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DYNAMIC GROUND RESPONSE ANALYSIS ALONG FUTURE BELGRADE METRO LINE

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Summary: *This paper presents the results of dynamic response analysis of earthquake induced ground surface motions along future Belgrade metro line. Soil properties were obtained from existing geotechnical documentation. Analysis was performed using one dimensional (1D) equivalent linear approximation of nonlinear response, induced by vertically propagating SH-waves. Soil is represented as the layered half-space with different layer properties and viscoelastic behavior. Comparative analysis for two chosen earthquakes with different frequency spectrum is presented and appropriate conclusions were made.*

Keywords: *Wave propagation, layered half-space, equivalent linear approximation of nonlinear response, Belgrade metro, earthquake engineering*

1. INTRODUCTION

Evaluation of ground response is one of the most important problems in geotechnical earthquake engineering. Despite the fact that soil deposit is much thinner than the rock, its effect to the ground response is significant. Methods of analysis depend on the problem dimension. 1D analysis is the simplest one, but it can predict ground response with high accuracy [1]. It is based on two assumptions - layers must be horizontal and infinite in horizontal direction with constant soil/rock properties, and dynamic response is induced by vertically propagating SH-waves. This is commonly satisfied because shallow layers usually have lower wave propagation velocities than deeper layers, so the inclined wave ray that reach horizontal boundaries is reflected to a more vertical direction.

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2. METHOD OF ANALYSIS

1D analysis used in this paper is based on the transfer function of the vertically propagating SH-wave in the frequency domain. This function represents response parameter (displacement, acceleration etc.) with respect to an input motion parameter (such as bedrock acceleration). It is usually defined with the following expression:

$$H(\omega) = \frac{A_1(\omega)}{A_n(\omega)}, \tag{1}$$

where A_1 and A_n are amplitudes of the motion parameters on the ground surface and on the bedrock, respectively. Transfer function is a complex function that can be visualized by its modulus which is called amplification function. This has local maximums at so called natural frequencies of the soil deposit. Soil behavior is assumed to be viscoelastic, according to Kelvin-Voight model, and bedrock is elastic.

Initial step in the analysis is to express bedrock motion time history as a Fourier series, so the stochastic input motion is converted into the sum of harmonic functions. By multiplying each term in series with the transfer function, Fourier series of the ground surface motion is calculated. Output motion in time domain is expressed by inverse FT. This analysis, therefore, uses the principle of the superposition – it is limited to the analysis of linear systems, where shear modulus G and damping ξ are assumed to be constant. In real soil they are strain-dependent. Nonlinear soil behavior is approximated by iterative procedure. In first iteration initial estimates of G and ξ are made and ground response is calculated. Then the effective shear strain γ_{eff} in each layer is calculated, and it is assumed as 65% of maximum shear strain to avoid influence of local maximums in input motion [1]. Based on γ_{eff}, new values of G and ξ are chosen for next iteration, and procedure is repeated until differences between dynamic properties in two successive iterations fall below defined tolerance (assumed 5%) in all layers. Described method is still linear analysis – G and ξ are constant during single iteration, but they are compatible with the achieved strain level. The main step in the analysis is calculation of the transfer function for the layered half-space, consisting of N layers, where N^{th} layer is bedrock. Equation of motion for vertically propagating SH-wave state as follows:

$$u(z,t) = Ae^{i(\omega t + k^* z)} + Be^{i(\omega t - k^* z)} \tag{2}$$

where A and B are amplitudes of the transmitted and reflected waves, travelling in the $-z$ (upward) and the $+z$ (downward) directions, respectively, and $k^* = \omega/v_s^*$ is the complex wave number [1]. From compatibility conditions and equilibrium equations on the layer boundaries, the following recursion relation between amplitudes in two nearby layers can be obtained:

$$A_{m+1} = \frac{A_m}{2}\left(1+\alpha_m^*\right)e^{ik_m^* h_m} + \frac{B_m}{2}\left(1-\alpha_m^*\right)e^{-ik_m^* h_m}, \; m=1,,,N \tag{3}$$

