

Primljen / Received: 23.6.2020.

Ispravljen / Corrected: 30.10.2020.

Prihvaćen / Accepted: 3.11.2020.

Dostupno online / Available online: 10.11.2020.

# Geotechnics as an unavoidable segment of earthquake engineering

## Authors:



Assit.Prof. **Mario Bačić**, PhD. CE  
University of Zagreb  
Faculty of Civil Engineering  
[mario.bacic@grad.unizg.hr](mailto:mario.bacic@grad.unizg.hr)  
Corresponding author



Prof. **Tomislav Ivšić**, PhD. CE  
University of Zagreb  
Faculty of Civil Engineering  
[tomislav.ivsicc@grad.unizg.hr](mailto:tomislav.ivsicc@grad.unizg.hr)



Prof. **Meho Saša Kovačević**, PhD. CE  
University of Zagreb  
Faculty of Civil Engineering  
[meho.sasa.kovacevic@grad.unizg.hr](mailto:meho.sasa.kovacevic@grad.unizg.hr)

Subject review

**Mario Bačić, Tomislav Ivšić, Meho Saša Kovačević**

## Geotechnics as an unavoidable segment of earthquake engineering

A broader overview of the role of geotechnics in earthquake engineering is given, and a set of practical examples of the quantification of geotechnical seismic indicators for construction of individual buildings is provided. An overview of oncoming changes to the current design standards for evaluating the effect the soil has on buildings in earthquake conditions is also given. Considering the level of seismic activity in Croatia, the need for adopting a comprehensive approach to seismic microzoning is emphasized, which involves a whole array of indicators, from lithological, engineering geological, and hydrogeological properties, and position of active faults, to identification of unstable slopes and zones of pronounced liquefaction potential, for which extensive geophysical and geotechnical investigations are required.

### Key words:

geotechnics, amplification of seismic excitation, liquefaction, landslide, seismic microzoning

Pregledni rad

**Mario Bačić, Tomislav Ivšić, Meho Saša Kovačević**

## Geotechnika kao nezaobilazan segment potresnog inženjerstva

Ovaj rad daje širi pregled uloge geotehnike u potresnom inženjerstvu te obuhvaća niz praktičnih primjera kvantifikacije geotehničkih seizmičkih pokazatelja za potrebe izgradnje pojedinih objekata, kao i osvrt na nadolazeće promjene u sadašnjim projektnim normama koje evaluiraju utjecaj tla na građevine u potresnim uvjetima. S obzirom na seizmičku aktivnost područja Hrvatske, istaknuta je nužnost sveobuhvatnog pristupa seizmičkom mikrozoniranju koji uzima u obzir čitav niz pokazatelja, od litoloških, inženjerskogeoloških i hidrogeoloških karakteristika te položaja aktivnih rasjeda, do identifikacije nestabilnih padina i zona izraženog likvefakcijskog potencija, za što je potrebna provedba opsežnih geofizičkih i geotehničkih istraživanja.

### Ključne riječi:

geotehnika, amplifikacija seizmičke pobude, likvefakcija, klizanje tla, seizmičko mikrozoniranje

Übersichtsarbeit

**Mario Bačić, Tomislav Ivšić, Meho Saša Kovačević**

## Geotechnik als unvermeidliches Segment der Erdbebentechnik

Diese Arbeit bietet einen umfassenden Überblick über die Rolle der Geotechnik in der seismischen Technik und enthält eine Reihe praktischer Beispiele für die Quantifizierung geotechnischer seismischer Indikatoren für den Bau einzelner Objekte sowie einen kurzen Einblick in die bevorstehenden Änderungen der aktuellen Planungsnormen, mit denen die Auswirkungen des Bodens auf Gebäude unter seismischen Bedingungen bewertet werden. In Anbetracht der seismischen Aktivität in Kroatien wird die Notwendigkeit eines umfassenden Ansatzes für die seismische Mikrozonierung hervorgehoben, der eine Reihe von Indikatoren berücksichtigt, von lithologischen, technisch-geologischen und hydrogeologischen Merkmalen sowie der Position aktiver Verwerfungen bis hin zur Identifizierung instabiler Hänge und Zonen mit ausgeprägtem Verflüssigungspotential, wofür umfangreiche geophysikalische und geotechnische Untersuchungen notwendig sind.

### Schlüsselwörter:

Geotechnik, Verstärkung der seismischen Anregung, Verflüssigung, Erdbeben, seismische Mikrozonierung

### 1. Introduction

An earthquake is a result of release of a huge quantity of energy due to movement of plates in the Earth's crust, occurring at considerable depths and constituting a geohazard of great destructive power, with severe consequences to people and structures on the ground surface [1]. Despite an extensive literature dealing with the genesis of earthquakes [2, 3] and with the role of geotechnics in earthquake engineering [4, 5], the fact remains that earthquakes are most often placed into focus only after significant earthquake events. However, as earthquake engineering, together with its geotechnical part, is a discipline that is "still learning", every new stronger earthquake in the world brings additional knowledge, and often also encourages changes in engineering practice and regulations [6]. In addition, an increasing number of seismic records, and development of instruments, improve the database for determination of seismic activity, while also enabling a more objective determination of seismic input for engineering applications. The last stronger earthquake that hit Zagreb in March 2020 [7] has revealed that, despite knowledge and capacities of the scientific and professional community, practical implementation of this knowledge is most often lacking, primarily because of insufficiently regulated laws and regulations. This is mostly the consequence of the earthquake being perceived as an "abstract" hazard, something that is quite opposite to "real/visible" hazards such as floods, landslides, fires, etc. For that reason, an integrated approach to deal with the earthquake, its causes and its consequences, is generally inexistent, although the estimation of earthquake hazard and its effect on structures, including also its geotechnical part, is an obligatory portion of civil engineering design that is in Croatia covered by Eurocode 8 [8]. In this standard, just like in earlier seismic regulations (especially for highly significant structures with pronounced safety aspects, such as power facilities like nuclear power plants or LNG terminals, large dams or bridges), the need for further development of seismic design criteria properly suited to individual localities is emphasized, and it is furthermore specified that these criteria must take into account local geology, seismicity, geotechnical conditions, and nature of the project.

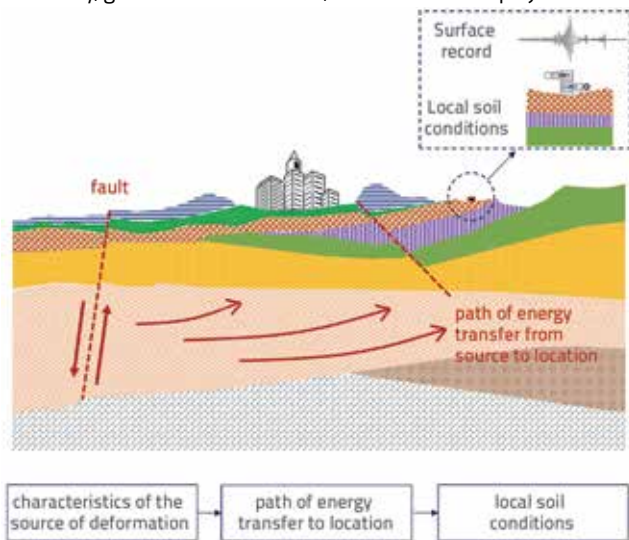


Figure 1. Propagation of seismic waves from focus to building location

Figure 1 shows the path taken by seismic waves from the earthquake focus (source) deep in the Earth's crust, through geological formations in the underground, to the foundation soil at the location of the building and, finally, to the ground surface where ground motions are manifested as actions affecting buildings and infrastructure. Displacements on the ground surface are the consequence of the propagation and modification of waves along the entire above mentioned route.

Properties of the source and path taken to a particular site are generally considered in the scope of seismology and structural geology, while local soil conditions are considered within the engineering geology and geotechnics. Geotechnics considers soil deposits above the bedrock as being a "structure" which – after the seismic excitation from the underground – has its response and dominant motion patterns, and which is formed by material of recognisable mechanical (stiffness, hardness, damping) and hydraulic properties. The soil motion response spectrum is also defined by relative influences of spectral properties of the source of earthquake in a particular region and by attenuation properties of geological materials that transfer seismic waves from the bedrock to the building location. Geotechnical circumstances at a particular construction site, which have to be determined or estimated during investigation works, are:

- a) foundation soil profile
  - response of local soil to the propagation of seismic waves from the bedrock to the ground surface (amplification and modification or response spectrum)
  - occurrence of dynamic instabilities of soil (liquefaction) and excessive settlement
- b) global stability of the location: presence of active faults and unstable slopes
- c) increase of earth pressure imposed on foundations, support structures, earth-filled structures and buried structures due to earthquake action

### 2. Amplification of seismic response as a consequence of local soil conditions

On their way from the focus toward the ground surface, seismic vibrations are greatly altered as to their amplitude and spectral composition, which is dominantly caused by local engineering geological conditions in soil, including the thickness of sediments and ground water level, as shown in Figure 2.

