SEISMIC HAZARD AND MICROZONATION OF BUDAPEST

1. MOTIVATION AND PURPOSES

Earthquake vulnerability of large cities has increased dramatically in recent decades; earthquakes can cause serious economic damages even in areas characterized by medium or low seismicity. Seismicity around Budapest is moderate but somewhat higher than the average in Hungary. The largest (M5.6) well known historical earthquake in the vicinity of capital occurred in 1956 in Dunaharaszti, about 5-10 km distance from the southern boundary of the capital.

The majority of the buildings located in Budapest downtown was built in the XIX-XX. century following the architectural styles of that time, and according to the given technical knowledge and practice of civil engineering possibilities and limitations. As the people and planners usually had no personal experiences of earthquakes, the seismic safety was typically not a concern. A large part of the masonry buildings in the downtown area are higher than four floors, many places are 6-storey brick buildings and installations are common in the attic. The use of reinforced concrete in everyday architectural practice were gain ground only in the twentieth century. In earlier built buildings, reinforced concrete and reinforced concrete structures cannot be found. Fixing of the stone and brick walls developments were previously resolved differently, however these buildings are not able to withstand a dynamic load caused by a major earthquake. In recent decades, the ground floor of a large number of buildings were reconstructed, the reinforcing filler is decomposed in partitions, expanding business-related fields without rigidity tests. Another major problem is the bad physical condition of a large part of the older buildings due to the failure of routine maintenance. In the light of today engineering seismological knowledge, most of the buildings are very prone to suffer serious damage in case of a major earthquake in or near to Budapest. (Our observations about the condition of buildings in Budapest was published in Építés-Építészettudomány (Völgyesi et al. 2014).)

In order to decrease potential damages, it is important to know, what level of ground motion can be expected in a specific area. Presently the seismic hazard assessment are performed mainly by probabilistic method. Depending on the purpose of the use, usually two types of quantities are determined. Engineering applications require the knowledge of horizontal accelerations, while intensities are necessary to risk estimations. For larger areas, the seismic hazard is mapped for a standard ground condition, usually rock or stiff soil. However, past experiences have shown that the local geology strongly influences the damage level.

In the frame of this project we have intended to perform methodological research in seismic hazard assessment that allows to determine the seismic hazard in a well-supported manner in Hungary and also in Budapest. This includes the overview of earthquake catalogue, renewal of macroseismic data collection, study of attenuation of intensity and instrumental parameters.

We have studied the historical and present earthquakes that occurred in the vicinity of Budapest because they give valuable information about the shaking strength and the amplification of local geological environment.

Our purpose was to study different types of the microzonation methods which take into account the local soil conditions. In microzonation the soil classification is based on the shear wave velocity of the upper soil layers therefore we have studied the applicability of different types of V_S measurement method. From the realization of the project we expected new results for the seismic hazard of Budapest, however at the same time they may be useful in a more general context. Later, using the resulting elaborated methodology, microzonation can be performed for different end users, expressed both in accelerations and in intensity, for any probability level.

2. *METHODOLOGICAL RESEARCH IN SEISMIC HAZARD ASSESSMENT*

2.1. Overview of earthquake catalogue, separation of natural and man-made events

The main input for all seismic hazard computations is the reliable earthquake data. In the frame of the project we have begun to review the earthquake catalogue of Hungary and to remove the very uncertain, erroneous and duplicated events from it (ELTE students have taken part in the work).

Tectonic activity can be misinterpreted and earthquake statistics can be distorted if the catalogue is contaminated with artificial events. For example in 2014, out of the 487 seismic events recorded by the Hungarian seismograph stations, 175 were identified as natural earthquakes and 312 were known as quarry blasts. Therefore we have studied the discrimination methods of earthquakes and man-made events. Using methods that are based on determination of the polarity of P wave arrivals, amplitude ratios of different phases, cross-correlation matrix and dendrograms characterizing the waveform similarities, Mahalanobis distances, scalloping and steepness of the spectra, we could ascertain the origin of some questionable events. The results were presented in the EGU conference in Vienna (Kiszely and Győri, 2013) and were submitted to the journal „Geomatikai Közlemények" (Kiszely and Győri, 2014) and "Acta Geodaetica and Geophysica (Kiszely and Győri, 2015)".

2.2. Renewal of macroseismic data collection

High density macroseismic observations give valuable experience based information about site amplification. In the last few years the method of macroseismic data collection renewed, use of online resources prevailed. The online questionnaires on the Seismological Observatory's web page have become the main source of macroseismic data collection. In early 2013, the Facebook page of the observatory was launched. We use the Facebook page for information dissemination and as a tool for information capture. To make the access to our data even faster, a script has been developed using the Twitter API which automatically uploads the newly determined earthquake locations to the Twitter page of the observatory. In order to facilitate the communication with the public, a seismological application has been developed for the Android platform. Using the same data source as the web and Twitter pages it lists and displays the earthquakes in Hungary and the neighboring countries and enables the user to fill out the questionnaire, as well.

Using social media to collect macroseismic questionnaires had a great effect on the amount of the received data. It is especially true for Budapest where the internet coverage is the highest in the country. For example in case of Tenk earthquake in 2013, 825 questionnaires were filled in (373 from Budapest) and intensities were assigned to 211 settlements (including 23 districts of Budapest). Besides delineating areas where the earthquake have been felt we could gain information about intensity distribution. We have found that distribution of intensity values is strongly asymmetric. The event caused building damages in a number of villages west to the epicenter but in the east direction damages occurred only in close vicinity of the epicenter. Comparing the assigned intensities with the average attenuation curve of the Carpathian Basin (Zsíros 1996), it could be seen that the experienced epicentral intensity is one scale degree less than the predicted value and the attenuation rate is much smaller. Therefore using these and all of the previously collected data, we have begun to develop new intensity attenuation relationship to the Pannonian Basin.

We have made a poster presentation about our research in the Second Conference of Earthquake Engineering and Seismology in Istanbul (Gráczer et al. 2014), and published it in the Acta Geodaetica and Geophysica (Szanyi et al. 2014).

2.3. Study of intensity attenuation in the Pannonian Basin

Ground motion prediction equations play a key role in seismic hazard assessment. Earthquake hazard has to be expressed in macroseismic intensities in case of seismic risk estimations, for shake map generation where the map is used for prompt notification to the public, disaster management officers and insurance companies. Another important aspect of the study of intensity attenuation is that there are only few instrumental strong motion data recorded in the Pannonian Basin but we have numerous historical reports of past earthquakes since the 1763 Komárom earthquake. The aim of our research was to determine an intensity attenuation formula for the inner part of the Pannonian Basin.

