05 Apr 1995, 1:30 pm - 3:30 pm

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Recommended Citation

Juhásová, E., "Application of Weak Earthquake Records in Soil-Structure Interaction Analysis" (1995). *International Conferences on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics*. 9.
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Proceedings: Third International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, April 2–7, 1995, Volume I, St. Louis, Missouri

Application of Weak Earthquake Records in Soil-Structure Interaction Analysis

Paper No. 5.28

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SYNOPSIS The problem concerns cases when the structure is situated in the geological conditions with different soil layers including soft ones. The wave motion in the subsoil is described for linear and non-linear soil media, damping is included through complex modulus of elasticity. Variation of damping, obtained from laboratory experiments, answers to frequency and time influences. The properties of weak earthquakes are discussed as they are used like input data before soil transfer. The response of layered subsoil describes extremes of seismic vibration at different depth. It has been recognised that site effects can significantly affect the nature of seismic input and the response of structures.

INTRODUCTION

Earthquakes with catastrophic consequences do not occur in Slovakia. But part of its territory is endangered by seismic shocks, causing severe damage. These earthquakes are usually of tectonic origin and are connected with simultaneous tectonic motion. The national seismic standard includes the design procedure for civil engineering structures and gives basic data for accounting soil properties in seismic design.

The important structures, however, are the subject of special more detailed investigation and design. In spite of new calculation procedures and codes one can feel the lack of more rich database of seismic input and dynamic soil properties for different site conditions.

The promising way is the completion and utilisation of all available data from site and laboratory investigation, weak earthquakes records, microtremor measurements and their implementation into calculation codes. The supporting large geology data seem to be a good starting point taking into account the previous data from archives.

WAVE MOTION IN SUBSOIL

Let us discuss the main features of wave motion in subsoil. We can meet many theories that try to describe the travelling of seismic waves from the source to the place of interest - usually the building site. 1D, 2D, 3D linear or non-linear models use frequency dependent or non-dependent relations to describe dissipation of energy in subsoil. Increasing number of records of strong or weak seismic motions in different depth below the ground gives the opportunity to verify the reliability of individual theoretical solutions. It was confirmed that the seismic motion in ground is lower than that on the surface, what can be utilised in the design of foundation.

Attenuation characteristics of soil deposits are very important factor for the evaluation of earthquake motions at ground surface. The complex modulus theory can be advantageously used for including the damping into equations of motions. Describing mechanical properties of soil materials through complex modulus G^*, E^*, we can write

$$G^* = G(1 + i2\zeta), \tag{1}$$

$$E^* = E(1 + i2\zeta), \tag{2}$$

where ζ is damping ratio.

Let now analyse the case of vertically propagating seismic shear waves with wave velocity V_S, where we have

$$\frac{\partial^2 u}{\partial t^2} = V_S^{*2} \frac{\partial^2 u}{\partial z^2}. \tag{3}$$

As

$$V_S^{*2} = (1 + i2\zeta)\, V_S^2, \tag{4}$$

the solution of (3) can be introduced

$$u(z,t) = e^{(i-\zeta)\omega t} f(z). \tag{5}$$

Then

$$(i - \zeta)^2 \omega^2 f(z) = V_S^{*2} \frac{d^2 f(z)}{dz^2}. \tag{6}$$

Considering

$$f(z) = e^{\alpha^* z}, \tag{7}$$

there is

$$(i - \zeta)^2 \omega^2 = V_S^{*2} \alpha^{*2}, \tag{8}$$

or

$$\alpha^* = \pm(i - \zeta)\omega / V_S^*, \tag{9}$$

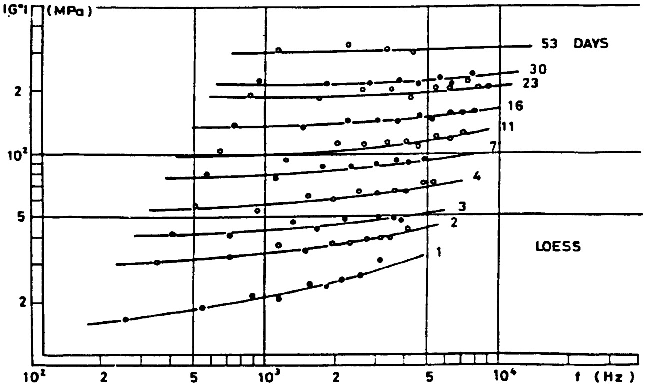

FIG. 1. Changes in complex shear modulus of loess.

