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Партизански одреди 24,
П.Фах 560, 1001 Скопје
Македонија

Partizanski odredi 24,
P. Box 560, 1001 Skopje
Macedonia

mase@gf.ukim.edu.mk
http://mase.gf.ukim.edu.mk

Slobodan RADOVANOVIC[1], Ratko SALATIC[2]

PARAMETRIC ONE DIMNESIONAL DYNAMIC ANALYSIS OF LAYERED SOIL

SUMMARY

The propagation of the seismic waves through the soil layers was analysed in this paper. Seismic excitation is going to rock mass below the soil layers and extends vertically up to the surface. For the design of buildings, one needs to know the acceleration of earthquakes on the surface where the structure will be founded. In this paper it is shown the basic theories of wave motion and in particular the methodology for the implementation of one-dimensional dynamic analysis of layered soil. The parametric study on the influence of the height of the overburden was done and the dynamic characteristic changes in response on the soil surface were defined. Based on this analysis, the paper gives summary conclusion about the influence of certain parameters on the response of the soil on the surface.

Keywords: one-dimensional parametric dynamic analysis, layered soil

Слободан РАДОВАНОВИЌ[1], Ратко САЛАТИЌ[2]

ПАРАМЕТАРСКА ЕДНОДИМЕНЗИОНАЛНА ДИНАМИЧКА АНАЛИЗА НА СЛОЕВИТА ПОЧВА

РЕЗИМЕ

Во овој труд анализирано е распростирањето на сеизмичките бранови низ слоевита почва. Сеизмичката возбуда оди во карпеста маса под слоевите и се шити вертикално до површината. За проектирање на згради, треба да се знае забрзувањето на земјотресите на површината каде конструкцијата ќе биде темелена. Во овој труд се покажани основните теории за распространување на брановите и подетално методологијата за применување на едно-димензионална динамичка анализа на слоевита почва. Извршена е параметриска анализа за влијанието на висината на преоптоварувањето и дефинирани се промените на динамичките карактеристики во одговорот на почвената површина. Базирано на оваа анализа, трудот дава заклучок околу влијанието на одредени параметри врз одговорот на почвата на површината.

Клучни зботови: параметарска едно-димензионална динамичка анализа, слоевита почва

[1] Assist. PhD student, Faculty of Civil Engineering, University of Belgrade, Republic of Serbia, sradovanovic@grf.bg.ac.rs
[2] Prof. PhD, Faculty of Civil Engineering, University of Belgrade, Belgrade, Republic of Serbia, salatic@grf.bg.ac.rs

1. INTRODUCTION

For the purpose of designing civil engineering structures, it is essential for one to know seismic conditions at the terrain surface. It can be said that the seismicity at the observation point on the surface depends on the seismicity on the bedrock and on local geological-seismological features of the surface. During propagation of seismic waves from the bedrock to the surface, seismic waves are modulated regarding amplitude and frequency, giving at the same time their own local seismic feature at the surface. The total effect of an earthquake on a structure depends on the seismicity of the terrain on the surface and dynamic features of the structures themselves. The seismicity of the location can not be affected on, since it depends on regional and local seismic-geologic factors, but the features and distribution of structures during urbanistic design and construction can be influenced. Therefore, seismic micro-regionalization contains: study of regional seismic-geological features of the terrain, study of local seismic-geological features of the terrain and their influence on the seismicity of the location, study of seismic parameters of earthquakes, criteria and conditions for planning, designing and constructing (Šlimak 1996).

Here, it is analysed passing of a seismic wave through a layered soil from the bedrock upwards, treating it as a one dimensional issue. This is also conducted in the paper (Salatić et al. 2014) where the responses at the surface were determined at the location of the Ada Bridge. In the paper (Radovanović 2008), seismic micro-regioning was conducted at the location in New Belgrade.