The intensity attenuation in the Carpathian region was studied earlier by Zsíros (1996). He collected isoseismals of 124 earthquakes but a large part of the events occurred outside the basin. Strength of the earthquakes was expressed in epicentral intensity. Its disadvantage is that even if the epicentral intensity can be determined, it is not available right after the earthquake so these relations cannot be used for example in shake map computations.

Because the crust beneath the Pannonian Basin is thin and warm and it is overlain by thick sediments, the attenuation of seismic waves is different from the attenuation in the Alp-Carpathian mountain belt. Therefore we have collected intensity data only from the inner part of the Pannonian Basin and defined the boundaries of the studied area by the crust thickness of 30 km. Most of the intensity data originate from the intensity catalogue of Zsíros (2014) that contains data until 2010. After 2011 we used the Hungarian National Seismological Bulletins (Gráczer et al. 2012, 2013, 2014, 2015). To eliminate the subjectivity of drawing isoseismals, we have used individual intensity points.

In the first step a careful quality control has been made on the dataset. Different types of magnitudes given in the catalogue have been converted to local magnitudes. The focal depths given by the primary sources were accepted. In total we could use 243 earthquakes of magnitude 3.0 to 6.6 with 10492 intensity data points. Most of the events occurred in the center and southwestern part of the Basin so data coverage is the best there (Fig. 1).

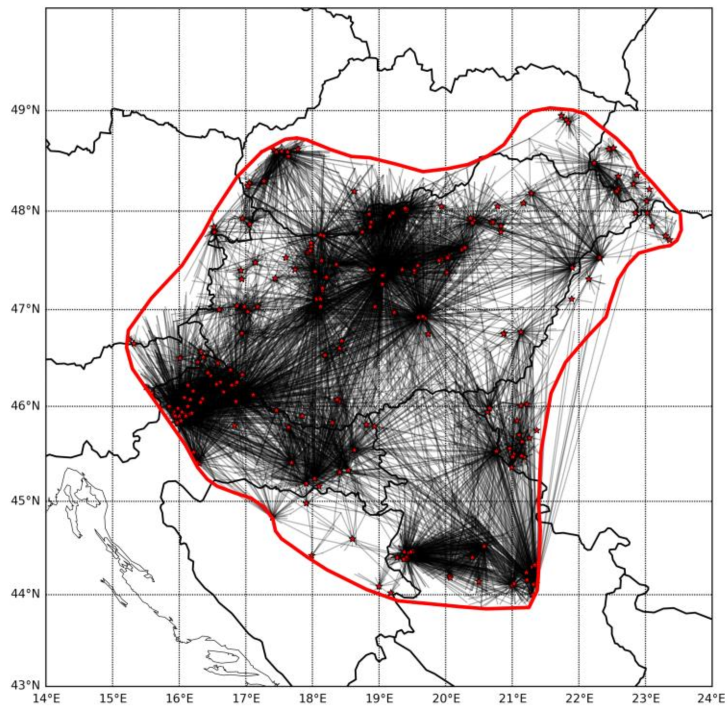


Fig. 1. Epicenters of the earthquakes (red stars) used in the analysis. The end points of the black lines denote the sites of the observed intensities while the red line is the boundary of the Pannonian Basin.

We applied the attenuation formula of Sorensen et al. (2009):

$$I = c \cdot M_L + d \cdot \log(h) + e + a \cdot \log\sqrt{\frac{R^2 + h^2}{h^2}} + b \cdot \left(\sqrt{R^2 + h^2} - h\right)$$

where I is the intensity, M_L is the local magnitude, h is the focal depth, R is the epicentral distance and a, b, c, d, e are constants. The sum of the first three terms represents the epicentral intensity, the fourth term the geometrical spreading and the last one concerns the energy absorption. This expression is comparable with the common type of strong-motion attenuation equations. Because of the relatively small size and the unknown fault plains of the earthquakes, point sources have been assumed and epicentral distances have been used.

The weighted least-squares regression method of Stromeyer and Grünthal (2009) was used to estimate the attenuation parameters a–e of the equation. The weighting scheme assigns the same weight to each different intensity level to eliminate the great variety in the number of observations within the levels.

The calculated mean attenuation parameters and their standard deviations are summarized in Table 1. It is notable that the value of parameter b is almost zero. This means that the energy absorption proved to be insignificant at the studied relatively short epicentral distances.

Table 1
Mean values of regression parameters with their standard deviation

	a	b	c	d	e
mean	-2.39701	-0.00059	1.07401	-1.46328	2.35939
std. dev.	0.02622	0.00020	0.00716	0.02541	0.03500

In the large majority of cases the computed attenuation curves fit well to the intensity observation points. Figs. 2a, c, e show three example earthquakes. Figs. 2b, d, f illustrate the deviations of observed intensities from the calculated average intensities. These can help to reveal the goodness of the fit, the possible azimuthal variations and site amplifications.

The fit was very good at most of the studied earthquakes. But in case of some large magnitude earthquakes (M>5) we have found significantly larger epicentral intensities and much faster attenuation with distances than predicted from the newly determined intensity attenuation equation. (This was also the case in 1956 Dunaharaszti earthquake.) This phenomenon might indicate inaccuracy in magnitude, depth determination or necessity of applying magnitude dependent attenuation coefficient in the equation. In addition, azimuthal variation in energy decrease could be found in some cases, that raises questions about the nature of direction dependence of intensity attenuation and necessitate the continuation of our research.

The results have been presented in the EGU conference in Vienna (Győri et al., 2015), but because of the problems encountered, it was not submitted yet to scientific journal. First we will revise the primary macroseismic data and try to take into account the nonlinear magnitude dependent attenuation.

2.4. Attenuation of instrumental ground motion parameters

Engineering applications need the knowledge of exceedance probabilities of some instrumental ground motion characteristics. These are mainly the horizontal and vertical maximum and spectral accelerations. Because there are only few acceleration measurements in Hungary, we have collected published ground motion equations of last decades and have selected some for further studies. The selection criteria were as follows:

- the equations should be based on large, quality controlled global database,
- the database have to contain shallow crustal earthquakes occurred in active tectonic regimes, similar to the Pannonian Basin
- the equations have to be well documented, verified and applicable also for small and moderate, strike-slip and thrust earthquakes,
- the equations should treat not only the near surface soil conditions but also the basin effect,
- the authors should have equation for vertical ground motion too,
- aleatoric and epistemic uncertainties need to be treated properly.

Taking into account these criteria, we have found that on the one hand the new 2014 equations of NGA–WEST2 project seem the best that are based on a comprehensive global dataset and five groups of prestigious scientists have worked on their developments. On the other hand the pan-European strong motion database was significantly expanded as RESORCE in the frame of SHARE and SIGMA projects in 2013. Based on the larger database, various working groups have developed five new pan-European attenuation models. After thorough study, we have chosen four equations from the ground motion models of the two projects to compute seismic hazard in Hungary:

- Akkar et al. (2014),
- Boore et al. (2014),
- Campbell & Bozorgnia (2014),
- Chiou & Youngs (2014).