and

$$u(z,t) = \mathrm{e}^{(i-\zeta)\omega t}\ \mathrm{e}^{\frac{-(\mathrm{i}-\zeta)\omega}{V_{\mathrm{S}}^{*}} z}, \tag{10}$$

$$u(z,t) = \mathrm{e}^{(\mathrm{i}-\zeta)\omega\left(t-z/V_{\mathrm{S}}^{*}\right)} = \mathrm{e}^{\mathrm{i}\omega\left(t-z/V_{\mathrm{S}}^{*}\right)}\ \mathrm{e}^{-\zeta\omega\left(t-z/V_{\mathrm{S}}^{*}\right)}. \tag{11}$$

Damping and stiffness parameters of soil materials can be determined from field or laboratory measurements. The complex modulus G^*, E^* are frequency dependent. Besides of that for some materials (loess, clay, bentonite, etc.), we can observe the influence of the time in development of stiffness and damping of tested soils. This can be caused by changes in moisture, porosity, or microstructure of the soil material. The experiences with the changes of complex moduli in dependence on time and frequency can be seen in Fig. 1. The corresponding changes of damping ratio ζ_{E}, ζ_{G} and the Poisson ratio ν are in Fig. 2 , Martinček (1983).

The problem of transmission and reflection of seismic shear waves in layered subsoil is generally known , e.g. Juhásová, (1991). We will remember here only that at the boundary of 2 layers we can write

$$f_{\mathrm{r}}(t) = f_1(t)\beta_{1,2}, \tag{12}$$

$$f_{\mathrm{t}}(t) = f_1(t)\alpha_{1,2}, \tag{13}$$

where $f_1(t)$ is an incident shear wave coming from layer 1, $f_{\mathrm{t}}(t)$ is the wave transmitted to layer 2, $f_{\mathrm{r}}(t)$ is the wave reflected to layer 1.

The coefficients α_{ik}, β_{ik} are

$$\alpha_{ik} = \frac{2}{1+\frac{\rho_k V_{\mathrm{S}k}^{*}}{\rho_i V_{\mathrm{S}i}^{*}}}, \tag{14}$$

$$\beta_{ik} = \frac{\frac{\rho_k V_{\mathrm{S}k}^{*}}{\rho_i V_{\mathrm{S}i}^{*}} - 1}{\frac{\rho_k V_{\mathrm{S}k}^{*}}{\rho_i V_{\mathrm{S}i}^{*}} + 1}, \tag{15}$$

where the second subscript of α_{ik}, β_{ik} denotes the layer into which the wave component is entering and the complex shear wave velocity $V_{\mathrm{S}k}^{*}$ is denoted with the index of the soil layer involved. For multi-layered subsoil we can write , Juhásová and Koleková, (1993)

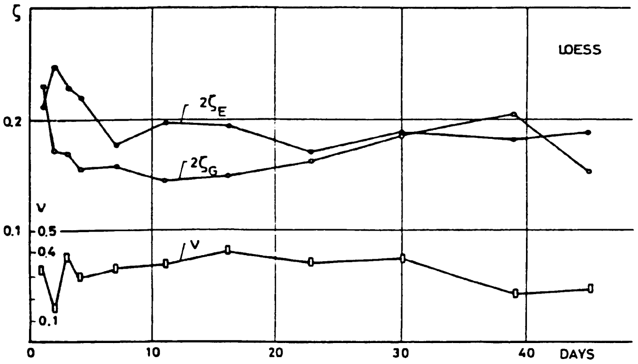

FIG. 2. Changes in damping ratio ζ and Poisson ratio ν.