This paper shows algorithm for calculation of dynamic response at the terrain surface caused by an earthquake. There was also conducted the parametric analysis of influence of layer thickness and change of dynamic characteristics during earthquake. There are separately given cases where the influence of dynamic characteristics of soil is neglected, and separately when reduction of dynamic characteristics of soil is taken into consideration. The objective of the analysis is to show how the change of dynamic characteristic of soil and overburden height affects the response of the soil at the surface.

2. THEORETICAL ASSUMPTIONS

The basic assumptions used in one-dimensional dynamic analysis are as follows:

- A layered soil with horizontal layers is to be taken into consideration, and its response to a seismic excitation dominantly depends on transversal waves (SH) which move vertically upwards from the rock mass to the soil surface through layers of soil which have different characteristics.
- A layered soil is to be taken into consideration; it has damping and lies on an elastic rock.
- The soil is approximated with Kelvin model of material.
- It is assumed that the principle of superposition is valid. Non-linear behaviour of soil can be approximated using iterative procedures with equivalent linear parameters of soil.

The assumption that the soil is layered is justified because the fact is that soil is often layered; it consists of different lithological members starting from the soil surface downwards. Dissipation of energy or damping is present in the soil meaning that the assumption on a damped soil is justified. Velocity of waves in the depth is greater than the velocity of waves at the soil surface. Waves refract going from one medium into another. If a wave passes from a high-velocity medium into a low-velocity medium, then an angle of incidence of that wave at the contact of the two media is larger than the angle of refraction of that wave in relation to the vertical line. This means that spatial waves going through a layered medium are nearly vertical towards the soil surface, which justifies the assumption on propagation of vertical waves. The assumption on elastic rock mass means that while the seismic waves approach, a part of energy of waves passes through the rock mass and continues deeper in the rock, and the other part of energy reflects from the rock and continues to move vertically upwards (Krame 1996). In reality, the principle of superposition in non-linear materials does not apply. However, due to complex behaviour of the soil when seismically excitated, the assumption that superposition of waves applies is adopted, but the impact of non-linearity of the material is introduced via parameters of soil (shear modulus and damping modulus) through iterative procedure (Krame 1996).

3. THEORETICAL ASSUMPTIONS ON UNDULATION

Propagation of seismic waves through soil belongs to undulation. Within this chapter, there are given basic equations which define wave motion.According to the D´Alembert principle, the condition on balance of a dynamic system is tested as in a static system, but relevant inertial forces are taken into account (Ćorić et al. 1998).

During propagation of seismic waves, a part of elastic energy dissipates due to friction, plastic deformations, heating, etc. A precise mechanism of energy dissipation is not simple to describe and model for each cause, so the impact of various causes is usually observed unified. Elastic energy dissipation is followed by lowering of amplitude of oscillation. This is called damping, and such oscillations are called damped oscillations. The most used model of damping is the so called viscous damping, where the damping force F_c is proportional to the velocity of moving points (Ćorić et al. 1998), that is:

$$F_c = -c \cdot \dot{u} = -c \cdot \frac{\partial u}{\partial x} \tag{1}$$

In the following text, there are given equations and results of the equations of free damped oscillations with one-degree of freedom. The differential equation of free damped oscillations of a system with one degree of freedom (Ćorić et al. 1998) is as follows:

$$m\ddot{u} + c\dot{u} + ku = 0 \tag{2}$$

where:

u- displacement of mass m in the direction of oscillations;

k- rigidity of the elastic spring;

c- damping of the system.

The equation (2) can be transformed into the following form:

$$\ddot{u} + 2\zeta\omega\dot{u} + \omega^2 u = 0 \tag{3}$$

where:

ω - natural angular frequency of oscillations;

ζ - relative damping.