$$B_{m+1} = \frac{A_m}{2}\left(1-\alpha_m^*\right)e^{ik_m^* h_m} + \frac{B_m}{2}\left(1+\alpha_m^*\right)e^{-ik_m^* h_m}, \ m=1,,,N \quad (4)$$

where $\alpha_m^* = \rho_m^*(v_s^*)_m / \rho_{m+1}^*(v_s^*)_{m+1}$ is impedance ratio between layers m and $m+1$ [1]. From stress boundary condition at the ground surface (τ=0) follows that $A_1=B_1$. The amplitudes A_m and B_m in each m^{th} layer are calculated successively using the Eqs. (2) and (3). The transfer function is finally obtained from the Eq. (1).

3. SOIL PROFILE AND CHOSEN EARTHQUAKES

Table 1. Dynamic model parameters

Profile	Layer	Soil/Rock Type	h [m]	ρ [g/cm^3]	v_s [m/s]	ξ [%]	G/G_{max} curve ξ curve
P1 Zemun	1	Silty sand sediments	32.0	1.70	100	2	Clay PI=5-10 [4] Clay – Average [4]
	2	Alluvial gravels	26.0	2.00	450	1	Gravel [5]
	3	Clay sediments	12.0	2.10	750	1	Clay PI=5-10 [4] Clay – Average [4]
	4	Limestone		2.25	1155	1	Rock [7]
P2 Novi Beograd	1	Alluvial sands	14.0	1.90	300	1	Sand – Average [6]
	2	Alluvial gravels	15.5	2.00	450	1	Gravel [5]
	3	Clay sediments	15.5	2.10	750	1	Clay PI=20-40 [4] Clay – Average [4]
	4	Limestone		2.25	1155	1	Rock [7]
P3 Center	1	Silty sand sediments	7.5	1.65	100	2	Clay PI=5-10 [4] Clay – Average [4]
	2	Clay sediments	20.0	2.00	325	1	Clay PI=20-40 [4] Clay – Average [4]
	3	Marl	17.5	2.00	450	1	Rock [7]
	4	Limestone		2.25	1155	1	Rock [7]
P4 Tašmajdan	1	Silty sand sediments	6.5	1.85	130	2	Clay PI=5-10 [4] Clay – Average [4]
	2	Limestone		2.25	1155	1	Rock [7]
P5 Đeram	1	Silty sand sediments	9.0	1.90	130	2	Clay PI=5-10 [4] Clay – Average [4]
	2	Clay sediments	8.0	2.00	325	1	Clay PI=20-40 [4] Clay – Average [4]
	3	Marl	28.0	2.00	450	1	Rock [7]
	4	Limestone		2.25	1155	1	Rock [7]
P6 Ustanička	1	Silty sand sediments	14.0	1.85	130	2	Clay PI=5-10 [4] Clay – Average [4]
	2	Clay sediments	5.0	2.00	325	1	Clay PI=20-40 [4] Clay – Average [4]
	3	Marl	26.0	2.15	450	1	Rock [7]

	4	Limestone		2.25	1155	1	Rock [7]

Soil profile along future Belgrade metro line consists of several soil and rock types: clay sediments, alluvial sands and gravels, silty sand sediments, limestone and marl. Dynamic parameters for six characteristic profiles (P1-P6) were obtained from the existing geotechnical data [2] and are stated in the Table 1. The appropriate modulus reduction curves (G/G_{max}) and damping (ξ) curves were adopted from [4-7]. Two earthquakes Loma Prieta (LP) and Chi-Chi (CHC) were chosen for the analysis [8]. Their characteristics are given in Table 1. Maximum horizontal peak ground acceleration (PGA) corresponds to a maximum PGA for Belgrade for the return period of 475 years [3]. The maximum peak ground displacements (PGD) have almost the same values.

Table 2. Earthquake data

Earthquake	Magnitude	PGA [g]	PGD [cm]	Δt [ms]
Loma Prieta 18.10.1989. (LP)	6.9	0.08	5.3	5
Chi-Chi, Taiwan 20.09.1999. (CHI)	7.6	0.08	5.6	5

Input bedrock motions and Fourier Amplitude Spectrums (FAS) for chosen earthquakes are shown in Figures 1 and 2, respectively.