$$\begin{aligned} D_{n-1}(t) = {} & \alpha_{n,n-1}\, \mathrm{e}^{-\zeta_n 2\pi f \frac{H_n}{V_{\mathrm{S}n}^{*}}} D_n\left(t-\frac{H_n}{V_{\mathrm{S}n}^{*}}\right) + \\ & + \beta_{n,n-1}\, \mathrm{e}^{-\zeta_{n-1} 2\pi f \frac{H_{n-1}}{V_{\mathrm{S}n-1}^{*}}} U_{n-1}\left(t-\frac{H_{n-1}}{V_{\mathrm{S}n-1}^{*}}\right), \end{aligned} \tag{16}$$

$$\begin{aligned} U_{n-1}(t) = {} & \alpha_{n-2,n-1}\, \mathrm{e}^{-\zeta_{n-2} 2\pi f \frac{H_{n-2}}{V_{\mathrm{S}n-2}^{*}}} U_{n-2}\left(t-\frac{H_{n-2}}{V_{\mathrm{S}n-2}^{*}}\right) + \\ & + \beta_{n-2,n-1}\, \mathrm{e}^{-\zeta_{n-1} 2\pi f \frac{H_{n-1}}{V_{\mathrm{S}n-1}^{*}}} D_{n-1}\left(t-\frac{H_{n-1}}{V_{\mathrm{S}n-1}^{*}}\right), \end{aligned} \tag{17}$$

together with the application of the complex modulus theory. This approach is simply available for harmonic source seismic motion. The non-harmonic source motion should be modified using integral transformations. Naturally, in the case of zero damping the solution is the same as we have in the case without considering the complex modulus theory , Juhásova and Koleková, (1993).

The approach, we have used for non-harmonic transfer, applies FFT technique. Input seismic motion at the bedrock is entered into calculation like sampled record. The amplitude components and phase shift distribution in frequency domain could be calculated with regard to properly chosen frequency window. Having this operation we continue with successive transfer of individual harmonic components accounting for changes in damping, phase shift and controlled non-linear behaviour in the surface soil layer. It is worth to say that phase shift does not influence the seismic response spectra in whole. Its influence is actually remarkable in time domain. However, the damping should be higher if we expect larger changes of resultant motions in chosen points of layered halfspace.

The described procedure can be also applied when using the weak earthquakes records like input functions. The eventual lack of low frequencies in original records can be removed by e.g. linear extrapolation of missing components. The weak earthquakes registered on the rock subsoil were used for numerical calculations.

For the calculation we have chosen six-layered subsoil with basic parameters of two upper layers as is in Table 1.

The input was introduced through harmonic deconvolution of weak earthquake record, time step $\Delta t = 0.002$ s, the input duration $t = 10$ s. The response extremes were investigated in the frequency range 0.2 - 20 Hz with the frequency step $\Delta f = 0.2$ Hz. The peaks in the response spectra denote the influence of the transfered properties of individual soil layers. (Figs. 3, 4,5).

The expressions (16), (17) were derived to fulfil the conditions of equilibrium of shear stresses at the boundaries of two adjacent layers. For the free surface the resultant motion is $u_s(t) = 2D_n(t)$. The applications of 2D, 3D models are usually used to analyse the influences of surface irregularities, of the hills, of sediment deposit basins, of slopes of embankments and cuttings on increasing or decreasing of the soil surface vibration. We must keep in mind that the resultant motion coming to the free soil surface is influenced by transfer characteristics of soil layers, which modify the input signal similarly as we know from dynamic analysis of structures. Resultant motion answers to the frequency composition of input signal which is modified by dynamic transfer characteristics of subsoil. Nevertheless, when the strong seismic motion is coming from the bedrock, we can expect also the non-linear behaviour of soil, at least near the surface of terrain.

In the vibrating subsoil we must identify areas and regions where the non-linear effects can appear. Usually it means some part of soft soil layers near surface, embankments, cuttings and sometimes also some weak lower layers. The theory of complex modulus can be spread to non-linear region using separate functions for real and imaginary parts as follows:

$$G^*(\gamma,\tau) = G_R(\gamma,\tau) + G_I(\gamma,\tau)\ ,\ E^*(\varepsilon,\sigma)=E_R(\varepsilon,\sigma)+E_I(\varepsilon,\sigma) \quad (18)$$

For the solution we can utilise the application of finite difference or finite element methods. The shear wave velocity is considered variable or constant depending on the stress-strain conditions in the vibrating soil. In this way we can analyse the soil layered system either in linear or non-linear regions and follow its behaviour at the different input source .