The solution of this differential equation is (Ćorić et al. 1998):

$$u(t) = e^{-\zeta\omega t}\left[A_1 e^{i\omega_d t} + A_2 e^{-i\omega_d t}\right] \tag{4}$$

The parameter $\omega_d = \omega\sqrt{1-\xi^2}$ is called angular frequency of damped oscillations. From the form of solution of damped oscillations, it can be seen that this is periodical movement, with angular frequency ω_d and the amplitudes are constantly reduced exponentially. In accordance with previous analyses, the obtained solution can be additionally broadened so that the distance between the observed point and the source of seismic waves is taken into account, and the final solution of the function of movement is in the following form (Krame 1996):

$$u(t) = A(t)\, e^{i(\omega_d t - kz + \varphi)} \tag{5}$$

4. BEHAVIOUR OF SOIL DURING SEISMIC EXCITATION

Stress-strain characteristics of soil, under dynamic loading, mostly depend on the size of amplitude of shear deformation. Where shear deformations are very small (smaller than 0.001%), the soil behaviour is completely elastic. Where shear deformations are greater (0.001-1%), apart from elastic, there are also plastic deformations. Where deformations are even greater (over 1%), the soil is breaking. With the increase in shear deformations, the complexity of soil behaviour also increases, as well as the mathematical model of that behaviour, given in the form of constitutive equations or soil models. For small deformations, linear elastic model of the material can be applied; for medium deformations, the elastic model with hysteresis damping (or viscosity which is reversely proportional to the excitation frequency) is suitable; for great deformations, a complex elastic-plastic model (Aničić et al. 1990) is needed. Regarding the shear deformations, the soil can be modelled to be viscoelastic object, meaning that its resistance to shear is a sum of the elastic force and force of viscose damping. This kind of a model of a material is called Kelvin´s model and can be shown as parallel link of the elastic spring (Hooke´s object) and viscose piston (Newton´ s object) (Deretić et al. 2008). The relation between the stresses and strains in the Kelvin´ s model can be defined as:

$$\tau_{xz} = \tau_s + \tau_d = G\gamma_{xz} + \eta \frac{\partial \gamma_{xz}}{\partial t} \tag{6}$$

Where the deformations of shear of spring and piston are equal, and the total shear stress equals the sum of stresses in the spring τ_s and stresses in the piston τ_d. From the condition of balance of horizontal forces present in a basic part of soil, a differential equation of oscillations of soil exposed to transversal seismic forces given in (Krame 1996) can be obtained:

$$\frac{\partial^2 u}{\partial t^2} = \frac{G}{\rho}\frac{\partial^2 u}{\partial z^2} \tag{7}$$

G/ρ is squared velocity of propagation of transversal waves v_s, that is:

$$\frac{G}{\rho} = v_s^2 \tag{8}$$

Since the oscillations of the actual soil are always damped, further analysis is conducted using model of soil which simulates damping. For the previously given Kelvin´s model of viscoelastic material, the following partial differential equation given in is obtained:

$$\rho \frac{\partial^2 u}{\partial t^2} = G \frac{\partial^2 u}{\partial z^2} + \eta \frac{\partial^3 u}{\partial z^2 \partial t} \tag{9}$$

The solution of this partial differential equation is the function of movement *u(z,t)*:

$$u(z,t) = Ae^{i\left(\omega t + k^* z + \varphi\right)} + Be^{i\left(\omega t - k^* z + \varphi\right)} \tag{10}$$

where $k^* = \sqrt{\frac{\omega^2 \rho}{G^*}} = \omega\sqrt{\frac{\rho}{G^*}}$, and it is a complex wave number, and $G^* = G(1 + 2i\xi)$ is a complex shear modulus. The labels *A* and *B* are the amplitudes of seismic waves which spread vertically upwards and vertically downwards, respectively (Krame 1996).

5. METHODOLOGY OF CALCULATION

Through this chapter, it is given the method in which the one-dimensional dynamic analysis of propagation of seismic waves through a layered soil on a deformable rock is conducted. A seismic wave moves from the deformable rock vertically upwards and passes through layers of soil of various dynamic characteristics. The incident wave amplifies due to different dynamic characteristics of soil while passing vertically upwards.