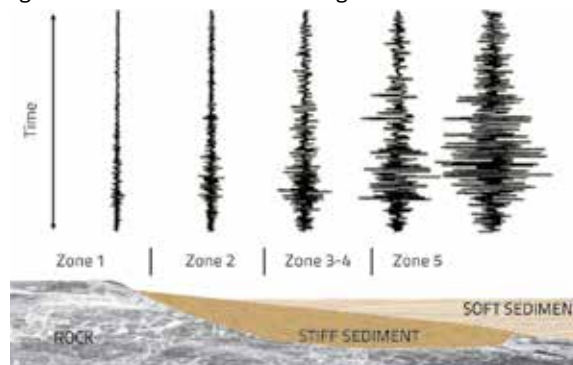


Figure 2. Amplification of seismic excitation dependent on local soil conditions, modified from [9]

The amplification (increase) of seismic excitation at the ground surface is due to the difference in impedance between surface layers of soil and the bedrock, which constitutes the resistance to the vibration of soil particles. The amplification of seismic excitation is also influenced by wave amplitude damping as caused by inelasticity and heterogeneity of the system.

To estimate amplification of seismic waves due to their propagation from the focus toward the ground surface, it is necessary to adequately define the geotechnical seismic model, which requires knowledge of the velocity of shear waves of characteristic layers, soil density in layers, and nonlinear relationships of shear modulus and damping with shear strain. It is also necessary to determine the profile depth down to the bedrock (characterized by shear wave velocities greater than 800 m/s). The determination of these values requires an extensive programme of geotechnical investigations with various geophysical measurements down to greater depths, and appropriate laboratory testing.

The shear modulus of soil at very small strains ( $G_0$  or  $G_{max}$ ) is determined as a product of the square of shear wave velocity ( $v_s$ ) and soil density ( $\rho$ ). Typical nonlinearities of normalised shear modulus and damping of soil material, in relation to the level of cyclic shear strain values determined in laboratory, are shown in Figure 3. Moderate and stronger earthquakes induce shear strains in soil greater than  $10^{-2}\%$ , thus being in the area of highly pronounced nonlinearity and increase in pore pressure.

Once the geotechnical soil model is formed, with the defined seismic excitation and the use of one-dimensional analysis of propagation of seismic waves, the dynamic amplification factor (DAF) can be determined as a ratio of peak soil acceleration at ground surface to input peak base acceleration. Many commercially available programs that are based on the one-

dimensional analysis of propagation of shear waves, such as SHAKE [11] or DEEPSOIL [12], enable realisation of the convolution procedure, which is a conventional analysis of seismic response of soil. However, limitations of these programs in the simulation of complex soil conditions prevent the use of advanced analyses of amplification of seismic excitation.

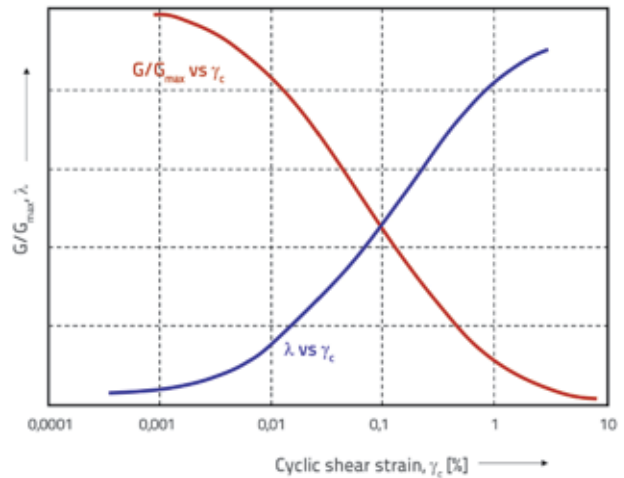


Figure 3. Nonlinear relations between shear modulus and soil damping depending on cyclic shear strain ( $G$  – shear modulus,  $\lambda$  – damping), modified from [10]

An example of seismic amplification assessment for the design and construction of the future bulk cargo terminal in the Port of Osijek is presented below. Several assumed design profiles of shear wave velocities ( $v_s$ ) at the site under study are shown in Figure 4a. Greater number of the assumed profiles is the result of the use of various geophysical test methods (ReMi,

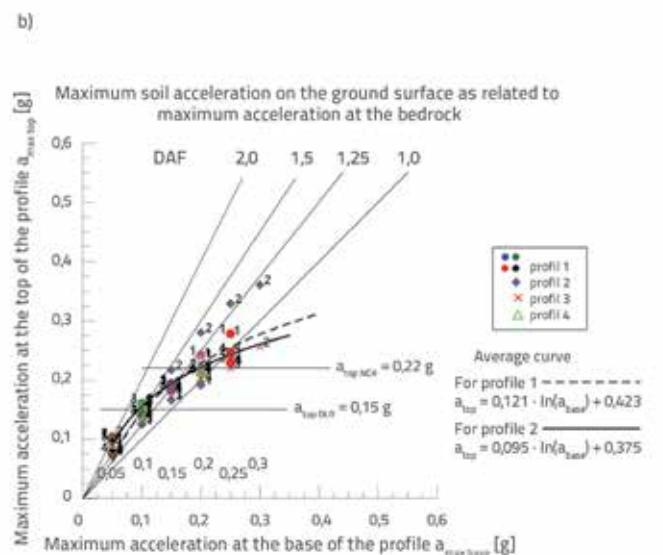
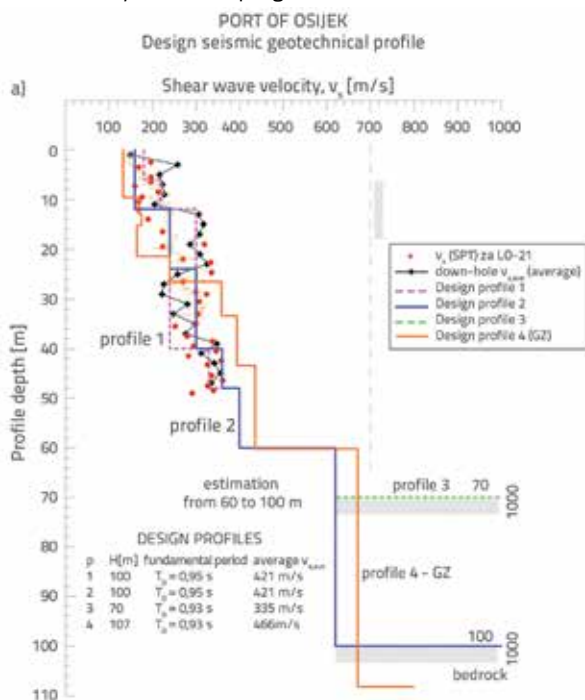


Figure 4. Dynamic testing at Osijek Port locality: a) design seismic geotechnical profiles; b) seismic response analysis with DAF calculation, adopted from [6]

Table 1. Ground types according to actual version of EN 1998-1, according to [14]

Ground type	Description of stratigraphic profile	$v_{s,30}$ [m/s]	$N_{SPT}$ (n / 30cm)	$c_u$ [kPa]	Amp. factor S
A	Rock or other rock-like geological formations, including at most 5 meters of weaker material at the surface	> 800	-	-	1.00
B	Deposits of very dense sand, gravel, or very stiff clay, at least several tens of metres in thickness, characterised by a gradual increase of mechanical properties with depth.	360 - 800	> 50	> 250	1.20
C	Deep deposits of dense or medium-dense sand, gravel or stiff clay with thickness from several tens to many hundreds of metres.	180 - 360	15 - 50	70 - 250	1.15
D	Deposits of loose-to-medium cohesionless soil (with or without some soft cohesive layers), or of predominantly soft-to-firm cohesive soil.	< 180	< 15	< 70	1.35
E	A soil profile consisting of a surface alluvium layer with $v_s$ values of type C or D and thickness varying between about 5 m and 20 m, underlain by stiffer material with $v_s > 800$ m/s.				1.40
S1	Deposits consisting, or containing a layer at least 10 m thick, of soft clays/silts with a high plasticity index ( $PI > 40$ ) and high water content	< 100		10 - 20	
S2	Deposits of liquefiable soils, of sensitive clays, or any other soil profile not included in types A – E or S <sub>1</sub>				

downhole), and correlations with in-situ SPT and CPT tests, as well as the fact that the drilling depth (50 m) was not sufficient to attain the “seismic” bedrock depth ( $v_s > 800$  m/s). According to design profiles estimated in this way, the DAF values were calculated using the SHAKE software (cf. Figure 4b), where the DAF for higher initial accelerations of the profile base is lower than that for lower initial seismic accelerations, which is due to nonlinear behaviour of soil. The nonlinearity of average curves presented in the figure is in accordance with the amplification analysis results obtained at numerous earthquake events worldwide, as presented in [13].

The influence of local ground conditions on the amplification of seismic excitation is also covered by the current version of the standard for the design of structures, Eurocode 8 – Part 1 [14], where various ground types are defined and, for each type, relevant linear response spectra are defined as an input data for seismic analysis of structures. Ground types are associated with amplification factors, Table 1, which are usually relevant for small seismic accelerations.

