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Seismic response analysis for representative ground profile in the area of city of Zagreb

Analyse de réponse sismique pour des profil de sol représentatifs dans la région de la ville de Zagreb

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ABSTRACT: Ground seismic response for typical soil conditions in the Zagreb area is presented in the paper. The investigated region is in the alluvial area at the bottom of the Medvednica mountain. This area was heavily affected by the recent earthquake in Zagreb, in March 2020. The results of detailed investigation project for seismic and geotechnical microzonation of part of City of Zagreb were used for establishing typical soil profile. The scope of investigations included geotechnical boring, laboratory and in-situ testing, engineering-geology investigation, and geophysical investigation. The soil profile for the ground model is evaluated from several 35m deep boreholes performed within the seismic study. The seismic ground response was assessed by 1-D linear and nonlinear analyses for the range of expected maximal accelerations in investigated area, using several well-known earthquake motions covering the wide spectral range. Critical review is also given in the paper comparing the result of the analyses to the recommendation of the Eurocode 8 for particular seismic soil types.

RÉSUMÉ: La réponse sismique du sol pour des conditions de sol typiques dans la région de Zagreb est présentée dans l'article. La région étudiée se situe dans la zone alluviale au pied de la montagne Medvednica. Cette zone a été fortement touchée par le récent tremblement de terre à Zagreb, en mars 2020. Les résultats du projet d'enquête détaillée pour la microzonation sismique et géotechnique d'une partie de la ville de Zagreb ont été utilisés pour établir des profils de sol typiques. La portée des enquêtes comprenait des forages géotechniques, des essais en laboratoire et in situ, des enquêtes géotechniques et géophysiques. Le profil du sol pour les modèles de sol est évalué à partir de plusieurs forages de 35 m de profondeur réalisés dans le cadre de l'étude sismique. La réponse sismique du sol a été évaluée par des analyses linéaires et non linéaires 1-D pour la gamme des accélérations maximales attendues dans la zone étudiée, en utilisant plusieurs mouvements sismiques bien connus couvrant la large gamme spectrale. Une revue critique est également donnée dans l'article comparant le résultat des analyses à la recommandation de l'Eurocode 8 pour les types de sols sismiques.

KEYWORDS: Seismic response, seismic microzonation, dynamic soil properties, bender elements, dynamic triaxial test.

1 INTRODUCTION

This study of seismic response analysis is performed based on the results of the project: Seismic and geological zonation of the part of the City of Zagreb (Miklin et al. 2018, 2019), developed in the period 2017-2019 year (Padovan et al. 2021). City of Zagreb is the capitol of Croatia with more than 0,8 million residents covering the area of approximately 640 km^2. The area is subjected to various geohazard risks like landslides, floods (great flood in 1964) and earthquakes (four significant earthquakes: 1880, 1905, 1990, and 2020 with magnitudes M = 6.2, 5.6, 5.1 and 5.5). This project was developed following the previous studies of the seismic characteristics of Zagreb area (Jurak et al. 2008). The area can be divided in four characteristic geomorphological units shown at Figure 1. (I. Medvednica mountain, II. Podsljeme zone i.e. southern slopes of Medvedenica Mountain, III. River Sava area with hilly steam and sediment zone and IV. Vukomeričke gorice hilly area). The area of interest in this paper is marked by purple polygon (≈114 km2). Great amount of geotechnical, geological, geophysical, and seismic investigations was preformed within the area to evaluate the geological and seismic conditions of the site. Deep boreholes (27 boreholes) to the depth of 35 m were positioned along the 14 characteristic profiles (yellow lines at the figure). Three of them were defined as detailed geotechnical boreholes corresponding to characteristic geological unit – engineering soils (Figure 2.).