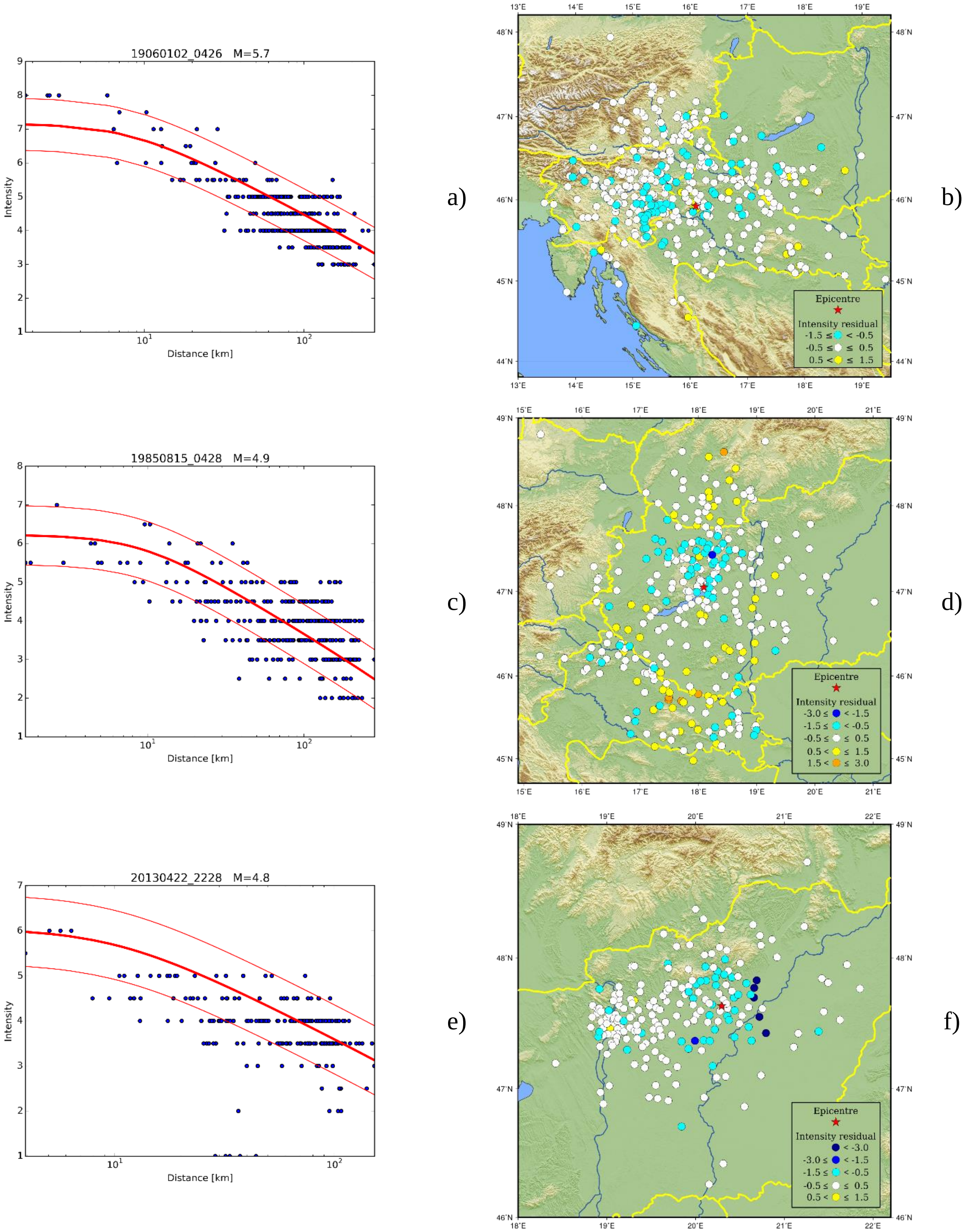


Fig. 2. Observed intensities with the fitted attenuation curves (mean with 68.3% confidence bounds) and the intensity residuals for a 1906 Croatian (a, b), 1985 Berhida (c, d) and 2013 Tenk (e, f) earthquakes

To verify and to apply weights to the attenuation models in logic tree which is used to handle epistemic uncertainties in seismic hazard assessment, we have collected the records of earthquakes occurred in the Carpathian Basin and registered by the Hungarian seismological stations. Only digital seismograms can be used so we have selected 164 events from 1995. The magnitude of these events is between 3.5 and 5.8, and altogether 839 seismograms are available. The signal-to-noise ratio of them is very different therefore a careful quality control has to be made first on the records. The amplitudes are proportional with the ground velocity and these are recorded by different types of instruments therefore instrument correction, filtering and differentiating have to be applied to compute accelerations. (A BSc student from ELTE helps us in quality control and data processing.)

Figure 3 shows the horizontal peak ground accelerations computed from earthquakes only with epicentral distances less than 300 km (478 data points). The figure shows all the data without quality control so the number of useful data points will be less. It can be seen that nearfield stronger earthquakes are missing from the database therefore a reliable attenuation model cannot be developed only from these data. Therefore we plan to supplement the database with the available seismograms of seismic stations of neighboring countries moreover the Carpathian Basin Project (2005–2007) and the South Carpathian Project (2009–2011) of University of Leeds. The latest one will be available in 2017.

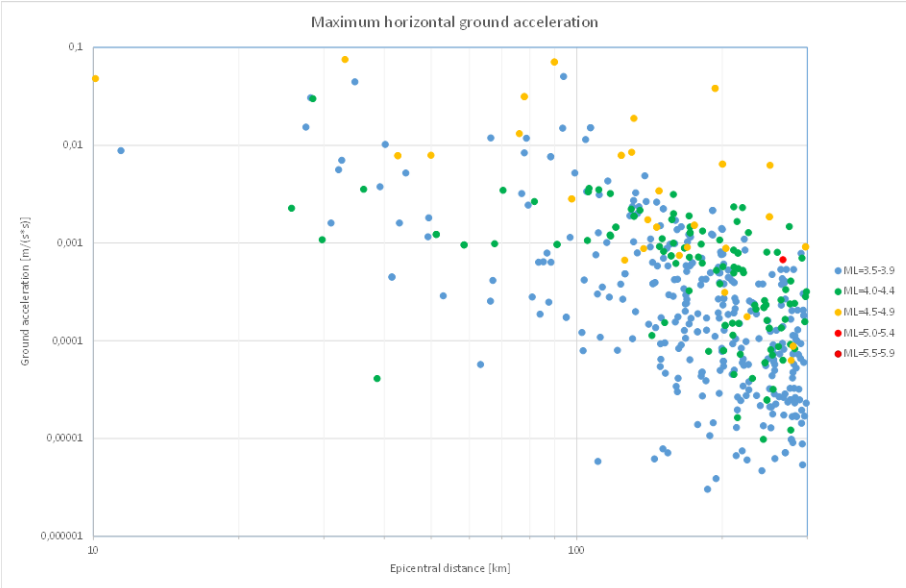


Fig. 3. Maximum horizontal accelerations (larger horizontal component) computed from records of Hungarian seismic stations