The selection of an appropriate spectrum is made for various types of ground which are estimated as a “compromise” based on the data for the top 30 m of the profile. These data mostly comprise an average velocity of shear waves determined by geophysical methods or, alternatively, the data on undrained strength of soil or on the number of blows during the in-situ SPT testing. The current version of this standard recommends the velocity  $v_{s,30}$ , which is defined as:

$$v_{s,30} = \frac{30}{\sum_{i=1}^N \frac{h_i}{v_i}} \tag{1}$$

where  $h_i$  [m] and  $v_i$  [m/s] are the layer thickness and the velocity of shear waves (at shear strain of  $10^{-5}$  or less) for the  $i$ -th layer, respectively, while  $N$  is the total number of layers in the top 30 m of soil.

However, in this currently valid version of the standard, some descriptions of soil types are insufficiently accurate, e.g. regarding the total depth of soil layers or for profiles that have changes in the type of soil along the depth. This is usually ignored in standard practice and only an average velocity of shear waves in the first 30 m is most often used. Such a simplified formal approach does not enable a full geotechnical characterisation of soil layers on the location under dynamic conditions, especially in the case of presence of loose or softer types of soil. For instance, current definition of category A soil reads as follows “rock or other rock-like geological formations, including at most 5 meters of weaker material at the surface”, without defining what the term “weaker material” means. The soil that is composed of very weak deposits up to 5 m in thickness underlain by rock material will, as a rule, not behave in the same way as a stiffer layer, which will result in different linear spectra. The need for improving the soil type characterisation, as compared to that given in the standard, is expressed by Pitilakis et al. [15] who use, in their research, more than 3000 ground motion records from 536 locations all over the world. In order to propose new elastic response spectra and amplification factors, in addition to traditional geotechnical parameters such as the undrained strength, number of SPT blows or plasticity index, the authors use fundamental period of the location, thickness of deposits on the location, and average velocity of shear waves. In response to criticism of the existing soil categorisation, the new generation of Eurocode 8, which is currently intensively prepared and whose implementation is expected in the forthcoming years, the problem of soil categorisation is approached in a somewhat different way, i.e. by replacing the velocity  $v_{s,30}$  with velocity  $v_{s,H}$  which is defined as follows:

$$v_{s,H} = \frac{H}{\sum_{i=1}^N \frac{h_i}{v_i}} \tag{2}$$

where  $N$  is now the total number of layers from the ground surface to the depth  $H$ , and the depth  $H$  itself is defined as:

**Table 2. Proposed change in soil type categorisation according to new version of EN 1998-1, according to [16]**

Depth	Type of soil	Stiff	Medium	Soft
	$H_{800}$ range / $v_{s,H}$ range	$800 \text{ m/s} > v_{s,H} \geq 400 \text{ m/s}$	$400 \text{ m/s} > v_{s,H} \geq 250 \text{ m/s}$	$250 \text{ m/s} > v_{s,H} \geq 150 \text{ m/s}$
Very shallow	$H_{800} \leq 5 \text{ m}$	A	A	E
Shallow	$5 \text{ m} < H_{800} \leq 30 \text{ m}$	B	E	E
Medium	$30 \text{ m} < H_{800} \leq 100 \text{ m}$	B	C	D
Deep	$H_{800} > 100 \text{ m}$	B	F	F

$H = 30 \text{ m}$  if  $H_{800} \geq 30 \text{ m}$  (when  $v_{s,H}$  becomes  $v_{s,30}$ )

$H = H_{800}$  if  $H_{800} < 30 \text{ m}$ ,

where  $H_{800}$  is the depth of the rock that is identified with  $v_s$  greater than 800 m/s. If the information on  $H_{800}$  is not defined through direct measurement, it can be estimated from the resonant eigenfrequency of soil  $f_0$ , determined using the method for measuring microseismic noise, i.e. the so called HVSR (Horizontal-to-Vertical Spectral Ratio) method.

Based on the above, the soil type categorisation as given in Table 2 is proposed in accordance with [16].

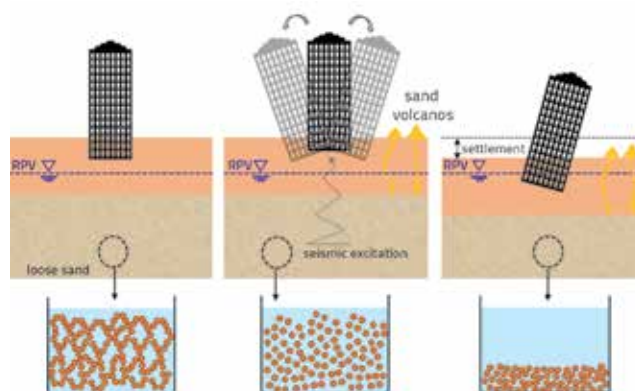
For instance, it can be seen in Table 2 that, for the very shallow position of rock (as material with  $v_s > 800 \text{ m/s}$ ) and in the case of soft deposits in the top 5 m, the soil is classified as type E, rather than as type A as it would be classified according to the current version, and hence the amplification factor  $S$  is much greater. The question remains whether these changes will be implemented in the final version of the new generation Eurocode 8 in the present form (Table 2) or in a somewhat modified form. In any case, the presented proposal is an indicator that the issue of characterization of soil types, as "amplifiers" of seismic excitation, will be elaborated more correctly.

### 3. Soil instabilities under seismic conditions and their evaluation

In addition to determining relevant linear spectrum based on soil type, which serves as input for seismic analysis of structures, it is equally important to evaluate the possibility of occurrence of soil instabilities resulting from earthquake action, including soil liquefaction and instabilities such as formation of landslides and earth/rock falls.

#### 3.1. Soil liquefaction

Soil liquefaction is a natural phenomenon that occurs in water saturated granular materials during strong shaking, usually during strong earthquakes. Popularly speaking, sand layers below the ground water level are suddenly and temporarily converted into a dense liquid (they "liquefy"), losing in this process their shear strength and the ability to support building foundations, Figure 5. Due to earthquake action, which occurs as a rapid cyclical load, the soil does not have the possibility of draining water, and hence reaches an undrained state which is characterised by an increase in pore pressures as a consequence of prevented change in volume [17].



**Figure 5. Schematic of three typical phases of liquefaction due to cyclic earthquake action**

The soil liquefaction phenomenon therefore implies simultaneous occurrence of two factors:

- Soil material susceptible to liquefaction saturated with ground water. The most susceptible material is loose, clean, fine sand, while the occurrence of liquefaction in gravels is very rare, practically unbelievable, and it also has not been encountered in coherent materials such as silts and clays. In fact, the presence of fine particles in sand even somewhat increases resistance to liquefaction. Furthermore, liquefaction most frequently occurs in the top 12-15 m of the soil profile;
- Earthquake of appropriate magnitude represented with maximum (peak) seismic acceleration.

Cases of liquefaction registered worldwide show that its occurrence at the same location is very irregular, and that it probably also depends on other details in the foundation soil profile. In practical situations, liquefaction manifests itself as a loss of bearing capacity of foundations, excessive horizontal and vertical deformations, and overturning or inclination of buildings. Lateral displacements, i.e. soil spreading phenomena, also affect support structures (most often coastal ones), and landslides may also occur on sloping terrain. A known figure from international literature is that of the 1964 Niigata (Japan) earthquake where inclined buildings on liquefied soil can be seen, Figure 6. The structures of these buildings were solidly dimensioned and remained practically undamaged by the loss of bearing capacity of soil, but their functionality was lost due to unstable foundation soil.



Figure 6. Inclined buildings on liquefied soil in Niigata (Japan) following the 1964 earthquake event, adopted from [18]

Laboratory testing can offer a more detailed insight into liquefaction potential of a material, i.e. the data about its cyclic undrained behaviour and, therefore, adequate information can be obtained about soil parameters for complex numerical models in effective stresses. Soil compaction at cyclical load, as well as an increase in pore pressure, are determined experimentally in cyclic drained or undrained tests with controlled shear strain ( $\gamma$ ) or with controlled shear stress that is expressed through the ratio of applied shear and mean stress, i.e. through the so called CSR (cyclic stress ratio). As practical application of complex numerical models is limited, routine evaluations of liquefaction potential of soil are based on a simplified method involving in situ testing (SPT or CPT) or on empirical diagrams, the so called liquefaction diagrams [19], which are occasionally updated.

The use of such liquefaction diagrams can be illustrated by an example of the Port of Ploče where liquefaction potential was estimated for the location of the bulk cargo terminal [6]. The basic objective of this assessment was to determine, based on the measured number of SPT blows from eight exploratory boreholes, which surface acceleration is critical, i.e. for which acceleration most soil profiles would be at the limit of liquefaction occurrence. The results for surface acceleration of 0.2g are shown in Figure 7. It can be seen that most results are at the left side of the limit CRR line, which means that the factor of safety is less than 1, i.e. that the soil is susceptible to liquefaction. As to the results given on the right side of the curves, they show that the soil is resistant to liquefaction. For the design acceleration of 0.3 g, which can be expected on this locality, the entire profile is practically susceptible to liquefaction.