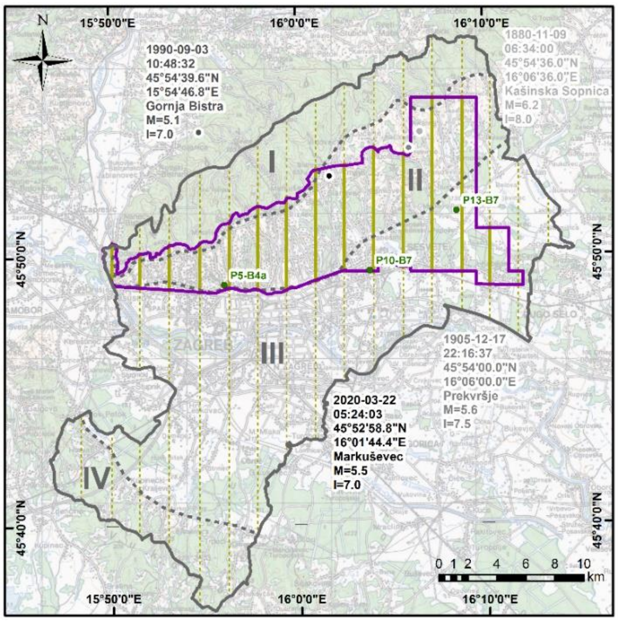

Figure 1. Zareb city area showing characteristic geomorphological units, research area (purple polygon), investigation profiles (yellow lines), position and characteristics of four major earthquakes in Zagreb (year 1880, 1905, 1990 and 2020), three detailed geotechnical boreholes.

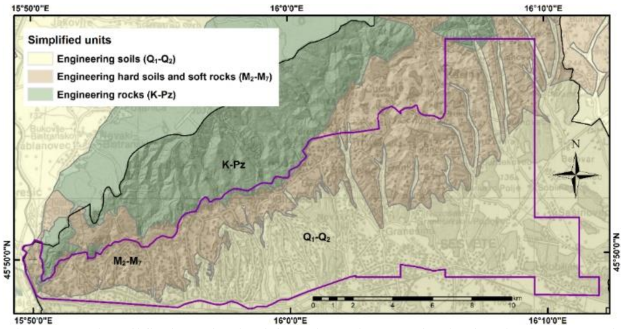

Figure 2. Simplified geological / engineering geological units in research area

Seismic response analysis is performed on borehole P5-B4a. The characteristic soil profile is given at Figure 3. showing the soil properties relevant for the model: type of soil, the results of in situ standard penetration test, undrained shear strength and shear wave velocity. Detailed information on the soil investigation program and results are given in the next paragraph.

2 GEOTECHNICAL INVESTIGATIONS

Geotechnical investigations for the Project consisted of field and laboratory investigations. The boreholes were drilled to the depth of 35 m, with continuous coring. The soil and rock classification were performed together with sampling of undisturbed and disturbed samples for laboratory testing. Pocket penetrometer and shear vane test were used to indicate soil consistency and strength. Standard penetration test (SPT) and undisturbed samples were taken generally in 2.0 m intervals, while in detailed geotechnical boreholes 1.5 m SPT interval was used. Undisturbed samples were taken mainly by split barrel sampler. Additionally, tin wall piston sampler was used in special areas of soft soil and double rotary core samples for rock. Laboratory testing was performed in according to HRN EN ISO 17025 standard in Geotehnički studio d.o.o. laboratory for soil and rock testing. Following tests were performed: (i) for physical properties - water content, Atterberg plastic limits, soil density, solid particle density, sieve analysis, carbonate content; (ii) and for mechanical properties - direct shear test, uniaxial strength test, unconsolidated undrained triaxial shear test, oedometer test, determination of shear modulus of soil for small strain by Bender elements, soil stiffness reduction and damping in dynamic triaxial test. For seismic zonation, 27 boreholes were performed to the depth of 35 m, additionally prepared for downhole measurements. Three boreholes (P5-B4a, P10-B7, P13-B7) were investigated in more detail, sampled and laboratory tested in order to define characteristic soil profile(s). Geotechnical soil profile for borehole P5-B4a is presented at the Fig. 3.

3 GEOPHYSICAL AND SEISMIC MEASUREMENTS

Geophysical measurements were concentrated along 14 profiles shown in Fig. 1. A total of 150 measurements were performed by 1D multichannel analysis of surface waves (1D MASW), 75 shallow seismic refraction profiles of longitudinal, P and transverse, S-waves 115 meters in length and 26 measurements of P and S-wave velocities in boreholes by downhole method. By processing the seismic data using the MASW method for each of the measurement positions, the average velocity of S-waves in the first 30 m depth, v_{s30}, was calculated. The microseismic noise was measured at 101 free field points (MNP). Noise was measured with the three axial seismographs Tromino (MoHo s.r.l., Italy) with the lowest frequency of 0.5 Hz. 526 additional MNPs, available from the repository of Geophysical Institute, were used together with the measured MNPs. Total number of MNPs for the Project was 627 with spatial distribution of 3.85 MNP/km^2. Results were used to approximate the depth of base rock layer, seismic soil type and amplification.