APPLICATION OF LOCAL WEAK EARTHQUAKE RECORDS

When calculating the seismic response of the structure, we can consider the input seismic motion either at the bedrock or at some reasonable level below the ground. We must keep in mind that every earthquake motion record is a result of source mechanism - input signal and the transmission characteristics of the strata through which the signal is travelling. The peaks caused by soil transfer characteristics can appear when respective frequency component is present in the input. In many countries there is not enough available data recorded from strong seismic motions. But the knowledge of the similitude between site transfer effects at weak and strong

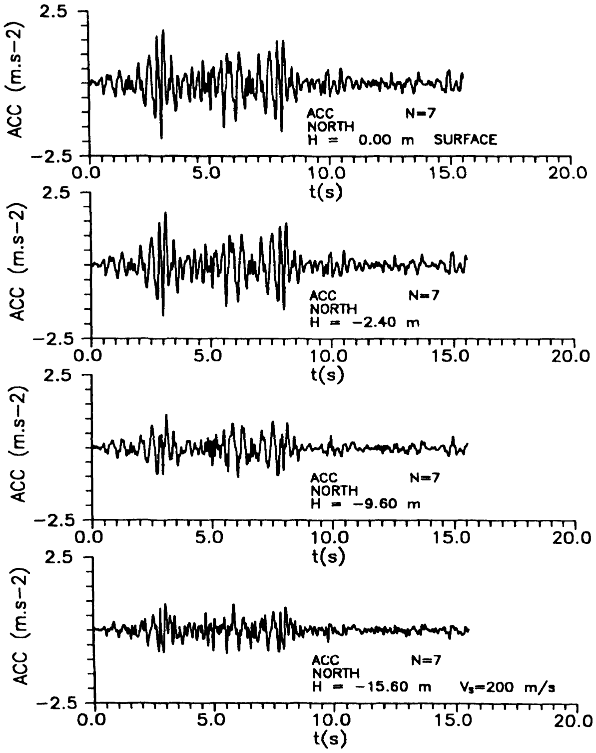

FIG. 3. Time history of seismic motion at different depth. Input at the bed rock - weak earthquake record.

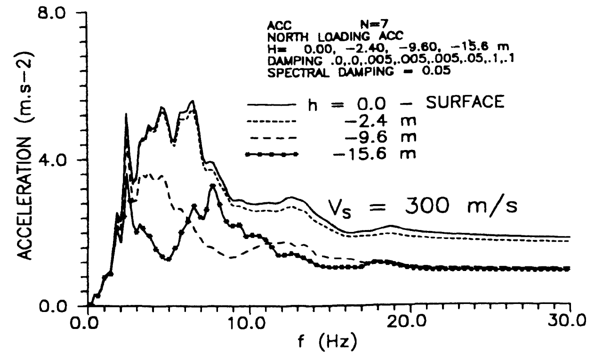

FIG. 4. Response spectra at different depth, $V_S = 300$ m/s.

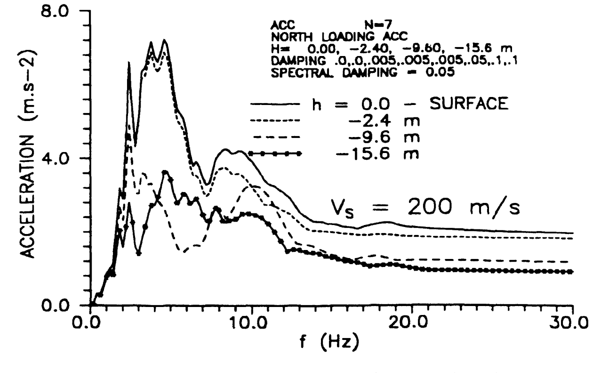

FIG. 5. Response spectra at different depth, $V_S = 200$ m/s.

TABLE 1. Properties of upper layers of analysed soil profile.