By analysing the possibility of liquefaction on a larger scale, i.e. for the wider Zagreb area, Veinović et al. [20] concluded, based on the analysis of relevant data, that liquefaction could occur at earthquake magnitudes of more than 6.3. This macrozoning of liquefaction potential is based on a simplified zoning criteria according to ISSMGE (International Society for Soil Mechanics and Geotechnical Engineering) [21]. The authors indicate that establishment of a correlation between occurrence of liquefactions in the past and geological–geotechnical properties of the studied zone is highly important during estimation of liquefaction potential. The result of the investigation is a preliminary qualitative zoning map of the Zagreb area according to liquefaction potential. However, the authors [20]

themselves state that it can be used as a rough estimate only, and they propose guidelines that must be implemented to gain a more accurate insight into liquefaction potential.

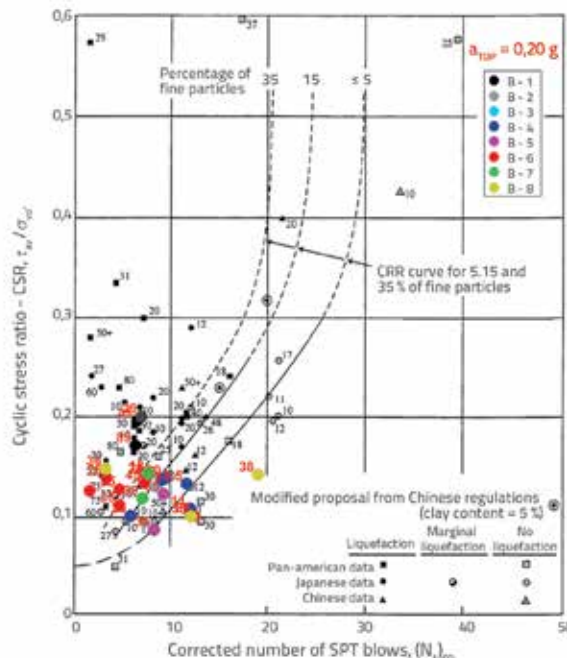


Figure 7. Estimation of liquefaction potential for the Port of Ploče based on the number of SPT blows, for the surface acceleration of 0.2 g, according to [6]

Although the best possible option is to avoid construction on soil for which a liquefaction potential has been established, there are many engineering solutions for preventing negative consequences in the case of an earthquake. This includes provision of adequate foundations properly adjusted to the soil susceptible to liquefaction, mostly in form of a deep foundations, or application of increasingly popular soil improvement methods (increase of compaction level and proper drainage). In the latter case, the most popular method involves use of gravel columns [22] in the scope of which these columns are installed by vibration thus increasing level of compaction of foundation soil while the columns, due to their high permeability, enable faster water drainage and reduction in liquefaction potential.

### 3.2. Activation of landslides

Earthquake action is one of possible landslide activation causes. The stability of slope is dependent on a number of factors such as its geometry, type of soil, ground water level, permanent and transient actions, etc. The estimation of slope stability is a demanding task already under static conditions, while in dynamic conditions the inertia loads increase, with a possible loss of shear strength of material due to cyclic load.

In recent times characterized by climate changes, landslides are becoming an increasingly alarming problem. Longer dry periods may cause occurrence of tensile cracks on the surface and the ensuing precipitation events, the number of which is generally

reducing while the intensity is increasing, can therefore saturate the soil quite easily [23]. A relatively smaller number of initiated, or at least registered, landslides after the March 2020 Zagreb earthquake can partly be explained by a relatively low saturation of soil at sites of greater landslide potential. An illustrative example of the destructive power of earthquakes is the Kumamoto magnitude 7.0 earthquake that occurred in April 2016 in Japan and caused activation of almost 3,500 landslides [24]. A large mass of sliding soil at Aso Bridge site, Figure 8, activated by seismic action, caused considerable damage to structures and infrastructure at the bottom of the slope.



Figure 8. Landslide activated after the magnitude 7.0 earthquake that hit Kumamoto in April 2016, adopted from [25]

Geotechnical analyses of slope stability under seismic conditions involve two possible approaches, the pseudo-static analysis of stability based on the factor of safety concept, and analysis of permanent deformation using the Newmark's sliding block approach. In pseudo-static analysis, the complex soil shaking is most often replaced with constant pseudo-static force which acts in one direction [26]. The factor of safety (FS) is used as a usual engineering measure for the stability of slopes. This factor represents the ratio of shear strength to shear stresses acting at the level of sliding surface. Under dynamic conditions, the seismic acceleration of soil – which brings the sliding mass of soil to a state of equilibrium ( $FS=1$ ) via an appropriate inertia force – is known as the yielding acceleration, and the latter should be defined separately for every location. Here the basic unknowns are the applied value of coefficient of seismic acceleration, and the value of the requested factor of safety with regard to sliding. The currently valid approach to the calculation of slope stability according to Eurocode 7 [27] comprises factorisation (reduction) of parameters of soil/rock material (the so called PP3 approach) and, at that, the standard itself does not differentiate partial factors of materials under static and seismic conditions, which often results in conservative design solutions, especially in areas characterised by high seismicity. There are some indications that the new generation of Eurocode 7 will introduce separate partial factors of materials for static and for seismic conditions. Seco e Pinto [28] stresses that pseudo-static methods should not be used for soils in which high pore pressures can be developed, nor in soils in which significant degradation of stiffness under cyclic load can be expected. On the other hand, the Newmark's theory [29], developed for evaluation of seismic stability of slopes, poses the question about

what if FS is lower than 1 and, if so, will this result in full collapse of the slope. If permanent deformation that occurred as a result of an earthquake action is within the limits of acceptability, then the collapse will not occur and, in this regard, numerous authors offer methods for the calculation of the mentioned permanent deformation [30-32]. Biondi and Maugeri [33] developed a modified Newmark's model for calculation of permanent displacement of natural slopes. This model includes the following possibilities: generation of pore pressures, time interval, calculation of cycles influencing cyclic degradation of soil, and calculation of critical acceleration degradation paths.

#### 4. Seismic microzoning: need for comprehensive approach

Microzoning is the separation of areas of the same or similar properties on detailed scale maps, which enables local differentiation of specific influences, or separation of a criterion under study [34]. From this aspect, microzoning of geohazards serves for rational spatial planning, and enables orientation of development toward areas of lower risk, or ensures that in riskier areas appropriate engineering measures are undertaken so that a satisfactory safety of people and their property can be provided. The mapping or zoning of seismic hazard at a local scale (such as 1:25,000 – 1:5,000) in order to include the effects of local soil conditions and time component, can be presented on seismic microzoning maps.

Figure 9 shows an illustrative example of "seismic microzoning on a real scale", where the correspondence between local soil conditions and the number and intensity of damage to structures after the 1979 earthquake can be seen for the old town of Dubrovnik. Here, a great number of buildings characterized by similar structure, height and age, are located in a relatively small area, and they differ in foundation soil: from the fill of variable thickness (ranging from 1 m to 7 m) south of Stradun to bedrock on the north side. Because of different local soil conditions, different levels of damage to buildings were noted for the same seismic action above the bedrock. The greatest damage was registered at buildings resting on the deepest fill material deposits.

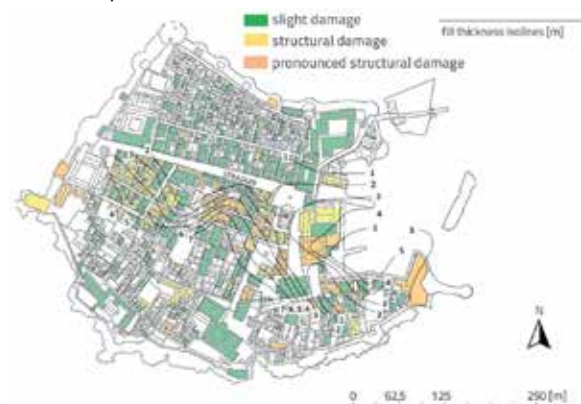


Figure 9. Isolines showing fill material thicknesses (ranging from 1 m to 7 m) in the Old Town of Dubrovnik, overlaid with the representation of damage to buildings after the 1979 earthquake, modified from [35]

In countries with a higher seismic hazard, there is a pressing need to conduct a comprehensive seismic microzonation, and so attempts are made to formalise a standard approach to seismic microzonation [21, 36, 37]. At that, the zoning primarily focuses on geotechnical phenomena caused by seismic action on the location and in foundation soil, such as the amplification and soil displacements, landslides and soil liquefaction [38]. According to ISSMGE [21], detailed geotechnical soil investigations are the basis for creation of high resolution seismic microzonation maps. Seismic microzonation maps developed in this way can then be used for creating design and construction policies, and for elaboration of emergency plans [39].