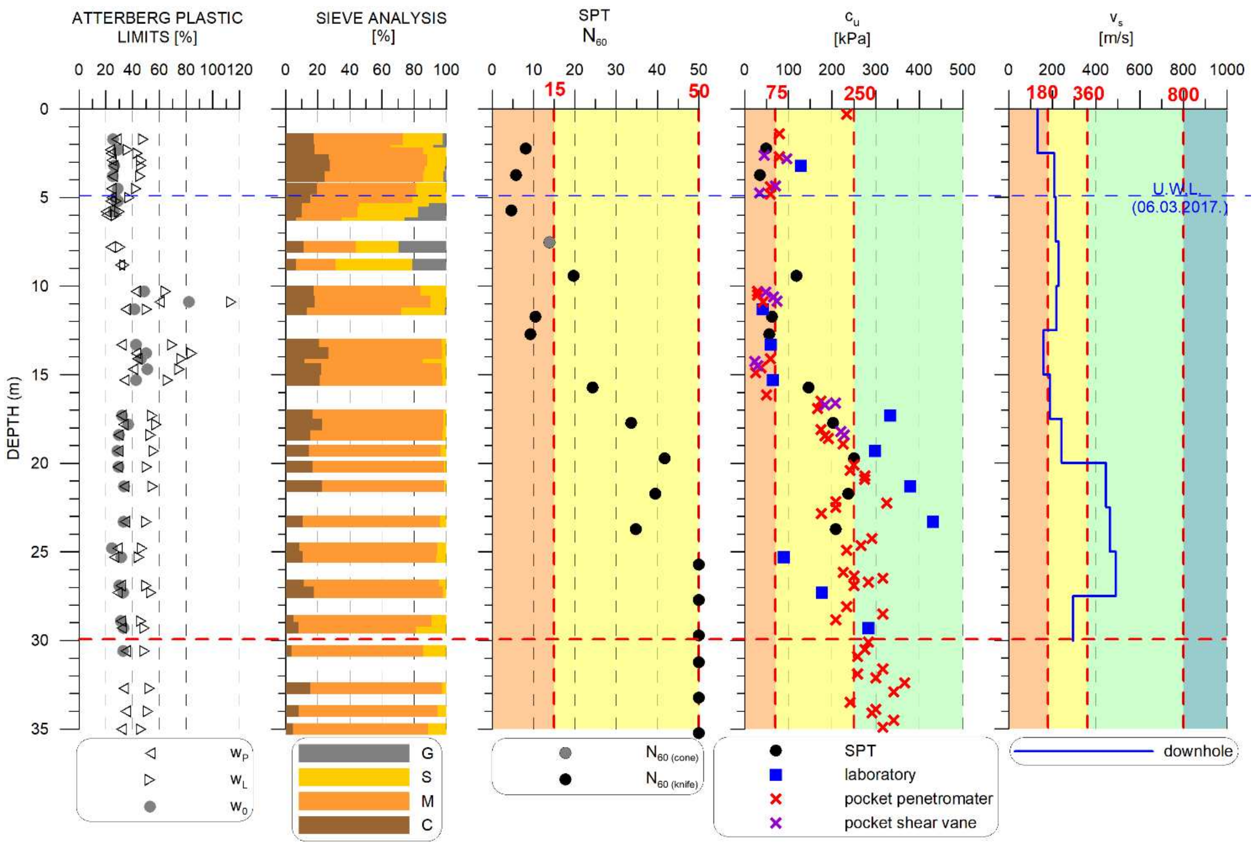

Figure 3. Geotechnical soil profile for characteristic (detailed) geotechnical borehole: P5-B4a [6]

4 LABORATORY TESTING OF DYNAMIC SOIL PROPERTIES

Laboratory testing of dynamic soil properties was performed by following laboratory tests:

- testing of small strain stiffness by bender elements
- testing of soil stiffness reduction and damping by dynamic triaxial apparatus

Testing was performed in laboratory Geotehnički studio d.o.o. by using GDS testing equipment. Bender elements consist of two sensors embedded into the sample cap and pedestal, which are inserted into the soil sample (Figure 4). One sensor serves as transmitter, while the other serves as receiver. Both shear velocity v_s (S wave) and longitudinal velocity v_p (P wave) can be measured with the same sensors. Initial stiffness shear modulus G_0 for small strain can be calculates according to equation:

$$G_0 = \rho v_s^2 \tag{1}$$

where ρ is saturated soil density.