The aim of the analysis is to determine the wave obtained as a response of the soil on the terrain surface. For determining the wave which is going to be obtained on the terrain surface, it is above all necessary to know the wave on the bedrock. The wave on the bedrock is multiplied by relevant function called the transfer function and the response of the soil surface is obtained. The transfer function *H* can be defined as the relation of amplitudes of the observed dynamic value (for example movement) on the surface and in the level of the bedrock (Krame 1996):

$$H = \frac{u_{max}(0,t)}{u_{max}(h,t)}$$
$$u_{max}(0,t) = H \cdot u_{max}(h,t) \tag{11}$$

The dynamic response on the surface is obtained by multiplying relevant input values with the transfer function. Since the actual loading and displacements which affect the soil are stochastic in nature, first it is necessary to express the input values in the form of sum of harmonic functions (Fourier series). By multiplying each individual input harmonical function with the transfer function and summing up the individual dynamic responses, the total dynamic response is obtained, and an analysis like this can be applied only in case of linear dynamic analysis, where the principle of superposition of impacts may be applied. The transfer function of the soil depends on the velocity of shear seismic waves and bulk density. The soil (Fig. 1) is observed, it contains n layers, where the last layer, the n^{th} one, is actually the bedrock.

Displacement on the borders between the layers must comply with the conditions of displacement compatibility (displacement of the top of one layer must be equal to the displacement of the bottom of the layer above the observed layer):

$$u_i(Z_i = h_i, t) = u_{i+1}(Z_{i+1} = 0, t) \tag{12}$$

From the condition that the shear stresses on the borders of the layers are equal:

$$\tau_i(z_i = h_i, t) = \tau_{i+1}(z_{i+1} = 0, t) \tag{13}$$

for the amplitudes of the wave in the layer $i+1$, the recursive formulas are obtained:

$$A_{i+1} = \frac{1}{2} A_i (1 + \alpha_i^*) e^{ik_i^* h_i} + \frac{1}{2} B_i (1 - \alpha_i^*) e^{-ik_i^* h_i} \tag{14}$$

$$B_{i+1} = \frac{1}{2} A_i (1 - \alpha_i^*) e^{ik_i^* h_i} + \frac{1}{2} B_i (1 + \alpha_i^*) e^{-ik_i^* h_i} \tag{15}$$

Where is:

$$\alpha_i^* = \frac{G_i k_i^*}{G_{i+1} k_{i+1}^*} = \frac{\rho_i v_{si}^*}{\rho_{i+1} v_{si+1}^*} \tag{16}$$

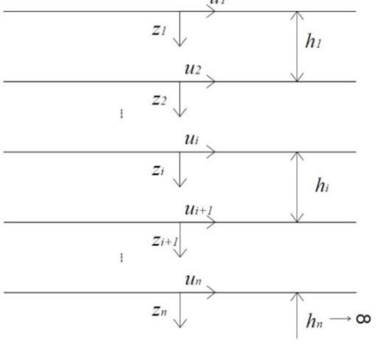

Figure 1. Scheme of layered soil

The transfer function of the layer i can be defined as the relation of amplitudes between the layer i and the layer $i+1$ as:

$$H_i(\omega) = \frac{A_i}{A_{i+1}} \tag{17}$$

Since that the following is valid for the harmonic oscillations:

$$\left|\ddot{u}\right| = \omega\left|\dot{u}\right| = \omega^{2}\left|u\right| \tag{18}$$

Apart from displacement, the amplification function describes the amplification of acceleration and velocity from the layer *i* to the layer *i+1*. With the amplification function, it is possible to determine displacement in every layer on the basis of displacement of the previous layer.