The geotechnical and seismic microzonation of the city of Zagreb has a long history [40]. The geozoning project based on modern principles was initiated already in 2004 through elaboration of the *Detailed engineering-geological map of the Podsljeme urbanised zone* on a scale of 1:5,000, Phase I (DIGK - Phase I) [41], while the DIGK - Phase II was completed in 2018 [42, 43]. Comprehensive geophysical and geotechnical investigations were conducted for the needs of this mapping. These projects comprise approximately 175 square kilometres of the Podsljeme urbanised zone, while the total area occupied by the City of Zagreb amounts to approximately 640 square kilometres [41-45]. In the scope of the mentioned partial mapping of the city (on a scale of 1:5,000), landslides and unstable slopes are especially singled out, while preliminary zones of soil types (A-D) based on the current Eurocode 8 [46] are also presented. As the zones of potential instabilities due to seismic action (liquefaction potential, evaluation of seismic stability of slopes) were not particularly marked out or overlaid, this zoning does not represent a full seismic microzonation according to the above-mentioned standards, and when the new version of Eurocode 8 is adopted, even these existing efforts will have to be revised. The mentioned efforts in the preparation of DIGK as invested in the city of Zagreb, resulted in publication of a part of these investigation on the web pages [47] of the City of Zagreb (e.g. map of tectonic activities, simplified map of landslides in the Podsljeme city district). The City of Zagreb is in fact the only city in Croatia that has a cadastre of landslides, which is a part of the geotechnical cadastre of the city of Zagreb, the latter being the central database for data related to soil and its properties [44]. The geo-zoning of other mostly plain parts of Zagreb is for now included in long-term plans.

A specific indicator of the condition of some landmark sites located in our regions are inter alia the churches which, after total collapse or great damage due to various reasons (fire, earthquake, war activities, etc.) are being traditionally rebuilt at very close microlocations or even on the very "foundations" or the buildings they are replacing. In Zagreb and its surroundings, there are many churches that have remained on the same spots for several centuries and that have suffered throughout their history both heavy damage or total collapse namely by earthquake action. Locations of some churches heavily damaged in the March 2020 earthquake are shown in Figure 10, i.e. which is a map showing tectonic activities and recent structural assembly of Medvednica and Zagreb. The southern part of Medvednica is situated in the

zone of the so-called Zagreb fault where the focuses of most earthquakes are situated, and boundaries of this zone (lines 1a and 1b) run through the Podsljeme urban zone (northern leg) and Sljeme foothills (southern leg) above Ilica and Maksimirska streets and Gornja Dubrava district [48]. The map also shows other important faults in this structural assembly (even outside of the city of Zagreb). Tectonically active parts of the structures and faults are presented in various colours. The presented faults are not always "visible cracks or lines" on the terrain, and are (mostly) not fully verified by deep underground investigations but rather they represent a narrow prognostic zone estimated on the basis of geological on-site indicators, topography, aerial photographs, and sporadic deep underground investigations.

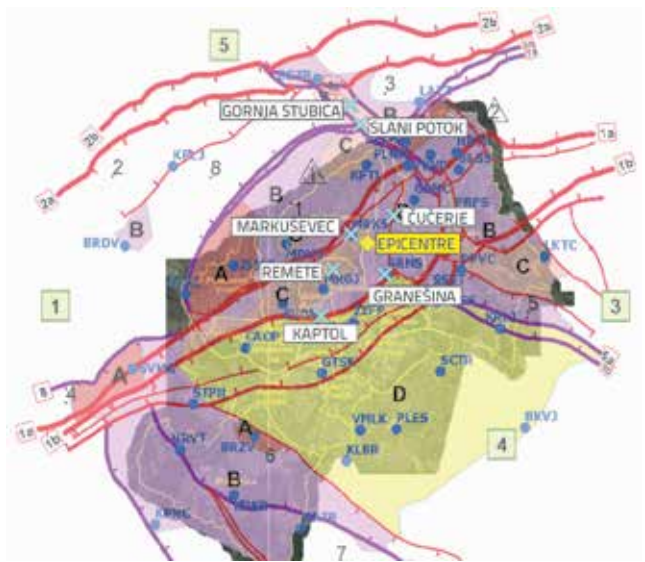


Figure 10. Locations of some churches damaged in the 2020 earthquake on the map of tectonic activities, basic map adopted from [47]

It can clearly be seen in Figure 10 that damaged churches are situated in the immediate vicinity of important faults both in Zagreb but also further to the north in Stubica area. Churches in Markuševac and Čučerje are situated practically in the epicentre of the earthquake. In the central part of Zagreb, damage was inflicted on the cathedral on Kaptol but also on other churches situated in nearby elevated locations (St. Mary, St. Francis and St. John churches on Kaptol and in Nova Ves, and St. Marc and St. Catherine churches on Grič). To the south, in a plane area (but still in the zone of the "Ilica fault") the churches in Palmotičeva and Frankopanska streets also suffered damage.

Most of the presented churches experienced earthquake generated collapses and heavy damage throughout their histories, registered in their annals, as shown for instance in [49, 50]. For example, earthquake due collapses of the church of Granešina were registered on several occasions since the 16<sup>th</sup> century. The church was heavily damaged in the 1880 Zagreb earthquake, and was rebuilt practically on the same spot. The tower suffered damage in the 1906 earthquake, and the church was greatly damaged in the last 2020 earthquake. Cracks due to tectonic movements





Figure 11. Locations of damaged churches: a) Church of Blessed Virgin Mary in Granešina on the detailed engineering-geological map adopted from [42]; b) church of Assumption of Blessed Virgin Mary in Remete and unstable nearby slopes, presented on the map adopted from [47]

were registered in the meantime on the church and on other nearby buildings. These cracks are the subject of recent geodetic measurements that are conducted in the scope of the geodynamic study of the city of Zagreb [51]. Figure 11a shows the site of the church in Granešina on the new detailed engineering geological map [42], where it can be seen that the church is located on an unstable slope (mark 1019), and that a "network" of smaller faults is situated in the vicinity of the church. Figure 11b shows the site of the damaged church located in Remete, which is also situated in the zone with several unstable slopes – marks 603, 608, 30029, etc. A situation quite similar to that of the described churches can be seen on the site of the church in Gorica Svetojanska, where several churches collapsed and were rebuilt in the past. It is only the new detailed investigations [52] that have revealed the fault which generates displacements in the foundation soil, and also causes instabilities along the slopes.

Such findings point to probable causes of building damage, which lie in geological phenomena within the foundation soil, rather than being only limited to structural weaknesses in the building. Repeated errors in the selection of site as committed in the past can be explained by the lack of knowledge but, at the present day and age, such errors should be neither acceptable nor permissible.

Extensive engineering geological, geophysical and geotechnical investigations are needed for the characterisation and a more accurate identification of the situation in the underground on unstable slopes or at sites with active faults. These data, together with those on the lithology and engineering geological and hydrogeological characteristics, would serve as basis for creation of the seismic microzonation map. The level of fault activity has not been equally investigated on all locations, and so these occurrences must be systematically investigated and registered during large-scope studies of wider areas, e.g. for microzonation or for infrastructure facilities. Sites of buildings of greater importance or belonging to cultural heritage must be investigated in detail and, if the described geological phenomena

are found, the buildings should be located away from possible greater cracks/faults and, if necessary, remedial measures should be taken for potentially unstable slopes.

## 5. Earthquake effects on geotechnical structures

Considering that shaking induces inertia forces that may result in the exceedance of some limit states of geotechnical structures, adequate consideration of these actions at the design stage is a precondition for obtaining a seismically safe geotechnical structure (foundations of buildings, embankments, retaining structures, tunnels). If this is neglected, an earthquake event may negatively affect the foundation system of buildings, such as for instance the foundation soil failure below foundations, or excessive soil deformations that may cause relative displacement of foundations with respect to the overlying structure. In the case of retaining structures, lateral seismic pressures may cause failure of the structure or its excessive displacements and, in the case of embankments, cracks may occur at the crown and local sliding may be registered. Of course, damage to geotechnical structures may also occur as a direct consequence of previously mentioned instabilities, where occurrences such as liquefaction or soil sliding may cause exceedance of limit states of geotechnical structures.

### 5.1. Foundations of structures

The behaviour of foundations under seismic conditions depends on the type of foundations, the way in which cyclic loading is applied, and on the type of soil and conditions in that soil. In the case of fine-grained soils, an excessive loss of strength generally does not occur due to cyclic load, which results in lower additional settlement, lateral displacements, or rotation of foundations. However, in the case of isolated footings and strip foundations realized in fine-grained soil, it is particularly significant to determine the bearing capacity of foundation soil

in undrained conditions, with careful quantification of undrained cohesion as a relevant parameter. On the other hand, due to cyclic shear load of dry sands, their volume is reduced, which may result in significant settlement of a shallow foundation structure, especially if the foundations have been realized in weakly compacted and loose sand. Liquefaction may occur in saturated sands, which results in significant settlement of soil after dissipation of additional pore pressure. It should also be noted that liquefaction might occur even after the shaking, in the post-earthquake period.

The effects of dynamic interaction between the soil and structure are often neglected during seismic design of structures. This neglect is usually explained by stating that the effects of dynamic interactions are favourable for most usual civil engineering structures, and that therefore their neglect is "on the side of safety". However, in some cases [8], such as in the case of foundations in weak soil, shallow foundations of tall buildings, or deep foundations, the analysis of the seismic soil-structure interaction must be made as its effects can be unfavourable.