3. *CONCLUSIONS REACHED FROM PAST EARTHQUAKES*

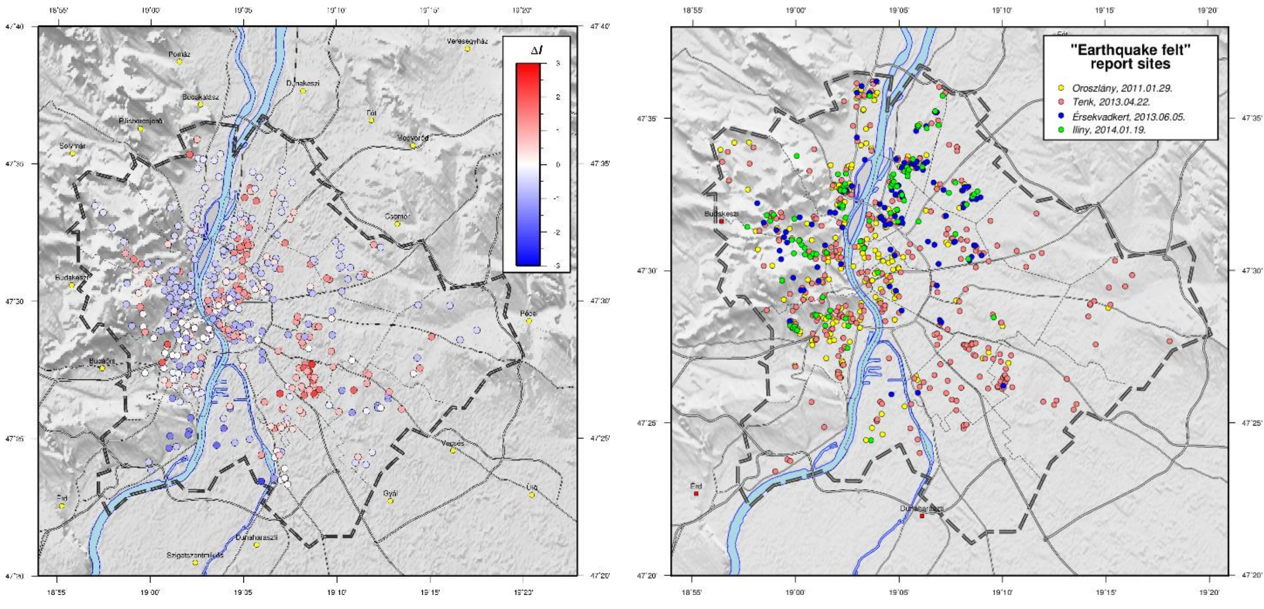
3.1. Intensity distribution in Budapest caused by the 1956 Dunaharaszti and some recent earthquakes

To study the soil amplification, we have collected the observations in Budapest that were gained from past (historical and recent) earthquakes. We have re-evaluated the intensity distribution of Dunaharaszti earthquake and delineated the areas that suffered heavier damages than the average (Fig. 4a). The average in a given point was computed using the average intensity attenuation computed only for this event. On the basis of questionnaires that had arrived at the Seismological Observatory, we have studied where the recent moderate earthquakes could be felt (2011 Oroszlány, 2013 Tenk, 2013 Érsekvadkert, 2014 Iliny) inside Budapest (Fig. 4b).

Direct use of these data requires great precautions but obviously contain the effect of local geology. For example large number of felt reports of recent earthquakes came from housing estates where the population density is the highest in the city and the people can feel even the weaker shakings in the upper floors. In case of Dunaharaszti earthquake, bad condition of houses caused larger damages while lack of damages data can indicate not only less damages but unbuilt areas too. Even if the locations of red points in Figure 4a and the high density of felt reports' sites (Fig. 4b) are coincident, it does not indicate site effect in every case. For example the József Attila housing estate was built on the area of former Mária Valéria slum area which was seriously damaged during Dunaharaszti earthquake because of the bad condition of the houses. Therefore we thoroughly have examined the correlation of these areas with the geological structures, local subsoil conditions, groundwater levels, built-up of the area and with the quality of buildings located there.

Generally it can be stated that although some dots with higher intensity can be seen in Buda, as well, but characteristically the Buda side was less damaged during Dunaharaszti quake. The areas with more serious damages are mainly located in the Pest side but their distribution is not even. For example Csepel and Soroksár lie at approximately equal distance from the epicenter, however Soroksár was more severely hit. Its reason is probably that the groundwater level is lower and thick gravel layers that have large bearing capacity can be found in Csepel Island. Our experiences were that larger intensities in Pest side (oldest part of Kispest, Belső és Közép-Ferencváros, Angyalföld, Külső-Erzsébetváros located south from the Városliget) were caused by the larger thickness of quaternary sediments, high groundwater level, and low bearing capacity of subsoil together with the poor construction of buildings.

The geology of the Buda side differs fundamentally from the one of the Pest side. On the right bank of the river - aside from the valleys - the older and harder rocks of the Buda Hills are on the surface. Therefore in most cases the intensities were lower than the average value. Larger damages were observed e.g. in the Hűvösvölgy part of the Ördögárok (Fig. 4a) which is a long valley filled up with Holocene sediments. On the two sides of the valley older formations are on the surface, and the waves reflecting from them can enhance further the intensity of the ground motion. This effect is detectable from the number of testimonies of recent earthquakes too (Fig. 4b).



a) b)

Fig. 4. a) Differences of reported and "expected" intensities caused by the Dunaharaszti earthquake b) sites from where people reported that they felt the four larger earthquakes of the last years

3.2. Conclusions reached from environmental effects of Dunaharaszti earthquake

Although it was not included in the original research plan, but is very important to examine any phenomenon that was generated by past earthquakes, from which conclusions can be drawn about the seismic hazard of Budapest. Usually attention is paid mainly to the analysis of effects on humans and manmade structures. During this research, which was carried out in collaboration with the Department of Engineering Geology and Geotechnics of BME, we have focused on the environmental effects, especially on soil liquefaction.

The epicenter of 1956 Dunaharaszti earthquake was located about 5 km from the southern boundary of Budapest. A Wiechert type seismometer was operated in the capital 15-20 km from the epicenter but it was saturated by the earthquake so instrumental information does not exist about the shaking strength. Ground accelerations caused by the event can be deduced only from the macroseismic intensity values and from the analogies of recent similar earthquakes where strong motion data exist.