The record describing movement of earthquake on the bedrock is $u_n(t)$. It is assumed that there are n layers of soil in total including the bedrock. The diagram showing layers of soil is given in the Fig. 1 . First, it is necessary to transform the incident wave on the bedrock into the Fourier´s series using the fast Fourier transformation (*FFT*) which is present in various software packages (Matlab, Excel, etc.). In that way, the function in the frequency domain is obtained:

$$U_n(\omega) = FFT(u_n(t)) \tag{19}$$

On the basis of dynamic characteristics and the Eq. (17), for each layer of soil it is determined the transfer function $H_i(\omega)$ which is shown in the frequency domain. The response of the soil in the layer *i* is obtained in the following manner:

$$U_i(\omega) = H_i(\omega)U_{i+1}(\omega) \tag{20}$$

This way, the displacement on the terrain surface is obtained through successive solving of the equations:

$$U_1(\omega) = H_1(\omega)H_2(\omega)\ldots H_n(\omega)U_n(\omega) \tag{21}$$

Where $H_1(\omega)H_2(\omega)\ldots H_n(\omega)$ is the transfer f unction of the entire system composed of n layers of soil. The transfer function of the entire system is the relation between the displacement amplitude on the surface and the displacement amplitude at the level of the bedrock. The obtained response on the surface is called the response of the soil when dynamically excitated on the bedrock. The given function is obtained in the frequency domain. The modulus of this function is the Fourier´s amplitude spectrum. With the inverse fast Fourier´s transformation of the function $U_1(\omega)$ it is obtained the response on the surface in the time domain:

$$u_1(t) = IFFT(U_1(\omega)) \tag{22}$$

More accurately, the real part of the inverse fast Fourier´s transformation is the time record of the displacement on the terrain surface $u_1(t)$.

Within this analysis, non-linear behaviour of soil has not been taken into consideration. During an earthquake, shear deformations increase which is manifested as a change in dynamic characteristics of soil (shear modulus and relative damping). Dynamic characteristics of soil depend on the level of stresses in soil, that is, on shear deformations. The dependence of the shear modulus and relative damping on the shear deformations in the soil shall be called hereinafter the curves of reduction of dynamic characteristics. The previously shown linear analysis assumed that the dynamic parameters of soil (shear modulus G and relative damping ζ) are constant throughout the analysis. However, the given parameters significantly depend on the level of shear deformations which appear in the soil, meaning that they are not the same at all levels of strain. Therefore, the described procedure of calculation must be additionally modified so that the change of dynamic parameters is taken into account. The modification implies that the dynamic parameters change through iterations depending on the values of shear deformations in the soil.

At the beginning of every iteration, the values of dynamic parameters are assumed. During the iteration, they remain constant, and then, linear analysis of dynamic response is conducted. Most often as the parameters in the first iteration, the values are used which correspond to very small deformations.

On the basis of the obtained dynamic response, maximum values of shear deformations are calculated for each layer of soil:

$$\gamma_{i\max} = \frac{u^{p}_{i\max} - u^{d}_{i\max}}{h_i} \tag{23}$$

where: γ_{imax} is maximum level of shear deformations in the i^{th} layer of soil, u^{p}_{imax} - maximum displacement at the upper border of the i^{th} layer of soil, u^{d}_{imax} maximum displacement on the bottom border of the i^{th} layer of soil, h_i- thickness of the i^{th} layer of soil. For the obtained value of the maximum shear deformation, the effective shear deformations (ProShake User Manual) are determined as:

$$\gamma_{ieff} = \frac{M-1}{10}\gamma_{i\max} \tag{24}$$

where *M*- is the earthquake magnitude.

For the calculated level of effective shear deformation, the values for shear modulus and relative damping are to be read from the reduction curves.The read values of the dynamic characteristics are to be compared with the values of the dynamic characteristics within iteration. In case there are significant discrepancies, the calculation is repeated in the next iteration with new dynamic characteristics of the soil. The calculation is finished when the difference between the dynamic parameters at the beginning of the iteration and at the end of the iteration is insignificant (cca 3-5%) (ProShake User Manual).

The reduction curves can be obtained by experiments conducted on the undisturbed samples of soil both in the laboratory and on site. The reduction curves show the size of the change of deformation modulus and relative damping after cyclic repetition of loading and unloading.