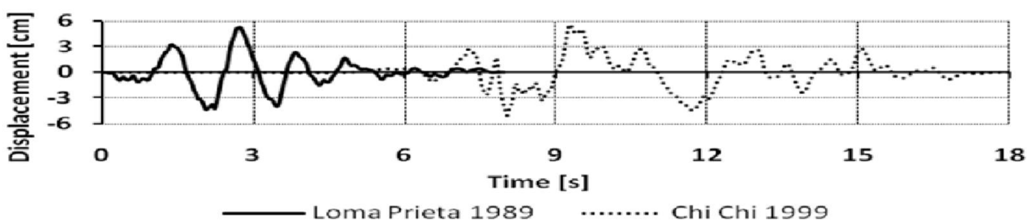

Figure 1. Bedrock displacements time history

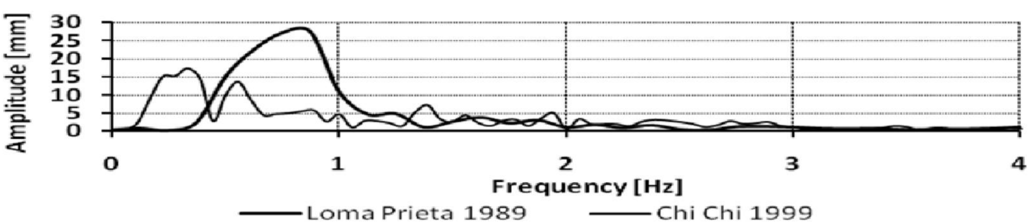

Figure 2. Fourier Amplitude Spectrum of bedrock displacements

4. RESULTS OF THE ANALYSIS

Ground response analysis was performed using MATLAB program written by the author. Calculated amplification functions and ground surface motion for six soil profiles are presented in Figures 3 and 4.