Poisson coefficient of the soil can be calculated according to equation:

$$\nu = \left\{\left(\frac{v_p}{v_s}\right)^2 - 2\right\} / \left\{2\left[\left(\frac{v_p}{v_s}\right)^2 - 1\right]\right\} \tag{2}$$

In this study cohesive soil samples were tested by bender elements for different confining effective pressure p' = 25, 50, 100, 200, 400 and 800 kPa. For each test initial shear stiffness and Poisson coefficient were calculated. Best fit correlation was derived by using following equation:

$$G_0 = A\frac{(2{,}17-e)^2}{(1+e)}\left(\frac{p'}{p_{ref}}\right)^m \tag{3}$$

Where: A and m are soil parameters, e is void ratio, p' is confining pressure and p_{ref} is reference pressure 100 kPa. Following principle was used for laboratory testing of samples: sample was divided into two specimens, first specimen was tested by bender elements to derive best fit initial shear stiffness parameters by using equation (3), second specimen from the same undisturbed sample was used for dynamic testing. The results from bender element test were used for interpretation of the initial stiffness modulus for each confining pressure.

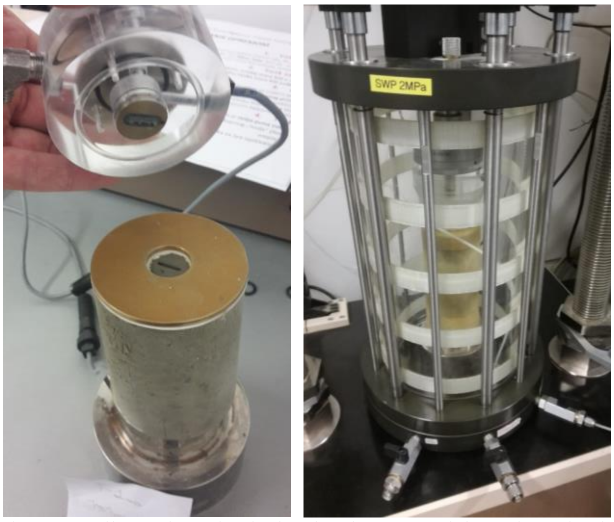

Figure 4. Soil sample testing by bender elements and dynamic testing in GDS ELDYN triaxial apparatus

Triaxial dynamic testing was performed according to ASTM D3999-91: Standard Test Methods for the Determination of the Modulus and Damping Properties of Soils Using the Cyclic Triaxial Apparatus. The test was performed by GDS ELDYN equipment (Figure 4).

Each sample was consolidated to initial confining pressure corresponding to the in-situ stress (taking into account overburden effective pressure and initial horizontal pressure coefficient K_0). Prior to cycling testing the samples were saturated (Betta parameter value from 0,76 to 0,89). After the saturation and consolidation, three cycles were performed with the frequency of 0,01 Hz by using strain control method in the range of the amplitude from 0,02 to 1,52 mm, which gives approximately 0,03 to 2,02% strain for 76 mm high samples. This range of amplitudes covers the main interval of strains necessary to derive stiffness reduction and damping curve. Characteristic soil stiffness reduction curve for soil is given at Figure 5. showing the applicable testing methods and the range for ELDYN system used in this study.

Following equations were used for interpretation of the results

$$E = \frac{\sigma_{max}}{\varepsilon_{max}} \tag{4}$$

$$G = \frac{E}{2(1+\nu)} \tag{5}$$

$$D = \frac{A_L}{4\pi A_T} \tag{6}$$

where E is Young modulus of the sample, σ_{max} is maximum axial stress during the cycle, ε_{max} maximum relative axial strain during the cycle (strain controlled test), G is shear modulus of the sample, D is damping, A_L is the surface of hysteresis loop and A_T is the area of triangle for ideal elastic behavior for the loop.