In particular, deep foundations must be designed in such a way to provide resistance to the action of inertia forces of the overlying structure, and also to the action of kinematic forces which are the result of deformation of the surrounding soil [28, 53]. Although linear behaviour of soil is normally considered during analysis of seismic interaction, in some cases it is also necessary to consider geometrical and material nonlinearities of the system. Nonlinear analyses and the complexity of three-dimensional analyses of interaction between the deep foundations and soil system, complicate their practical implementation, and so the methods in which the problem is divided into several simple steps can be used. An example is the method proposed by Gazetas and Mylonakis [54]. In addition, a cyclic seismic action of earthquakes can lead to opening of gaps

near the surface of the terrain next to the pile itself, which was analysed by numerous authors [55]. Pender and Pranjoto [56] give an interesting account of this effect for railway bridge piles after the 1989 Loma Prieta earthquake, Figure 12.

In some cases, it can be very challenging, even for experienced geotechnical engineers, to detect causes of deformation and failure of a building after an earthquake, i.e. to determine whether the damage occurred as a result of exceedance of limit states of the foundation structure or as a result of exceedance of limit states of elements of the structure itself. Often the exceedance of limit states of the foundation system is attributed to structural elements, especially when causes of damage are dominantly estimated by visual inspection. Readers are advised to consult relevant literature [57] where a detailed account is given of forensic procedures for visual detection of cracks in structures that occur because of problems related to the foundation soil or foundation system. At that, useful information about the behaviour of geotechnical structures in seismic conditions can be obtained by installation of the monitoring equipment, where changes in measurement results (displacement, deformation, stress, pore pressures, etc.) may point to a limit state exceedance mechanism. In recent times, an advantage is increasingly given to advanced geodetic survey methods [58] where highly accurate remote monitoring and measurements can be used to determine the extent of deformation/displacement of foundation soil in greater areas, that occur as a result of seismic action.

## 5.2. Embankment structures

Sherard et al. [59] indicate that, as a rule, two types of damage can be differentiated in most earth structures – such as dams or embankments – when subjected to a stronger earthquake action:

- longitudinal cracks at the top of the dam,
- settlement of the dam crest.

This has also been confirmed in the research conducted by Oka et al. [60] who investigated damage patterns in a series of river embankments following the 2011. Tohoku earthquake in Japan. This magnitude 9.0 earthquake damaged numerous infrastructure facilities, and the damage to as many as 2,115 locations was registered on earthfill river embankments. A typical damage pattern is shown in Figure 13 where the earthquake load first causes settlement of the crest with the ground heave-along the embankment toe, which was followed by formation of longitudinal cracks along the crest and, finally, by fragmentation and failure of the embankment.



Figure 12. Gap next to the top of the pile resulting from cyclic load imposed on pile in clay, adopted from [56]

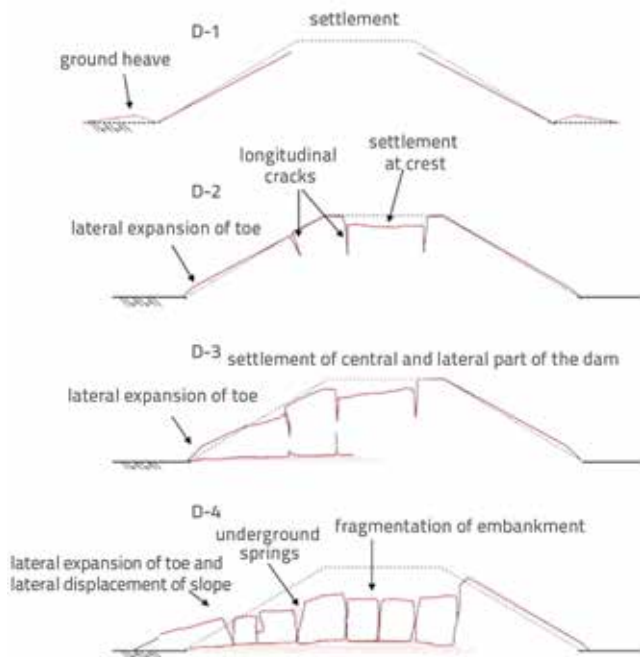


Figure 13. Phases of river embankment failure due to cyclic earthquake action, modified from [60]

To establish whether damage was incurred on levee (flood protection embankments) in the area of the city of Zagreb and in the Zagreb County as a result of the March 2020 earthquake, the employees of the Geotechnical Department of the Faculty of Civil Engineering – University of Zagreb conducted non-destructive specialist testing on 141 km of the Sava levees in sector C of the flood protection system (upper Sava reaches), at 21 retentions in the wider Zagreb area and at Maksimir embankments. In addition to specialist testing, *Croatian Waters* experts also conducted a detailed visual inspection. The method used for rapid assessment of the levee condition is the ground penetrating radar (GPR) method that has been successfully used nationally and internationally for estimating condition of a

variety of infrastructure facilities, including flood protection levees. The method is continuously being improved in the scope of the current international scientific project *oVERFLOW* [61] forming part of the EU Civil Protection programme, the coordinator of which is the mentioned Geotechnical Department of the Faculty of Civil Engineering. It is based on the emission of electromagnetic waves into the body of the levee via an appropriate antenna system and on reception of reflected waves, enabling – after data processing – establishment of a radargram [23], which then permits detection of potential damage that cannot be detected by visual inspection. As the frequency of the applied antenna defines the testing depth and testing resolution, which are inversely proportional (greater depth – smaller resolution, smaller depth – greater resolution), a multi-channel system with three (3) antennas is selected, with the following central frequencies: 100 MHz (up to 15 m in testing depth, with the resolution of 0.5 m), 250 MHz (up to 5 m in testing depth, resolution: 0.2 m), and 400 MHz (up to 4 m in testing depth, with the resolution of 0.125 m).

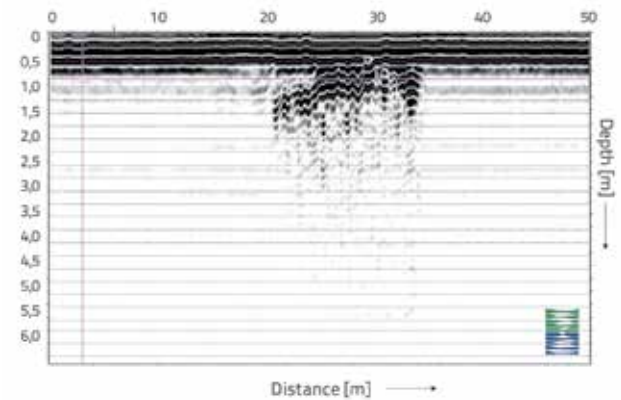


Figure 15. One of the radargrams from investigation of retention dam, after the March 2020 earthquake – visible reflex along the centre of the profile points to the presence of the retention dam gallery

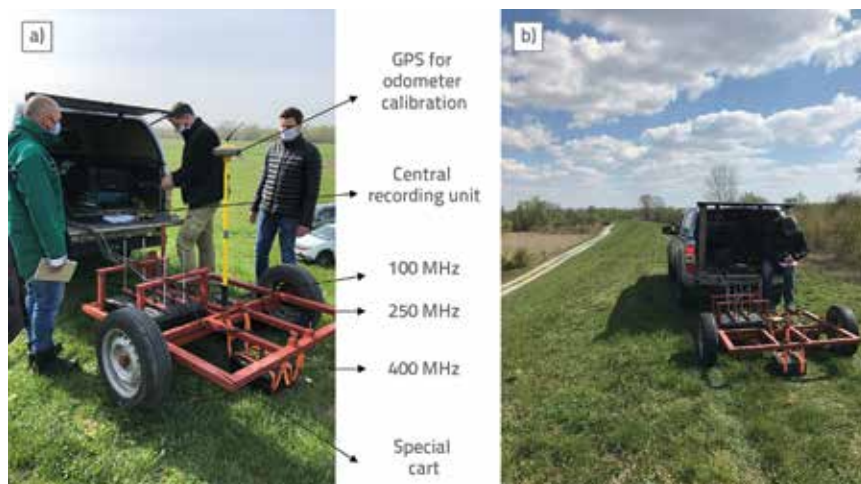


Figure 14. Data collection equipment (a), and collection of data (b) for assessment of possible damage to the Sava and levees in the City of Zagreb and the surrounding after the March 2020 earthquake

A cart specially built for this testing was connected to a car, which enabled faster collection of data, cf. Figure 14. Considering the possibilities of the method for detecting embankment structure (transition of layers, bottom of levee), localisation of disturbances (zones with loose material), identification of anomalies and non-homogeneities such as cavities and discontinuities, and for evaluation of integrity of the contact between soil and concrete galleries of retention dams, the GPR system was selected as an optimum first-pass method [62], which serves for preliminary estimation of damage. However, it is also necessary to highlight the limitations of the method in which highly saturated materials cause greater damping of electromagnetic signals. Considering the

non-uniformity of collected data, many numerical simulations were conducted prior to field testing to test behaviour of electromagnetic waves when encountering anomalies. Different anomaly types have been identified internationally on a number of levees in post-seismic period [63]. These simulations enabled evaluation of interpreted radargrams, such as the one shown in Figure 15, from the aspect of detection of earthquake-induced damage. The results showed that there was no significant reflection of electromagnetic waves emitted along the test profiles that would point to anomalies in the levee body, retentions and dams along their length, or at the contact between galleries and retention dams, resulting from seismic activity.