6. PARAMETRIC ANALYSIS

This chapter shows the results of the parametric analysis of impact of layer thickness on the frequency characteristic of response of the surface soil layer, and the impact of change in dynamic characteristic of the soil during excitation. The calculation is conducted by means of software package EduShake. There were observed two cases for one layer of soil which lies on the deformable rock mass, where the reduction in shear modulus and relative damping is used, and the case where the shear modulus and relative damping are constant during the earthquake. The cases are analysed when the thickness of the soil layer is changed and the spectrums of response are observed at the surface. The calculation is conducted separately when the overburden above the bedrock is sand, and especially when the overburden is clay. The following table contains characteristics of the materials (Maksimović 2005):

	$\gamma(\frac{kN}{m^3})$	$v_{s\max}$ (m/s)	ζ (%)
Rock	25	1500	2
Sand	20	250	5
Clay	18	200	2

Table 1. Characteristics of soil

The Fig. 2 shows the spectrums of response on the surface for various heights of the overburden of sand when measured from the bedrock for 10, 20, 30, 40 and 50 m and the response spectrum of the input earthquake El Centro at the level of the bedrock during the reduction of the dynamic parameters, and the Fig. 3 shows the response spectrums during constant dynamic parameters during the earthquake. Predominant period of the input earthquake is 0.683 s, and the maximum acceleration is 0.343 g .

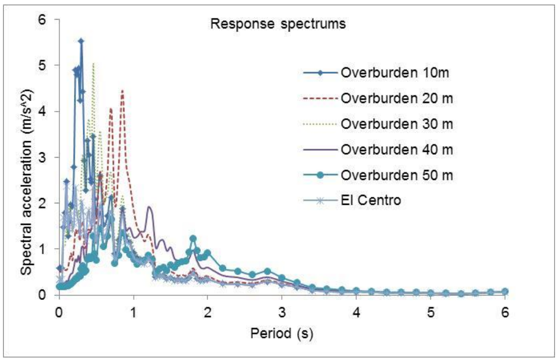

Figure 2. Response spectrums-variable dynamic parameters

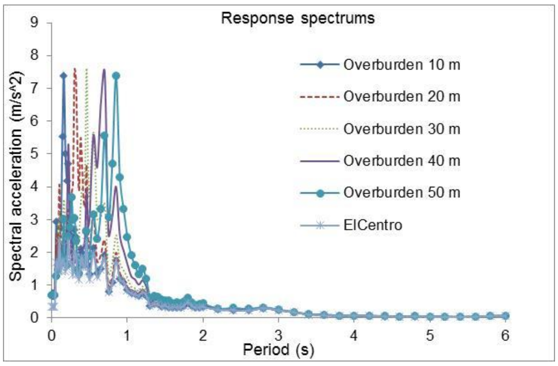

Figure 3. Response spectrums-constant dynamic parameters

For sand, it is used the curve of reduction of shear modulus and relative damping (Seed et al. 1986). The Fig. 4 shows the change of predominant periods (*T*) and peak acceleration (*PA*) at the surface, in case of sand overburden, for different parameters (overburden height and reduction of dynamic characteristics).

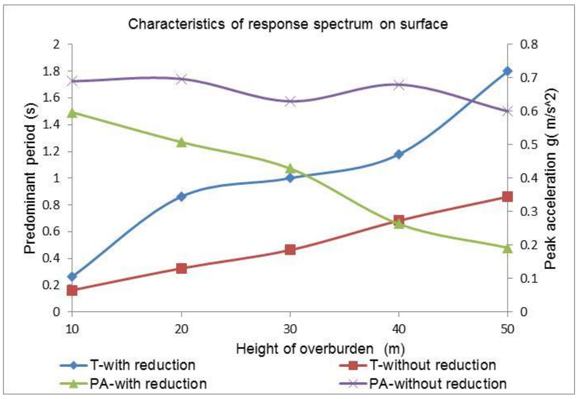

Figure 4. Change of predominant period and peak acceleration on the terrain surface