The results of the testing were compared to recommendations for the stiffness reduction and damping curves for different soils available in the literature (Mayne 2005 and Ishibashy & Zhang 1993). The comparison is given in Figure 6. The yellow area represents the range of values proposed by Ishibashi and Zhang 1993, for the range of soil plasticity index PI = 0 to 75. It can be seen that results of laboratory testing for the samples in clay/silt material from characteristic boreholes (PI in the range 18 to 34) fall quite well within the proposed area, which gives great confidence to the proposed correlations and the testing performed. The proposed correlation by Ishibashy and Zhang 1993 will be used for seismic response analysis used in this paper.

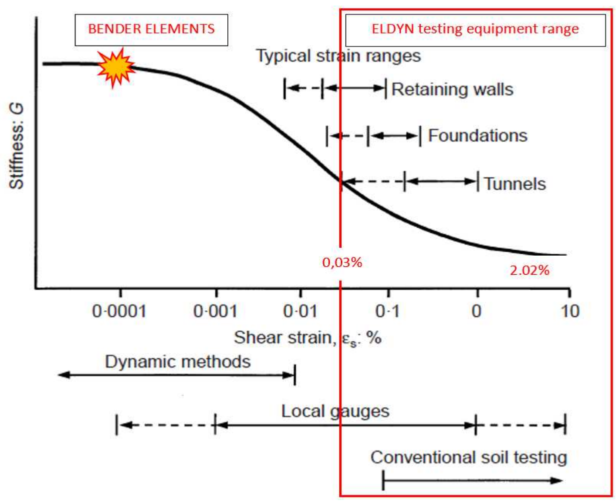

Figure 5. Characteristic soil stiffness reduction curve showing the range of applicable investigation methods and the range for ELDYN system.

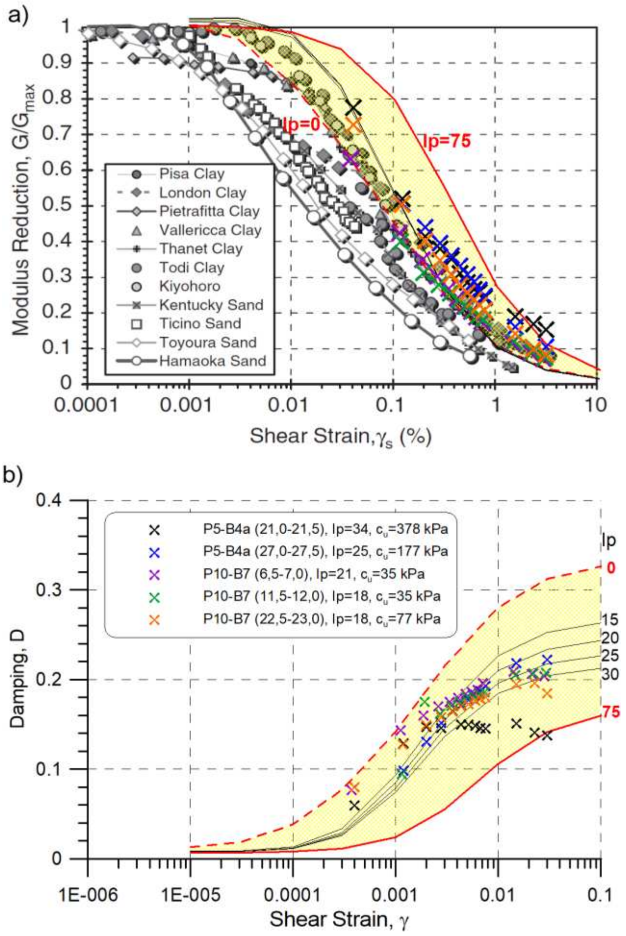

Figure 6. Dependence of shear modulus and damping on the cyclic shear strain. Comparison of test results to reference literature (Mayne 2005, Ishibashy & Zhang 1993)

5 SEISMIC RESPONSE ANALYSIS

The preliminary analysis of seismic response of local soil above the bedrock was conducted in order to estimate relevant influences of the local soil on seismic design parameters.