## 6. Conclusion

A comprehensive overview of the role of geotechnics in earthquake engineering is presented in the paper through a number of practical examples involving evaluation of the influence of physicommechanical properties of soil on the behaviour of seismic excitation, including also the influence of excitation on the soil liquefaction, landsliding, and other forms of instability and exceedance of limit states of geotechnical structures. The mentioned aspects require a more detailed characterisation and evaluation of geotechnical circumstances at individual locations, through implementation of comprehensive geotechnical and geophysical investigations, and the appropriate in-situ and laboratory tests. These investigations, assisted with further development of the seismic database, will

certainly increase the reliability of seismic analyses. In this way, unreasonable technical solutions, resulting from application of simplified design procedures, would greatly be avoided. At the same time, aware of deficiencies in the characterisation of soil types in the way covered by currently applicable standards for the design of seismically resistant buildings, the European engineering community is making efforts aimed at revising and improving the standard. The main objective of these efforts is to describe better and more rationally the behaviour of soil as a "structure" that has its response and dominant motions in the case of an earthquake excitation.

In the light of consequences of the March 2020 Zagreb earthquake, the emphasis is placed in this paper on the need to adopt a comprehensive approach to seismic microzonation, that would take into account a whole array of indicators, from lithologic, engineering-geologic and hydro-geologic properties and positions of active faults, to identification of unstable slopes and zones of pronounced liquefaction potential. Such seismic microzonation, which is in line with guidelines developed and implemented in a number of earthquake-prone countries with a high level of awareness of the earthquake as a "real" and "omnipresent" hazard, constitutes a step forward as related to the current commendable efforts aimed at achieving seismic microzonation of the city of Zagreb. A comprehensive approach to seismic microzonation that has to be implemented at the level of the entire Croatia, taking into account its pronounced seismic activity, would result in development of an informational database that could be used for creating appropriate design and construction policies.

## REFERENCES

- [1] Bell, F.G.: Geological hazards: Their assessments, avoidance and mitigation. E&FN Spon Press, London, pp. 648, 2003.
- [2] Elnashai, A.S., Di Sarno, L.: Fundamentals of Earthquake Engineering: From Source to Fragility, 2<sup>nd</sup> Edition, John Wiley & Sons, 2008.
- [3] Harris, R.A.: Earthquake stress triggers, stress shadows, and seismic hazard, *Journal of geophysical research*, 103 (1998) B10, pp. 24347 - 24358, <https://doi.org/10.1029/98JB01576>
- [4] Ishihara, K.: Soil Behavior in Earthquake Engineering, Clarendon Press, Oxford, UK, 350 p., 1996.
- [5] Towhata, I.: Geotechnical earthquake engineering, Berlin Heidelberg: SpringerVerlag, 698 p., 2008.
- [6] Ivšić, T.: Potresno djelovanje i geotehnika, 7. savjetovanje Hrvatskog geotehničkog društva, Varaždin, pp. 29-37, 2016.
- [7] Markušić, S., Stanko, D., Korbar, T., Belić, N., Penava, D., Kordić, B.: The Zagreb (Croatia) M5.5 Earthquake on 22 March 2020, *Geosciences*, 10 (2020) 7, ID 252, doi: 10.3390/geosciences10070252
- [8] EN 1998-5: Eurocode 8: Design of structures for earthquake resistance, Part 5: Foundations, retaining structures and geotechnical aspects, European Standard, CEN, Brussels, 2004.
- [9] Seville, E., Metcalfe, J.: Developing Hazard Risk Assessment Framework for the New Zealand State Highway Network, Land Transport New Zealand, Report no. 276., 80 p., 2005.
- [10] Vucetic, M., Dobry, R.: Effect of soil plasticity on cyclic response, *J. Geotech. Eng.*, 117 (1991) 1, pp. 89-107, [https://doi.org/10.1061/\(ASCE\)0733-9410](https://doi.org/10.1061/(ASCE)0733-9410)
- [11] Ordonez, G.A.: SHAKE - A Computer Program for the 1-D Analysis of Geotechnical Earthquake Engineering Problems, GeoMotions, LLC, Lacey, USA, 2012.
- [12] Hashash, Y., Park, D., Tsai, C.C., Phillips, C., Groholski, D.R.: DEEPSOIL - 1-D Wave Propagation Analysis Program for Geotechnical Site Response Analysis of Deep Soil Deposits, Tutorial and User Manual, University of Illinois, USA, 2016.
- [13] Idriss, I.M.: Response of Soft Soil Sites during Earthquakes, *Proceedings of the H. Bolton Seed Memorial Symp.*, Vol. 2, BiTech Publishers, Vancouver, pp. 273-290, 1990.
- [14] EN 1998-1. Design of structures for earthquake resistance - Part 1: General rules, seismic actions and rules for buildings. European Standard, CEN, Brussels, 2004.
- [15] Pitilakis, K., Riga, E., Anastasiadis, A.: Design spectra and amplification factors for Eurocode 8, *Bulletin of Earthquake Engineering*, 10(2012)5, pp. 1377-1400, <https://doi.org/10.1007/s10518-012-9367-6>
- [16] Labbe, P.: Outlines of the revision of the Eurocode 8, part 1 - generic clauses, 16<sup>th</sup> European Conference on Earthquake Engineering, Thessaloniki, Greece, 12 p., 2018.