On the basis of the analyses, it can be said that the values of the predominant periods of responses at the surface are lower in case when the reduction of dynamic characteristics of soil is not taken into consideration in relation to the case when the reduction of dynamic characteristics of soil is taken into consideration. The values of peak accelerations of responses at the surface are greater in case when the reduction of dynamic characteristics of soil is not taken into consideration in relation to the case when the reduction of dynamic characteristics of soil is taken into consideration. The predominant periods increase with the increase in height of the overburden, and peak accelerations decline with increase in height of the overburden. Response spectrums differ in case when the reduction of dynamic characteristics is taken into consideration (Fig. 2) in relation to the case when the dynamic characteristics are constant during the earthquake (Fig. 3). The difference is not only in the values of predominant periods and peak accelerations, but also in the accelerations for different values of oscillating period.

The Fig. 5 shows the spectrums of response on the surface for various heights of the overburden of clay when measured from the bedrock for 10, 20, 30, 40 and 50 m during the reduction of the dynamic characteristics, and the Fig. 6 shows the response spectrums for the case when the dynamic characteristics are constant during the earthquake.

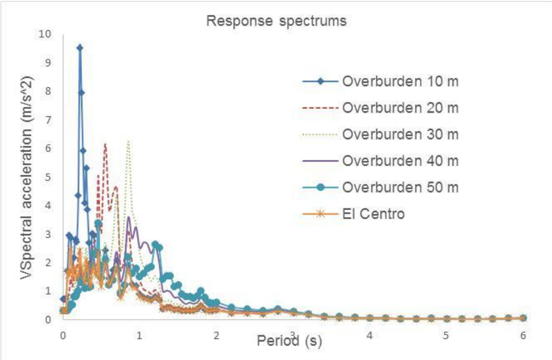

Figure 5. Response spectrums-variable dynamic parameters

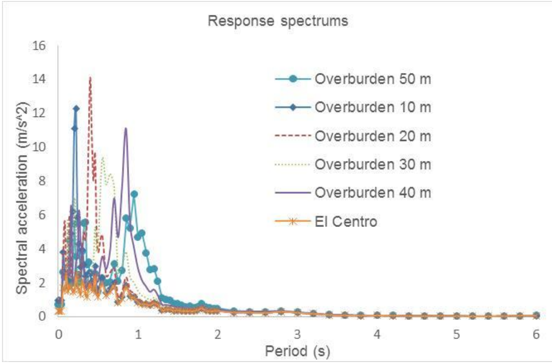

Figure 6. Response spectrums-constant dynamic parameters

For clay, it is used the curve of reduction of shear modulus and relative damping (Sun et al. 1988). The Fig. 7 shows the change of predominant period and peak acceleration at the surface, in case of clay overburden, for the case of reduction of dynamic characteristics and for the case without reduction.

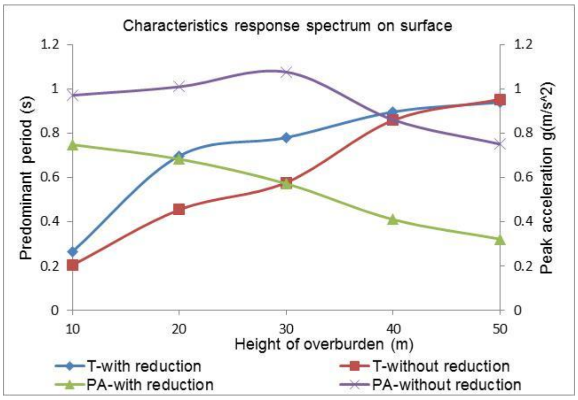

Figure 7. Change of predominant period and peak acceleration on the terrain surface

On the basis of the analyses, similar as in the case of sand, it can be said that the values of the predominant periods of responses at the surface are lower in case when the reduction of dynamic characteristics of soil is not taken into consideration in relation to the case when the reduction of dynamic characteristics of soil is taken into consideration. The values of peak accelerations of responses at the surface are greater in case when the reduction of dynamic characteristics of soil is not taken into consideration in relation to the case when the reduction of dynamic characteristics of soil is taken into consideration. The predominant periods increase with the increase in height of the overburden, and peak accelerations decline with increase in height of the overburden. From the response spectrums (Fig. 5 and Fig. 6) it can be seen that there is not only difference in relation to the values of predominant periods and peak accelerations, but in the rest of the spectrum as well.