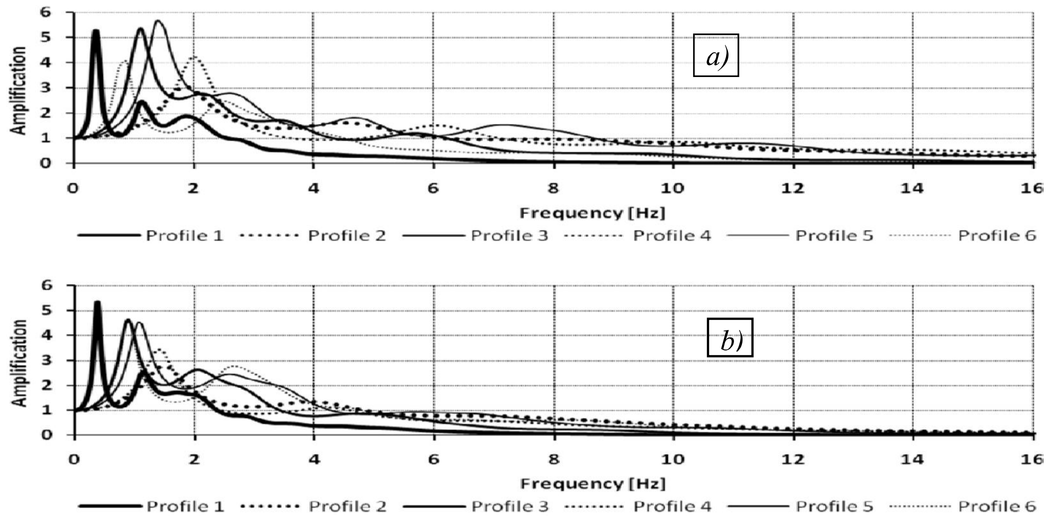

Figure 3. Amplification functions for a) Loma Prieta and b) Chi-Chi earthquake

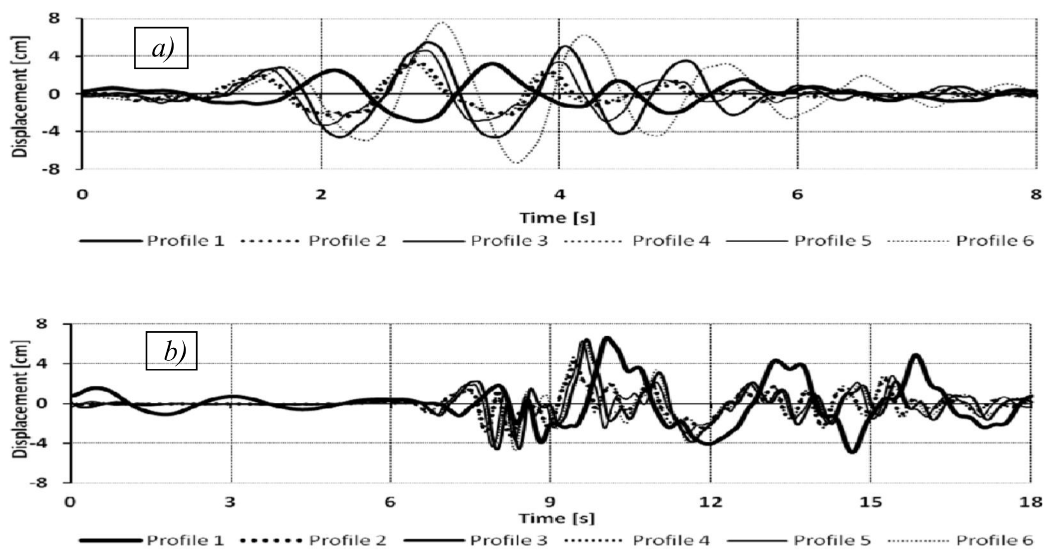

Figure 4. Ground surface motions for a) Loma Prieta and b) Chi-Chi earthquakes

5. CONCLUSIONS

From the results of ground response analysis presented above, the following conclusions were made:

- Maximum ground response is acquired for LP earthquake in P6. Reason for this can be that fundamental frequency of the LP earthquake (0.88 Hz) is the same as the fundamental frequency of soil deposit in P6. Also, there is relatively thick layer of marl directly above the bedrock with small damping ratio. Response in profile P3 is smaller (5.47 cm), despite the fact that its amplification is larger than in the profile P6, since the fundamental frequencies of earthquake and soil deposit don't match. Response in other profiles is smaller and deamplified.

- Maximum ground response for CHI earthquake is smaller than for LP earthquake, and is almost equable along the route – response in profiles P1, P3, P5 and P6 are between 6.31 and 6.64 cm. Reason for this can be almost similar layout of layers in the profiles P3, P5 and P6. Response in other profiles is smaller and deamplified.
- The smallest ground response for both earthquakes is obtained in profile P4 (3.25cm and 4.72cm), despite the fact that bedrock is very shallow. Small thickness of the layer above leads to the large shear deformations, even for relatively small input displacement. Large shear deformation combined with the very small v_s leads to the very large damping which consequently reduces the response.

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ДИНАМИЧКИ ОДГОВОР ПОДЛОГЕ ДУЖ ТРАСЕ БУДУЋЕ ЛИНИЈЕ БЕОГРАДСКОГ МЕТРОА

Резиме: *У овом раду приказани су резултати прорачуна динамичког одговора на површини слојевитог тла дуж трасе будуће линије Београдског метроа услед дејства два изабрана земљотреса. Подаци о тлу за шест карактеристичних профила преузети су из расположиве геотехничке документације. Прорачун простирања вертикалних SH-таласа извршен је методом еквивалентне једнодимензионалне линеарне анализе. Тло је представљено системом слојева одговарајућих карактеристика. Понашање тла је вискоеластично. За дејство два одабрана земљотреса различитог фреквентног састава приказана је упоредна анализа резултата и изведени су одговарајући закључци.*

Кључне речи: *Простирање таласа, слојевит полупростор, еквивалентна линеарна динамичка анализа, Београдски метро, земљотресно инжењерство*