The epicentral area of Dunaharaszti earthquake was located along the Danube River. Sand boils were observed in some locations that indicated the occurrence of liquefaction. Because their exact locations were recorded at the time of the earthquake, geotechnical measurements (SPT and CPT soundings, laboratory measurements) could be performed. Therefore an alternative possibility to estimate shaking strength can be the back-analysis of liquefaction field data. Unlike the paleoliquefaction studies, in our case the source of the earthquake and the magnitude is known, our purpose was only to estimate the peak ground acceleration.

Back-calculation of surface acceleration was performed at two locations, in Dunaharaszti and in Taksony. We have used stress-based methods that were originally developed for evaluating liquefaction potential of soils at sites subjected to future earthquake motions. Beside "forward analysis", these methods can be used for estimating the magnitude and the associated peak ground acceleration at sites of liquefaction for pre-instrumental earthquakes (i.e. "back-analysis"). The stress-based methods are based on an estimate of seismic demand (cyclic stress ratio, CSR) and comparing this to the liquefaction resistance (cyclic resistance ratio, CRR) of the given soil. Earlier methods define the factor of safety (FS) as the ratio of CRR to CSR, while the newer methods result in probability of liquefaction but their principle is similar. For the back-calculation of peak ground acceleration (PGA) both deterministic and probabilistic approach can be used, but probabilistic methods give better insight into the uncertainty of the result because deterministic methods usually have to start from an initial assumption of factor of safety, usually taken as 1.0.

We have used probabilistic methods and the estimation of PGA was carried out using two SPT-based (Cetin et al. 2004, Boulanger and Idriss 2014) and three CPT-based probabilistic methods (Moss et al. 2006, Juang et al. 2006, Boulanger and Idriss 2014) in both locations.

As a result, we have taken the arithmetic means of PGA values corresponding to 50% liquefaction occurrence probability and computed using different methods. The results showed very good agreement at the two locations; PGA was 0.18±0.03g at Taksony and 0.20±0.03g at Dunaharaszti. The corresponding methods (both Cetin et al. and Moss et al. methods were developed analogously in University of California, Berkeley) gave very similar results regardless of the in-situ method, but the difference between the different authors' procedures can be significant.

The results of our computations are in accordance with the accelerations measured during recent earthquakes and these can give a handhold in determination of seismic hazard in Budapest. The geotechnical back-analysis of historical and paleoliquefaction sites can be a useful tool to estimate the shaking strength caused by past earthquakes. But epistemic uncertainties should not be neglected that arise from the application of different methods.

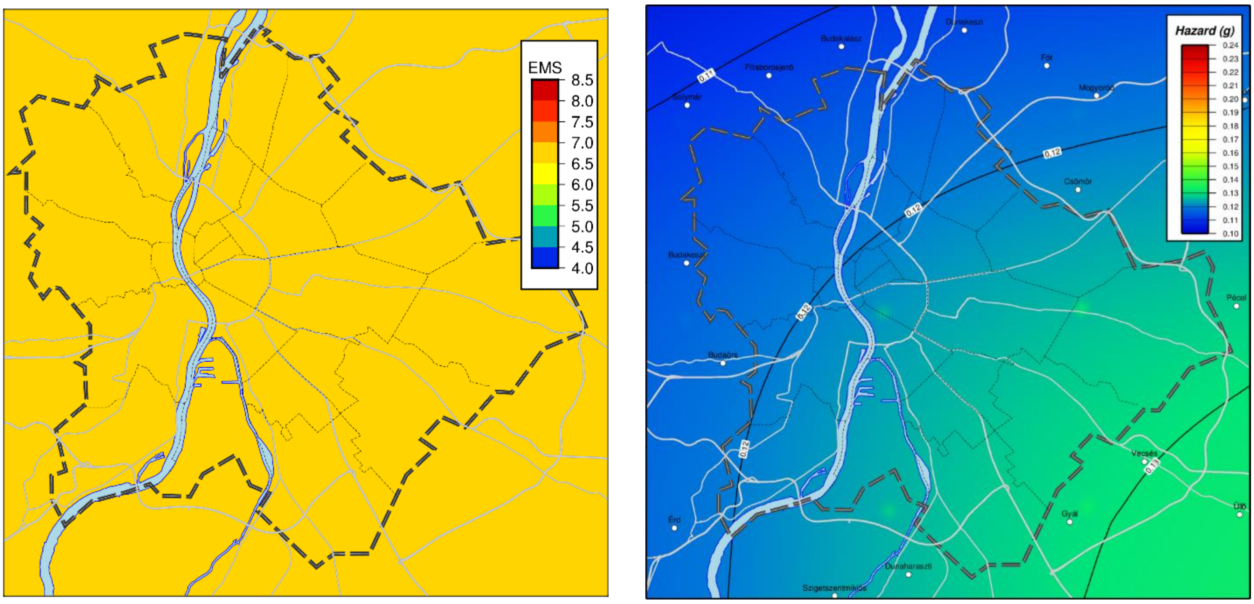
The results were presented in the form of poster presentation in the EGU conference in Vienna (Bán et al. 2015), and in the IUGG conference in Prague (Győri et al. 2015).

4. METHODOLOGICAL RESEARCH IN MICROZONATION

4.1. Overall methodology

A number of microzonation studies using different methods have been performed for cities characterized by high and moderate level of seismic hazard. Acceleration-based seismic hazard assessment including site effect can be obtained fundamentally using two different methods. In case of the first method the seismic hazard is computed for the surface of a bedrock and amplification of near surface deposits are estimated on the basis of their dynamic properties. This can be done by numerical computation of spectral amplification knowing the geometrical and geotechnical parameters or by specifying an amplification factor based on the V_{S30} value (V_{S30} is the average shear wave velocity in the upper 30 meters. Recently this is the most often used parameter to classify the type of near surface strata.). The second method is based on the use of attenuation relationships, which comprises the local site effects. The new attenuation relationships developed in seismically active areas contain the V_{S30} values as input data.

Reviewing the advantages and disadvantages of the two methods, we have decided on the application of the two-step process. The reason is that probabilistic seismic hazard assessment is a computationally intensive task. The resulted hazard values determined for bedrock change slowly in an area (Fig. 5) therefore it is enough to carry out the computations in a relatively rare grid points. On the other hand the subsoil can change very quickly in space, so it is expedient to compute the amplification separately. Furthermore, only the two-step procedure is applicable during intensity based microzonation if the hazard is computed using intensity attenuation formulas because these formulas do not include soil dependent term. Here it is important to note that the acceleration based seismic hazard that is computed for bedrock and the intensity based seismic hazard cannot be compared directly because the latter refers to some kind of "average" soil.



INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+
Shaking	Not felt	Weak	Light	Moderate	Strong	Very Strong	Severe	Violent	Extreme
Damage	None	None	None	Very slight	Light	Moderate	Moderate/ heavy	Heavy	Very heavy
Peak Acc	<0.17	0.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
Peak Vel	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16 - 31	31-60	60-116	>116

Peak Acc = Peak ground acceleration (g), Peak Vel = Peak ground velocity (cm/s)

a) b)

Fig. 5. Earthquake hazard maps of Budapest (10% exceedance probability in 50 years): a) Intensity based hazard map has been computed for an average soil condition using Zsíros (1996) intensity attenuation formulas b) Horizontal peak ground accelerations computed for the bedrock (Tóth et al. 2006)

V_{S30} is a key parameter in hazard computation and microzonation studies. In addition, this is the base of the soil classification in different building codes (e.g. Eurocode 8, UBC) but sometimes knowledge of shear wave velocities of deeper layers is also very important. Crosshole and downhole measurements are very expensive, carrying out seismic measurements using active sources are difficult in metropolitan areas. So in the frame of the project we have tested different types of V_S measurement methods that can be applicable in urban environment. Shear wave velocity measurements of MFGI and other geophysical companies, moreover P wave velocity measurements of Szeidovitz (1978-80) were also collected.

Besides the S wave velocities in near surface layers there are other circumstances that can amplify the surface motion and can aggravate the damages. These are the soil resonance, areas of artificial fills, underground cavities, areas prone to sliding, high groundwater level, sandy soil susceptible to liquefaction that are essential to take into account during microzonation studies. To study the areas where these phenomena can occur, geological, hydrogeological and geotechnical information have been collected from Series of Engineering Geological Maps (1:40000), Geomorphologic Map (1:20000) of Budapest, Extent and Thickness of Quaternary formations in Budapest (1:20000), online borehole map and database of Hungary available from MFGI homepage, geological and geotechnical profiles moreover historical maps and photos about the capital.

4.2. Use of topographic slope to estimate soil category

In case of large areas high resolution mapping of V_{S30} by field measurements are not feasible cost effectively. In 2007 and 2009, Wald and Allen (2007, 2009) presented an alternative method for mapping uniform global seismic site conditions, or V_{S30}, from the SRTM 30 and 9 arcsec digital elevation models. The basic premise of the method is that the topographic slope can be used as a reliable proxy for V_{S30} in the absence of geologically and geotechnically determined site condition maps through correlations between V_{S30} measurements and the topographic gradient. The parameters of the relationship between the topographic slope and the V_{S30} velocity were determined by collecting measured V_{S30} data from a number of places (including certain states of the US, Taiwan, Australia and Italy). During the processing, the data have been divided into two parts according the places of the measurements, namely whether they are coming from tectonically active or stable continental areas.

Budapest covers an area of 525 square kilometers. In the frame of this project, because of time, personal and financial limits, we could not perform velocity measurements systematically on the whole area. Therefore beside the use of velocities (measured before and during this project), geotechnical and geological information, first we have studied the applicability of topographic slopes on the studied area as a proxy for site conditions.

Two types of digital terrain models have been tested (Tildy, 2016). The DDM 10 model made by the MH TÁTI (Ágoston Tóth Cartographical Institute of the Hungarian Defence Forces) and the NASA SRTM models. The database of DDM 10 model was prepared by the interpolation of contour lines of scale 1:50,000 military topographic maps. However, after depicting the data, the stepped structure of the contour lines were conspicuous, so these data were not useable to compute topographic gradients. Therefore like Wald and Allen, we have used the SRTM data. In the first step we have studied the applicability of available different resolution (3, 9 and 30 arcsec) data. The resolution of 3 arcsec data is too high because these reflect the effect of canopy, while the resolution of 30 arcsec data seemed quite low; rather it can be useful for mapping on larger, regional scale. So we have used the 9 arcsec SRTM data to compute the topographic slopes.

Another question was that which type of correlation should we use, the correlation developed for tectonically active or stable continental areas? Or can we construct a better relationship between topographic slope and V_{S30} that is applicable in Hungary?

Until the end of 2014, Tildy et al. (2014) have collected 197 V_{S30} velocity data from the measurements of MFGI. (Students paid from the OTKA project took part in data collection.) Data was derived from shallow S wave refraction and surface wave measurements carried out in different parts of Hungary while 98 among them was measured in Budapest.

Depicting these data in function of topographic slope values, together with the relations of Wald and Allen (2007) developed for areas of active and passive tectonics (Fig. 6), it can be concluded that our data fit better to relations corresponding to areas of active tectonics (Tildy 2014). In case of relatively flat areas the measurement points are closely located however large scattering can be observed in velocities belonging to larger topographic slope values. Its main reason is the low velocities measured in areas covered by loess and slope debris. Figure 7.a shows the points of shear wave measurements carried out in Pestlőrinc, located in the flat Pest side of the capital, while in Figure 7.b the V_{S30} values measured on loess areas can be seen. The method was tested also in Óbuda which is an area of variable topography and geology. Comparing the soil class map of the area computed by the slope-V_{S30} correlations of Wald and Allen (2007) and the soil classes determined from the measurements at 18 points (Fig. 8), it could be observed that soil classes were different from each other at about half of the points and sometimes the computed velocity values showed significant deviations from the measured ones. The correlation was even weaker for the modified slope-V_{S30} relationship which was specified for high resolution data set by Allen and Wald (2009). The velocities computed from topographic data were larger in case of steeply dipping foothill areas, while there were underestimated at the nearly flat gravelly strata and limestone plateaus. Another experience was that scattering of slope angles belonging to soil category C in Eurocode 8 is very large.

Because of the small number of available data and the narrow range of slope angles, a detailed statistical analysis could not be made (Tildy, 2016) and we could not develop a better correlation applicable in Hungary. Therefore we could compute the topographic slope based V_{S30} map of Budapest using Wald and Allen (2007) correlation developed for active tectonic regions (Fig. 9a). The map gives an overall picture about site conditions, but its applicability is questionable mainly in areas covered by loess (eastern parts belonging to Gödöllő Hills) and foothill sediments (in Buda side), limestone plateaus (Tétény Highland). Moreover it cannot take into account the thickness of upper loose sediments and the possible resonance effects therefore applicability of slope angles in detailed soil condition mapping is quite limited.

This research is part of PhD dissertation of P. Tildy (Tildy, 2016).