- [17] Seed, H.B., Idriss, I.M.: Simplified procedure for evaluating soil liquefaction potential, *J Soil Mech Found Div*, 97 (1971) SM9, pp. 1249–1273
- [18] Seed, H.B., Idriss, I.M.: Analysis of Soil Liquefaction: Niigata Earthquake, *Journal of the Soil Mechanics and Foundations Division*, 93 (1967) 3, pp. 83–108
- [19] Idriss, I., Boulanger, R.: 2<sup>nd</sup> Ishihara Lecture: SPT- and CPT-based relationships for the residual shear strength of liquefied soils, *Soil Dynamics and Earthquake Engineering*, 68 (2015), pp. 57–68
- [20] Veinović, Ž., Domitrović, D., Lovrić, T.: Pojava likvefakcije na području Zagreba u prošlosti i procjena mogućnosti ponovne pojave tijekom jačeg potresa, *Rudarsko-geološko-naftni zbornik*, 19 (2007), pp. 111–120.
- [21] ISSMGE (International Society for Soil Mechanics and Geotechnical Engineering): Manual for zonation on seismic geotechnical hazards. The Japanese Geotechnical Study, International Society for Soil Mechanics and Geotechnical Engineering, 209 p., 1999.
- [22] Ranjbar, N., Choobbasti, A.J.: Mitigation of Liquefaction Using Stone Columns, *Journal of Geotechnical Engineering*, 13 (2008), Bund. F, 9 p.
- [23] Kovačević, M.S., Bačić, M., Stipanović, I., Gavin, K.: Categorization of the Condition of Railway Embankments Using a Multi-Attribute Utility Theory, *Applied Sciences-Basel*, 9 (2019) 23, ID 5089, doi:10.3390/app9235089
- [24] Xu, C., Ma, S., Tan, Z., Xie, C., Toda, S., Huang, X.: Landslides triggered by the 2016 7.3 Kumamoto, Japan, earthquake, *Landslides*, 15 (2018) 3, pp. 551–564, <https://doi.org/10.1007/s10346-017-0929-1>
- [25] URL: [www.mainichi.jp](http://www.mainichi.jp), 09.09.2020.
- [26] Terzaghi, K.: Mechanism of landslides, *Application of Geology to Engineering Practice (Berkey Volume)*, Geological Society of America, S. Paige (Ed.), New York, pp. 83–123, 1950.
- [27] EN 1997-1: Eurocode 7: Geotechnical design - Part 1: General rules, European Standard, CEN, Brussels, 2004.
- [28] Seco e Pinto, P.S.: Interaction between Eurocode 7 – geotechnical design and Eurocode 8 - design for earthquake resistance of foundations, *Proceedings of 2nd International Conference on Geotechnical Engineering for Disaster Mitigation and Rehabilitation*, (Eds.: Liu, H.L., Deng, A., Chu, J.), Springer, Beijing, pp. 37 – 65. 2008.
- [29] Newmark, N.M.: Effects of earthquakes on dams and embankments, *Geotechnique*, 15 (1965), pp. 139–159
- [30] Makdasi, F.I., Seed, H.B.: Simplified procedure for estimating dam and embankment earthquake-induced deformations, *ASCE Journal of the Geotechnical Engineering Division*, 104 (1978), pp. 849–86
- [31] Ambraseys, N.N., Menu, J.M.: Earthquake-induced ground displacements, *Earthquake Engineering and Structural Dynamics*, 16 (1988), pp. 985–1006
- [32] Yegian, M.K., Marciano, E.A., Ghahraman, V.G.: Earthquake-induced permanent deformations: probabilistic approach, *Journal of Geotechnical Engineering*, 117 (1991), pp. 35–50
- [33] Biondi, G., Maugeri, M.: Seismic response analysis of Monte Po hill (Catania), *Advances in Earthquake Engineering*, 14 (2005), pp. 177–195. <https://doi.org/10.2495/1-84564-004-7/10>
- [34] Fell, R., Corominas, J., Bonnard, C., Cascini, L., Leroy, E., Savage, W.Z.: Guidelines for landslide susceptibility, hazard and risk zoning for land use planning, *Engineering Geology*, 102 (2008) 3–4, pp. 85–98, <https://doi.org/10.1016/j.enggeo.2008.03.022>
- [35] Zavod za obnovu Dubrovnika: I. faza plana upravljanja - metodologija i baze podataka, [www.zod.hr](http://www.zod.hr), 12.09.2020.
- [36] GDDA (General Directorate of Disaster Affairs): Seismic Microzonation for Municipalities – Manual, Republic of Turkey, Ministry of Public Works and Settlement, General Directorate of Disaster Affairs, pp. 137., 2004.
- [37] SM Working Group: Guidelines for Seismic Microzonation, Conference of Regions and Autonomous Provinces of Italy – Civil Protection Department, Rome, 2015.
- [38] Mihalić, S., Oštrić, M., Krkač, M.: Seismic microzonation: A review of principles and practice, *Geofizika*, 28 (2011), pp. 5–20.
- [39] Levson, V.M., Monahan, P.A., Meldrum, D.G., Watts, B.D., Sy, A., Yan, L.: Seismic microzonation in the Pacific Northwest, with an example of earthquake hazard mapping in Southwest British Columbia, in *A paradox of power; voices of warning and reason in the geosciences*, (Eds.: Welby, C.W., Gowan, M.E.), *Reviews in Engineering Geology*, 12 (1998), pp. 75–88.
- [40] Jurak, V., Ortolan, Ž., Ivšić, T., Herak, M., Šumanovac, F., Vukelić, I., Jukić, M.: Geotehničko i seizmičko mikrozoniranje grada Zagreba - pokušaji i ostvarenje, *Zbornik radova konf. Razvitak Zagreba*, (ur. Radić, J.), Zagreb: SECON HDGK, pp.99–108, 2008.
- [41] Miklin, Ž., Mlinar, Ž., Brkić, Ž., Hečimović, I.: Detaljna inženjerskogeološka karta Podsljemenske urbanizirane zone mjerila 1:5000 (DIGK-Faza I), Hrvatski geološki institut, Knjige 1-4, Zagreb, 2007.
- [42] Miklin, Ž., Podolszki, L., Novosel, T., Sokolić, Ž., Sokolić, I., Ofak, J., Padovan, B., Zailac, K.: Detaljna inženjerskogeološka karta Podsljemenske urbanizirane zone mjerila 1:5000 (DIGK-Faza II), Hrvatski geološki institut, Knjige 1-6, Zagreb, 2018.
- [43] Ofak, J., Podolszki, L., Miklin, Ž., Sokolić, Ž.: Detaljna inženjerskogeološka karta Podsljemenske urbanizirane zone Grada Zagreba, *Zbornik 7. Savjetovanja Hrvatskog geotehničkog društva s međunarodnim sudjelovanjem: Geotehnički aspekti nestabilnosti građevina uzrokovanih prirodnim pojavama (Geotechnical aspects of damages caused by natural phenomena)*, (ur. Sokolić, I., Zlatović, S.), Zagreb: Hrvatsko geotehničko društvo, pp. 141–145, 2016.
- [44] Tomašić, E., Mazija, G.: Uloga geotehničkog katastra kod zahvata na području Grada Zagreba, *Zbornik 7. Savjetovanja Hrvatskog geotehničkog društva s međunarodnim sudjelovanjem: Geotehnički aspekti nestabilnosti građevina uzrokovanih prirodnim pojavama (Geotechnical aspects of damages caused by natural phenomena)*, (ur. Sokolić, I., Zlatović, S.), Zagreb: Hrvatsko geotehničko društvo, pp. 135–140, 2016.
- [45] Pivčević, N., Jukić, M.: Analiza pojavljivanja klizišta i odrona na području Grada Zagreba u razdoblju od 2012–2016 godine. *Zbornik 7. Savjetovanja Hrvatskog geotehničkog društva s međunarodnim sudjelovanjem: Geotehnički aspekti nestabilnosti građevina uzrokovanih prirodnim pojavama (Geotechnical aspects of damages caused by natural phenomena)*, (ur. Sokolić, I., Zlatović, S.), Zagreb: Hrvatsko geotehničko društvo, pp.115–120, 2016.
- [46] Miklin, Ž., Podolszki, L., Novosel, T., Sokolić, I., Ofak, J., Padovan, B., Savić, I.: Studija Seizmička i geološka mikrozonacija dijela Grada Zagreba - Hrvatski geološki institut, Knjige 1-4, 1 karta, Zagreb, 2019.
- [47] URL: <https://geoportal.zagreb.hr/Karta>, 19.09.2020.
- [48] Kuk, V., Prelogović, E., Savić, I., Kuk, K., Šariri, K.: Seizmološke i seizmotektonske značajke šireg zagrebačkog područja, *Građevinar* 52 (2000) 11, pp. 647–653

- [49] Simović, V.: Potresi na zagrebačkom području, *Građevinar*, 52 (2000) 11, pp. 637-645.
- [50] Aničić, D.: Zagrebačka katedrala u potresu 1880. i njena današnja obnova, *Građevinar*, 52 (2000) 11, pp. 655-661.
- [51] Pribičević, B., Medak, D., Prelogović, E., Đapo, A.: Utjecaj geodinamičkih procesa na izgradnju objekata i infrastrukture na području grada Zagreba, *Zbornik radova konferencije Razvitak Zagreba, SECON HDGK, Zagreb*, pp. 109-115, 2008.
- [52] Ivšić, T., Ortolan, Ž., Kavur, B.: Applicability of the RNK-method for geotechnical 3D-modelling in soft rocks. *Proceedings of the 18<sup>th</sup> International Conference on Soil Mechanics and Geotechnical Engineering, Paris, France, 1 (2013)*, pp. 551-554.
- [53] Seco e Pinto, P.: Seismic behaviour of geotechnical structures, Inaugural lecture, *Proceedings 13<sup>th</sup> Regional African Conference of Soil Mechanics and Geotechnical Engineering, Marrakech*, pp. 3-24, 2003.
- [54] Gazetas, G., Mylonakis, G.: Seismic soil structure interaction: new evidence and emerging issues, *Geotechnical Earthquake Engineering and Soil Dynamics, ASCE II*, 1998, pp. 1119-1174
- [55] Swane, I.C., Poulos, H.G.: Shakedown analysis of a laterally loaded pile tested in stiff clay, *Proceedings of the Fourth Australia-New Zealand Conference on Geomechanics, Perth, Western Australia*, pp. 165-169, 1984.
- [56] Pender, M.J., Pranjoto, S.: Gapping effects during cyclic lateral loading of piles in clay, *Proceedings of the 11<sup>th</sup> World Conference on Earthquake Engineering, Paper No. 1007*, 1996.
- [57] Holland, M.: *Practical Guide to Diagnosing Structural Movement in Buildings*, 1<sup>st</sup> Edition, Wiley-Blackwell, New Jersey, USA, 2012.
- [58] Kader, M.A., Jahan, I.: A Review of the Application of Remote Sensing Technologies in Earthquake Disaster Management: Potentialities and Challenges, *Proceedings of the International Conference on Disaster Risk Management*, 6p, 2019.
- [59] Sherard, J.L., Woodward, R.J., Gizienski, S.F., Clevenger, W.A.: *Earth and earth rock dams*, John Wiley & Sons, 1963.
- [60] Oka, F., Tsai, P., Kimoto, S., Kato, R.: Damage patterns of river embankments due to the 2011 off the Pacific Coast of Tohoku Earthquake and a numerical modelling of the deformation of river embankments with a clayey subsoil layer, *Soils and Foundations*, 52 (2005) 5, pp. 890-909, <https://doi.org/10.1016/j.sandf.2012.11.010>
- [61] oVERFLOW project, URL: [www.projectoverflow.eu](http://www.projectoverflow.eu), 16.09.2020.
- [62] Jarzyna, J.A., Dec, J., Karczewski, J., Porzucek, S., Tomecka-Suchoń, S., Wojas, A., Ziętek, J.: Geophysics in near-surface investigations, *New achievements in geoscience*, (ed. Hwee-San L), InTech, pp. 46-80, 2012, <https://doi.org/10.5772/37067>. ISBN: 978-953-51-0263-2
- [63] Mejia, L., Dawson, E.: Evaluation of Earthquake-Induced Cracking of Embankment Dams, *Proceedings of the 2019 USSD Annual Conference, Chicago, USA*, 20 p., 2019.