Generally, the spectral shape of the ground motions at site is determined by the relative influences of the source spectral characteristics for earthquakes in the region and the attenuation characteristics of geological materials that transmit the seismic waves from the base rock to the site area. In strata above the base rock the seismic waves in the free field are amplified or attenuated according to the frequency transfer characteristics of the strata and the strain level of the vibration. Thus, the spectral shapes of the incoming earthquake motion on the assumed outcropping base rock and the local overlaying strata may differ for a given site.

Taking these general statements into account, various procedures relevant for the determination of seismic design values are proposed.

In this section, site response modifications were analyzed in a parametric way, using the common 1-D procedure for determining the influence of local site effects which involves: establishment of the geotechnical seismic model (design seismic profile), selection of seismic excitation, and one-dimensional shear-wave propagation analyses. The analysis of the local seismic response was conducted using the computer program SHAKE (Schnabel et al., 1970). It is based on the assumption that the upward propagation of shear waves is the dominant cause of the soil strata response.

The results are presented as dynamic amplification factors (DAF), defined as ratios of peak accelerations at top of the local site profile over peak accelerations of the control motion. An immediate value of the design peak acceleration at the ground surface or at the level of foundations is also presented as an alternative.

5.1 *Geotechnical seismic profile*

The determination of the geotechnical seismic profile includes following data: shear wave velocities of typical layers, soil densities and nonlinear relationships of shear modulus and damping with shear strain. The profile depth down to bedrock (i.e. assumed model half-space) must also be determined.

Shear wave velocities, v_s, have been measured to the depth of 30 m, as shown in Figure. 3. The layers which can be characterized as bedrock (with v_s > 800m/s) have not been found during these investigations. So, the design seismic profile for further analyses was assumed in parametric way as presented at Figure 7. The design profile included the results of down-hole measurements in the upper 30 m of profile and assumed v_s values obtained by extrapolation of average shear velocities to greater depths. Several model depths to bedrock (modelled with v_s = 800 m/s) in range 30 m – 120 m have been examined.

For linear analyses constant material damping of 5% was used for layers in the profile, and for nonlinear analyses average curves from for typical materials from Figure 6. have been used. Soil densities used in analyses ranged from 1.7 t/m^3 for upper layers to 2.0 t/m^3 for deeper soil layers.

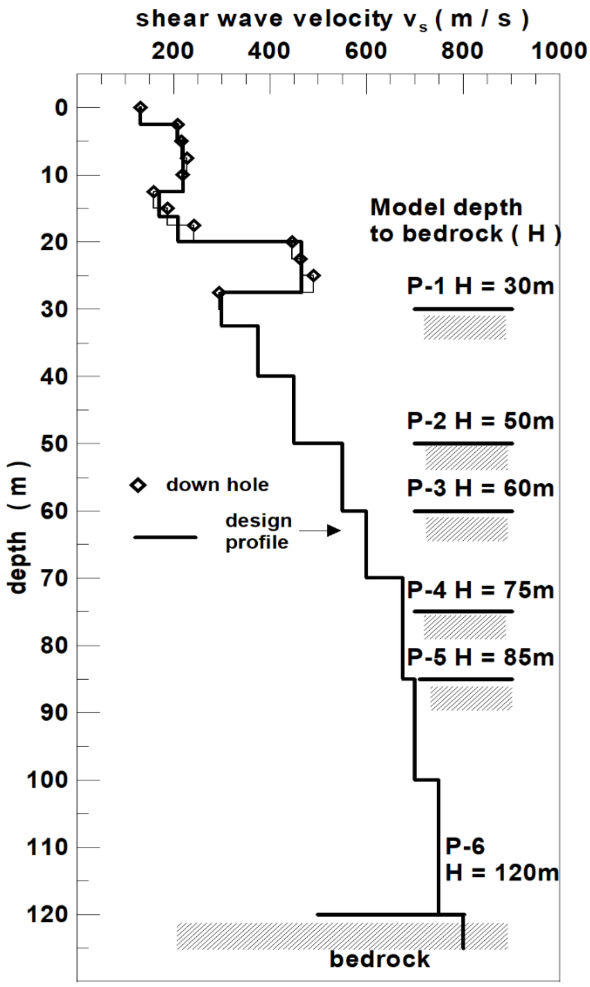

Figure 7. Design seismic profile alternatives used in analyses

5.2 *Seismic input*

Three accelerograms were used in the analyses. They represent time histories of real earthquakes that hit the Montenegrin littoral in 1979. These earthquake time histories are named ACC1, ACC2 and ACC3 with following properties:

ACC1 represents earthquakes of medium epicentral distance; ACC2 is for large epicentral distance (in excess of 100 km) and ACC3 represents earthquakes characterized by short epicentral distance (shock-type). These accelerograms cover wider frequency content and their response spectra normalized to 1.0 g of maximum acceleration at the 5% damping are presented in Figure 8.

5.3 *Seismic response analysis*

The results of seismic 1-D analyses using computer program SHAKE are presented at Figure 9. for linear elastic and Figure 10. for nonlinear analyses.

The dynamic amplification factors (DAF) for linear - elastic analyses show relatively small variations for profile depths between 50 m to 80 m (which is expected range of real profile depths to bedrock) - for particular earthquake. The range of DAF's from app. 1.5 to 2.3 seems to be more influenced by frequency content of accelerograms than by profile depth or variations in shear velocities profile. E.g. for ACC2, which has dominant period around 0.45 sec, the maximal response (DAF) is for model profile with H=30 m and natural period T= 0.44 sec. On the other side, the results for ACC3 time history (shock type) are consistently lower since the dominant period of this time history is quite distant from the periods of the analyzed design/model profiles.

The results of nonlinear analyses are presented at Figure 10 as illustration only for one profile depth (H=50 m). The raise of maximal base acceleration induces higher stresses and strains in soil layers and consequently lowering of shear modulus and higher damping ratios.

As a result, the dynamic amplification factor is not constant (as in linear analyses), and it is higher for lower seismic input, and lower for high input accelerations. This is pronounced for ACC1 where the peak acceleration at the top of profile is almost equal (DAF=1) to base acceleration already for values of about a max base = 0.2 g. In the range of periods 0.2-0.8 this time history has pronounced peaks which highly affect the considered profile response.

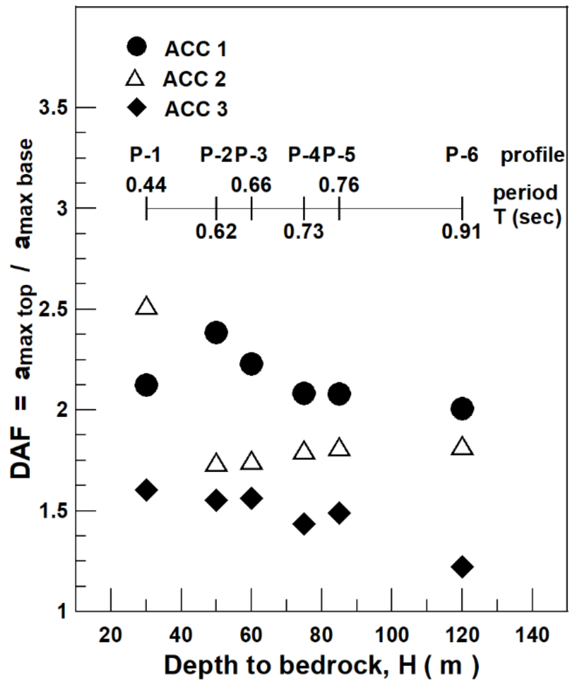

Figure 9. elastic analyses - dynamic amplification factors (DAF)