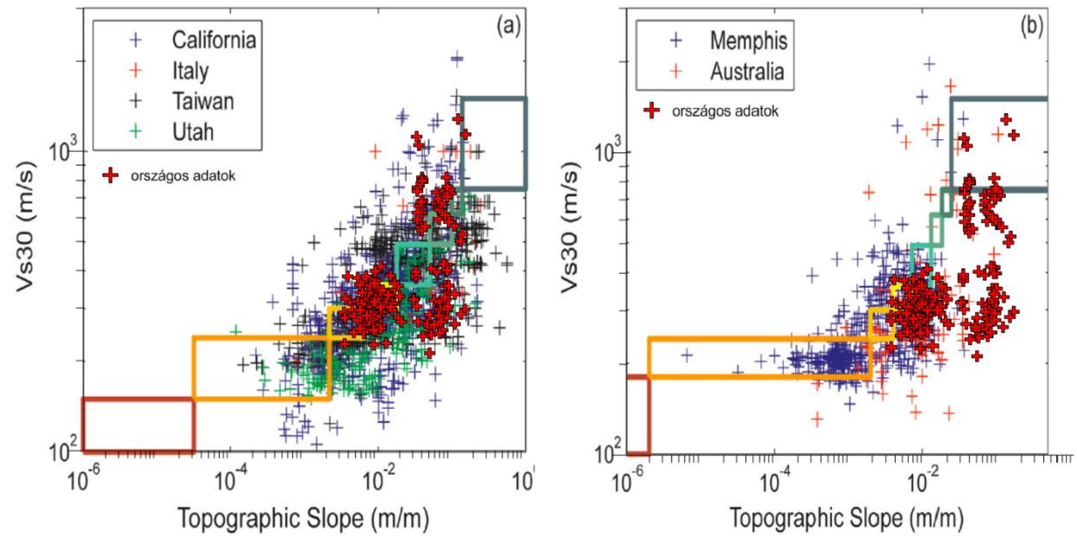
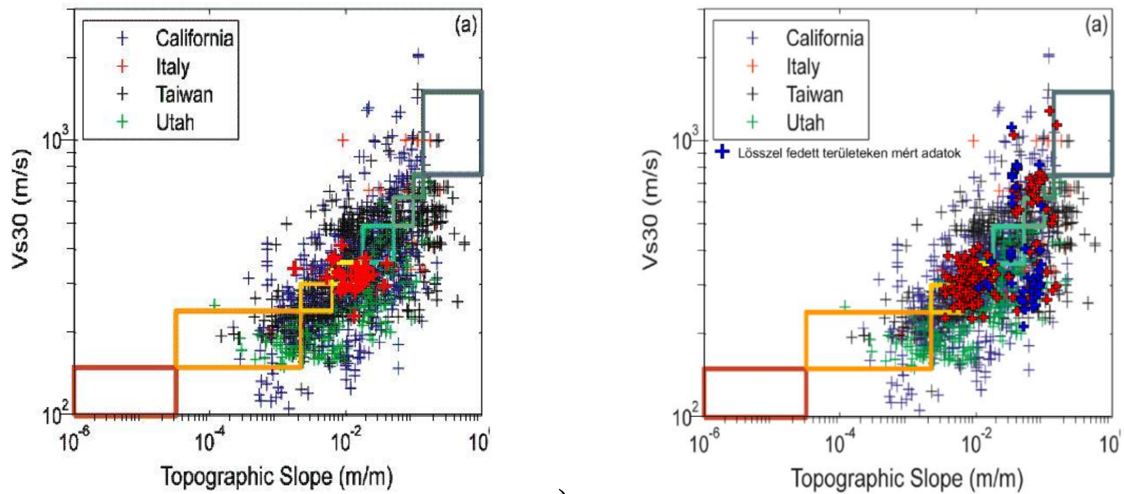


Fig. 6. Comparison of data measured in Hungary (thick red crosses) and data available on seismically active (left) and shield areas (right)



a) b)

Fig. 7. a) Pestlőrinc data (thick red crosses) b) V_{S30} data measured on areas covered by loess (thick blue crosses) plotted with data of active tectonic region (Tildy 2016)

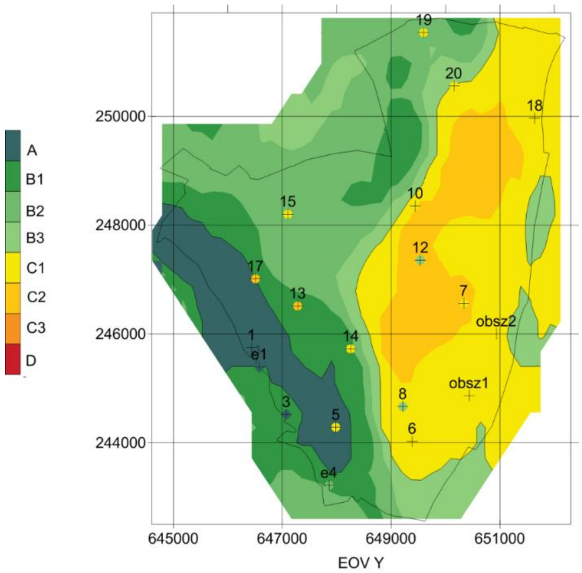
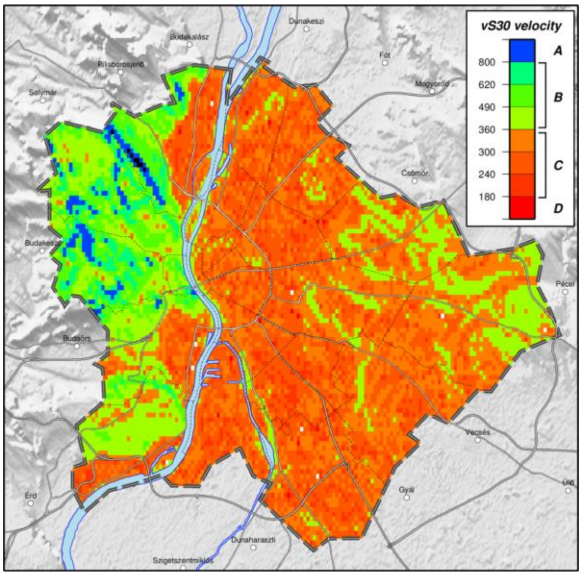
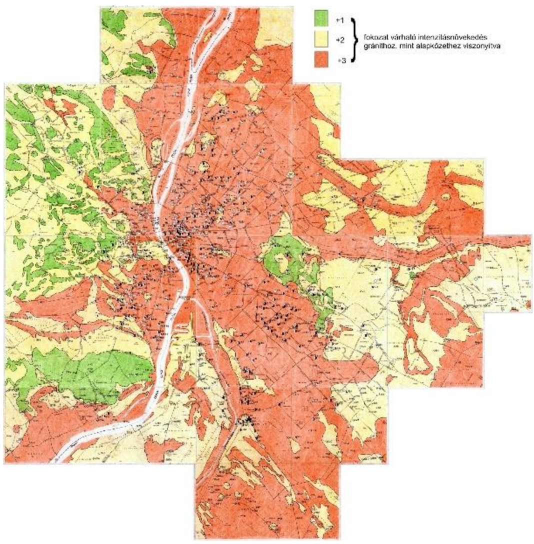