7. CONCLUSION

On the basis of the conducted analyses, it can be said that both in sand and in clay, the change in overburden height influence the changes in response of soil at the surface. The predominant periods increase, and the peak accelerations decline when the overburden height is increased. From the results for both types of soil, it can be observed that in case of neglecting the reduction of dynamic characteristics of soil during the excitation, there increases peak acceleration and decreases the predominant period on the terrain surface in relation to the case when there is reduction of dynamic characteristics using the reduction curves. Such behaviour is expected, since the soil is more rigid if it is not taken into consideration the reduction of dynamic parameters as the result of shear deformations in the soil during earthquake. It can be concluded that it is necessary to use reduction of dynamic parameters, since otherwise there would be obtained the conservative results of responses at the surface. This, of course, demands laboratory and in situ testing with an aim of defining the reduction curves.

In general, the analytical approach for determining the impact of local conditions on propagation of seismic waves has both advantages and disadvantages. The advantage is obtaining of numerical results which are based on theoretical laws of undulation and on the results of soil testing. The disadvantage is that the analytical approach always demands greater number of input data, and the reliability of one-dimensional analysis depends on the reliability of the input data. The most essential is to define soil profile as reliable as it can be, with thicknesses of layers and types of soils, and then dynamic parameters of soil are to be determined.

The described procedure of calculation of dynamic analysis of layered soil is simple and correct, and it can be easily automatized using softwares thus giving different values of the input data regarding the number of layers, layer size, earthquake record, reduction curves, etc. This way, it is enabled for a designer, on the basis of knowing the geological profile on the construction site of a facility, to relatively quickly and simple determine the change in seismic wave when passing through the layers of soil of various dynamic characteristics.

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REFERENCES

[1] Šlimak, Š. (1996). Engineering geophysics, Faculty of Mining and Geology, Belgrade.

[2] Salatić, R., Jocković, S., Mandić, R. (2014), The impact of local site conditions on ground response,, Proceedings 4th International scientific and professional conferences Earthquake Engineering and Engineering Seismology, Maj of 19-21 2014.Bor lake , pp. 133-140.

[3] Radovanović, S. (2008). Seismic micro test location in New Belgrade, Belgrade.

[4] Krame, S. L. (1996). Geotechnical Earthquake Engineering, Prentice-Hall Inc., USA.

[5] Ćorić, B., Salatić, R., Ranković, S. (1998). Dynamics of structures, Faculty of Civil Engineering, Belgrade.

[6] Aničić, D., Fajfar, P., Petrović, B., Szavits-Nossan, A., Tomaževič, M. (1990). Earthquake engineering, Građevinska knjiga , Belgrade.

[7] Deretić-Stojanović, B., Dunica, Š. (2008). Strength of material, Faculty of Civil Engineering, Belgrade.

[8] ProShake 1.1 - Ground Response Analysis Program (User‘s Manual), EduPro Civil Systems Inc., USA.

[9] EduPro Civil Systems, ProShake (1999). Ground response analysis program, EduPro Civil Systems, Inc., Redmond, Washington.

[10] Maksimović, M. (2005). Soil Mechanics, Građevinska knjiga, Belgrade.

[11] Seed H.B., Wong R.T, Idriss I.M., Tokimatsu K. (1986), Moduli and damping factors for dynamic analyses of cohesionless soils, Journal of Geotechnical Engineering, ASCE, Vol. 112, No. GT11, pp. 1016-1032.

[12] Sun, J.I., Golesorkhi, R., Seed, H.B. (1988). Dynamic moduli and damping ratios for cohesive soils, Report No. EERC-88/15, Earthquake Engineering Research Center, University of California, Berkley.

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