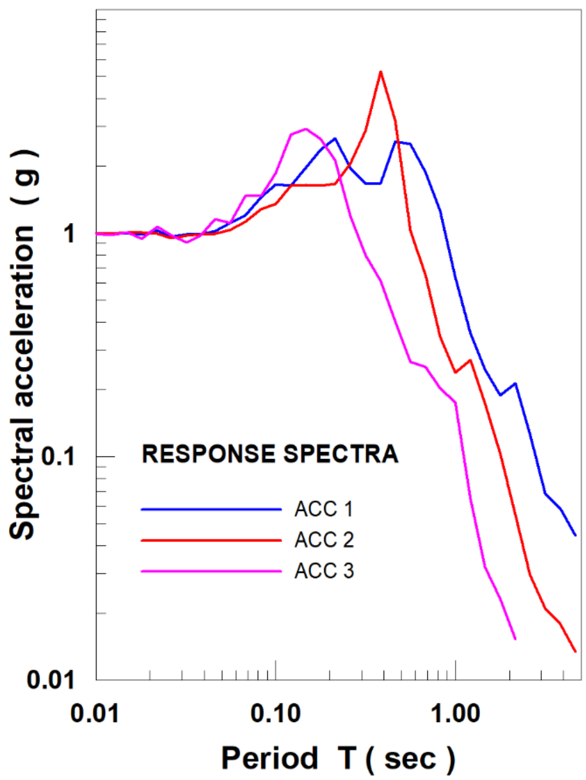

Figure 8. Normalized spectra of accelerograms used in the analyses

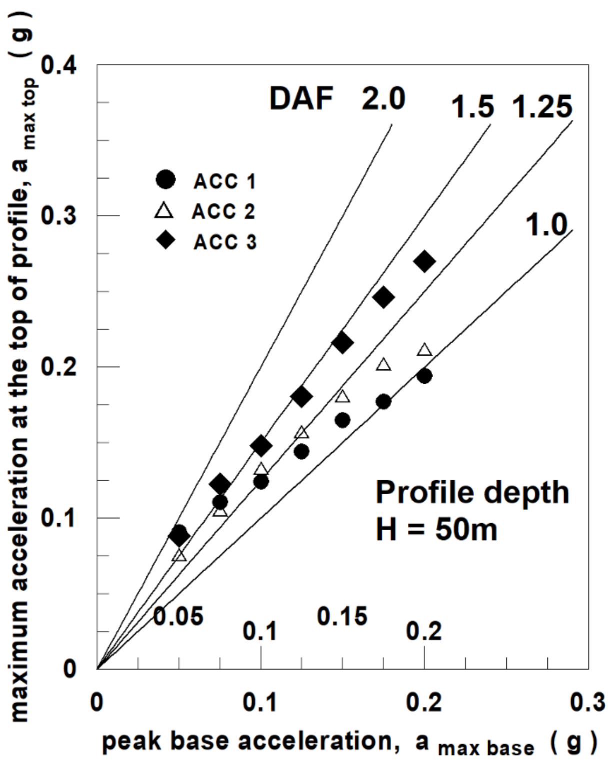

Figure 10. Nonlinear analyses - Calculated maximum soil accelerations at the top of the profile.

6 CONCLUSIONS

The comprehensive geological, geotechnical and geophysical investigations have been performed for the purpose of geotechnical (slope stability) characterization and seismic microzonation of northern, hilly, part of Zagreb. Along characteristic investigation profiles the detailed program of geotechnical investigations and geophysical measurements (down-hole, MASW) has been conducted on several boreholes. The depth of boreholes was 30-35m in order to obtain the relevant parameters for determining the zones of dominant soil type according to Eurocode 8 (EC-8, 2004). Most of the boreholes did not reach the base rock or hard soils with shear wave velocity v_s > 800m/s at the final boring depths.

The detailed investigations enabled the estimate of EC-8 soil types in the investigation area, and determination of appropriate parameters for further seismic analyses. However, the obtained data did not cover the appropriate extent (depths) to enable the calibration/comparison of EC-8 design amplification factors or other aspects of seismic site response, with other established appropriate procedures.

Preliminary seismic 1-D response analyses were performed in parametric way with alternative assumed seismic design profiles in order to estimate the sensitivity of final results (DAF) to input parameters. It is shown (as expected) that in these, more detailed, analyses, the deeper design profile affects the final results depending on matching of the dominant periods of soil profile and spectral characteristics of design accelerations.

Although the data from upper 30 m of soil profile (according to procedures in Eurocode 8) are enough for rough estimates of seismic free field input parameters, more detailed seismic analyses should be made with geotechnical data for the „full“ soil deposits profile from surface to base rock. For that reason, one of the main concerns for future investigation of seismic characteristics of geomorphological unit III (River Sava area with hilly steam and sediment zone) should be to determine base rock depth (at least to the depth of material with v_s>800 m/s).

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