Layer	i	H_i	V_{Si}	ρ_i	ζ_i	
		(m)	(m/s)	(kg m^{-3})	(1)	(2)
(i-1)	5	20	700	2050	0	0.05
Upper - (i)	6	15.6	300 (200)	2150	0	0.1

seismic motions help forecasting of strong seismic loading functions. The priority of soil transfer characteristics before the source signal properties is utilised in such cases.The example of weak earthquake response spectrum is in Fig. 6. The epicentral distance was 24.94 km . We can see nearly no participation of low frequencies in this record. Therefore, the frequency content of input should be slightly modified.

Let now pass to the behaviour of the structure which is placed on the subsoil that has different properties of soil layers. We can consider that the seismic response of a structure influences surrounding subsoil to reasonable distance and that behind this distance the dynamic effect of structure can be neglected. This assumption allows to solve independently the free surface response and the response of points inside of soil considering reasonable number of nodal points . The boundary conditions can be implemented into FE model of soil-structure system. For the seismic response solution one can use standard packages of FEM programs.

Another approach can start from the assumption that the structure behaves similarly as a stiff body system. For such model we can solve the seismic response of subsoil and structure simultaneously using the detected boundary points for the action of soil motion on a structure and vice-versa including into calculation the additional P- and S waves excited by the structure vibration, that propagate from the structure to the respective directions. This additional motion of soil, excited by the structure, is at some distance from the structure negligible.

Considering the travelling of seismic waves in subsoil and soil-structure interaction effect both on the vibration of structure and on the near subsoil we can appear several features of this process, that can influence the final behaviour in positive or negative sense. In some inappropriate combinations there can appear multi-resonance effects in the seismic response, which can be undesirable both for the structure and the subsoil. On the other hand we can also look for such soil layers combinations that can depress some unfavourable effects and to minimise the motion on the ground surface. This is usually reached by improvement of transfer and damping characteristics of upper surface layers, naturally in the reasonable degree. The example of the case study of the soil modification by the upper layer properties is in Fig. 7.

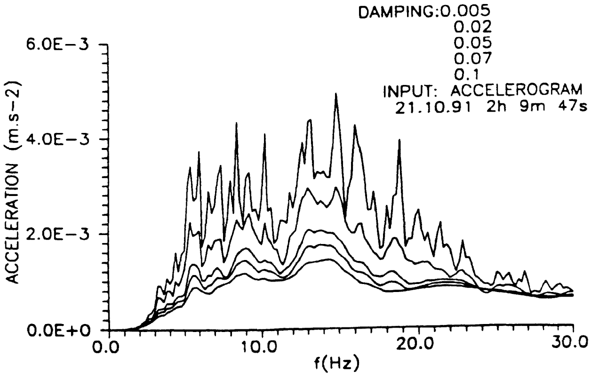

FIG. 6. Response spectra of weak earthquake record - north.

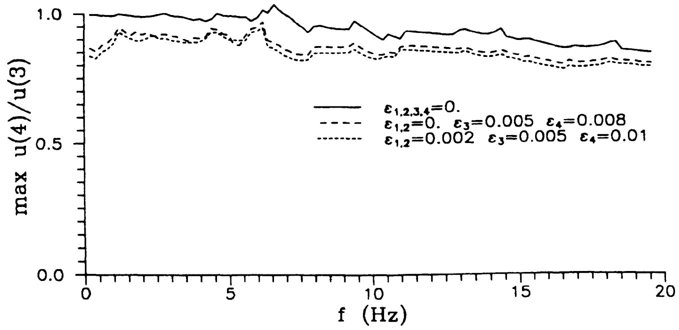

FIG. 7. Influence of upper layer properties on soil transfer.

CONCLUSIONS

In spite of implementation of more complicated calculation schemes we are able to solve some problems at the reasonable degree and some are still open for the next study and research. The promising way is in utilisation of results of field and laboratory experiments concerning damping and stiffness characteristics and those from investigation of main features of the mechanism of the transmission of input seismic motion from the source into the structure. The results show that also improvement of some soil properties can help the structures to survive the strong seismic motions with lower degree of vulnerability.

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