about 0.183 – i.e. near one fifth mentioned above.

The last comment is that the horizontal size of the pillow for successful 1D modeling should be great enough as compared to the pillow thickness to avoid considerable rocking of the pillow.

CONCLUSIONS

In soil sites with soft soils the considerable reduction in structural seismic response may be achieved by upgrading the soil under the base mat in the finite volume of the so-called “soil-pillow”. Hard “pillow” in the soft soil provides seismic protection.

Kinematical interaction plays the main role in the reduction of the effective seismic input in the sample case in horizontal directions. It means that the surface of the “soil pillow” gets smaller accelerations as compared to the free field - even without the upper structure. So, the “soil pillow” will protect even comparatively light civil structures in the horizontal direction. For heavy structures there appears the additional reduction at the overcritical frequencies due to the inertial interaction.

The second conclusion is that the protective effect does not depend significantly on the horizontal size of the “soil pillow” (though horizontal size should be large enough as compared to the thickness to avoid considerable rocking of the pillow). As a result, the protective effect in terms of kinematical soil-structure interaction may be estimated using 1D horizontally-layered soil models with the upper layer modeling soil pillow. In the simple case of the homogeneous initial soil one can use formulae, combining parameters of the initial and upgraded soils with thickness of the “soil pillow”.

Protective effect for weightless base mat (i.e., kinematical interaction) is controlled mainly by the ratio of the pillow thickness to the wavelength in the initial soil. The increase in the pillow stiffness leads to the limited reduction, while the increase in thickness leads to the unlimited reduction. However, for the great reduction the thickness must be considerably greater than the wavelength.

In the vertical direction, unlike the horizontal one, the protective effect in the sample case is caused only by the great mass of the considered structure. Kinematical interaction in vertical direction is of little importance – it does not change the motion at the surface of the “soil pillow”, as compared to the free field. The first reason for that is that the primary wave velocity Vp is considerably greater than the shear wave velocity Vs; as a result, the ratio of thickness to the wave length at the same frequency is much smaller for the primary waves as compared to the secondary (shear) waves. The second reason is that for the shear waves the degree of upgrade is considerably greater than for the primary waves (ratio of the upgraded velocity to the initial velocity is 2.6 for Vs versus 1.2 for Vp). The greater is the degree of upgrade, the more pronounced is the response reduction effect.

The protective effect of the “soil pillow” enables partial control over seismic response in certain frequency range without conventional seismic isolation. The main condition for that is soft initial soil in the site.

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