Fig. 8. Soil class map of Óbuda computed from topographic slopes and the points of measurements (The colors of points are the same as the areal soil classes) (Tildy, 2016)



a)



b)

Fig. 9. a) V_{S30} map of Budapest computed from topographic slope and b) MSK-64 intensity amplification compared to granite as a base rock (Bisztricsány and Szeidovitz, 1980)

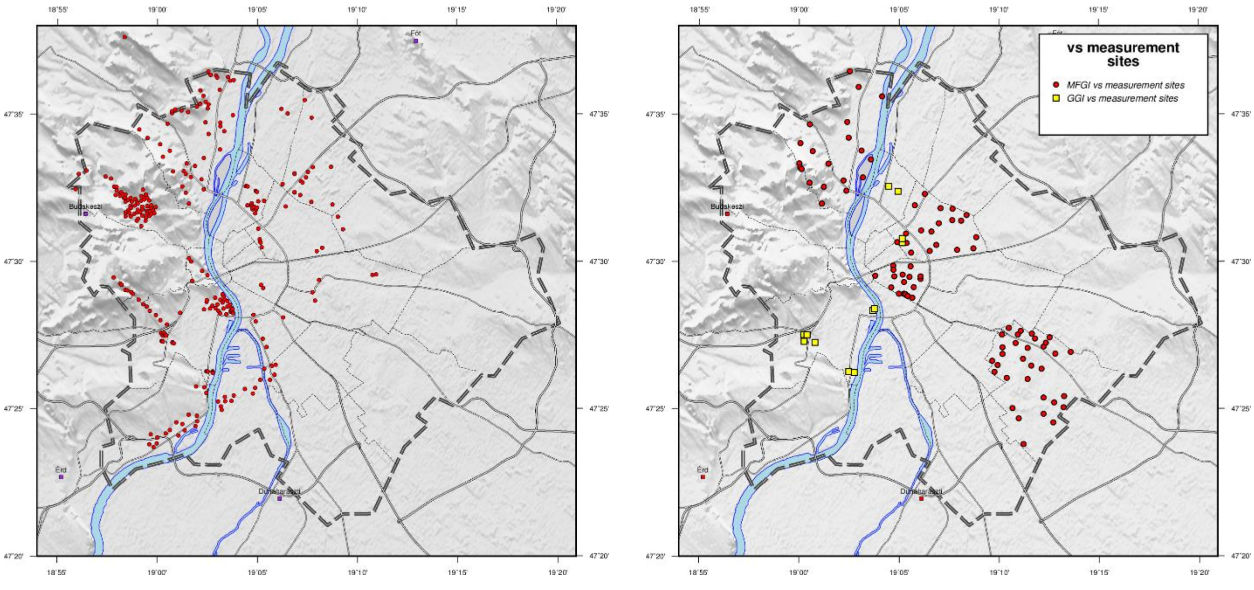
4.3. Methods of V_S determinations

4.3.1. Active and passive seismic measurements

V_S measurements in Budapest using surface wave method begun in 2001 in ELGI (Tildy 2016). The altogether 98 measurements were carried out in four districts of the capital (Fig. 10b); these form the basis of soil categorization in these districts (III, XIV, X, XVIII). Most of the measurements was carried out using an active, weight drop source operating by gunpowder cartridge. The source and the source-receiver configuration was proved to be good for inducing and recording large energy fundamental mode but its application is difficult in urban environment.

In 2014, the MTA CSFK GGI could purchase a multichannel seismic instrument with low frequency (4.5 Hz) vertical geophones from other grant. In the frame of this project, we have purchased a data processing software WinMASW (Dal Moro, 2014) which can be used for processing of different types of surface wave measurements. We began to perform experimental measurements in 2014 to determine shear wave velocities in urban environment.

We have carried out both active (MASW – Multichannel Analysis of Surface Waves) and passive (ESAC – Enhanced Spatial AutoCorrelation, ReMi – Refraction Microtremor) seismic measurements in different points of the city (Fig. 10b). In addition, these have been supplemented by microseismic noise measurements to reveal the possible subsoil resonance by computation of H/V ratios. Our other purpose was to study the local applicability of ambient noise correlation method (e.g. Shapiro & Campillo, 2004) in noisy urban environment. The measurements were carried out mainly at such locations, where the engineering geological maps indicate unfavorable subsoil conditions (Lágymányos, Városliget, Rákospatak, Dobogó, some areas of Keserűvíz wells, Budafok).



a) b)

Fig. 10. a) Locations of microseismic noise measurements, b) V_S measurements carried out by the MFGI in 2000–2014, and test sites of GGI (H/V, MASW, ReMi, ESAC, noise cross-correlation measurements)

We have used a 24 channel instrument and 4.5 Hz vertical geophones for the seismic measurements. The geophone distances were 3 and 4 m; the minimum offsets at the MASW measurements were 15 m and 20 m respectively. The source was an 8 kg hammer and we have stacked the traces from multiple shocks to attenuate incoherent noise. The ReMi measurements were performed using the same linear geophone array as was used by the MASW and we have used L-shaped arrays for the ESAC measurements. Processing of active and passive seismic data, computation of H/V ratios have been done by WinMASW software (Dal Moro, 2014).

Usually the MASW and ESAC measurements provided good results, velocity spectra computed form them were clear and well usable. In case of ReMi measurements, distribution of noise sources strongly influenced the appearance of velocity spectra so their interpretation was much more subjective. The measurements were processed first separately but because sometimes the result of inversion are not unequivocal, we have performed joint inversion of different types of measured data. One example of computations performed from the measurements in Városliget, is shown in Figures 11-13.

Damages caused by the 1956 Dunaharaszti earthquake were larger than the average at the southeast corner of the Városliget. According to the available geological maps and borehole data, low bearing capacity peat can be found in shallow depth on the area (Fig. 11.) so our purpose was to determine the shear wave velocity of these strata. Because of the available free park area, we could perform MASW, ReMi and ESAC measurements, apply cross-correlation method and compute H/V ratios.

Dispersion curve of Rayleigh-waves was determined primarily from velocity spectrum of MASW measurement. The source was a hammer so the low frequency part of the spectrum is quite uncertain. The background noise contains more low frequency component so the passive methods (Fig. 12.) supplement the low frequency part of the spectrum. After that we have performed the joint inversion of H/V and dispersion curves (Fig. 13.) using genetic algorithm. Figure 13b shows the bi-objective space with a cloud of misfits of the models showing the general congruency of the inversion process (Pareto front analysis).

However it has to be note that while the velocity spectrum is objective and mathematically obtained from the seismic traces without any personal interpretation, dispersion curves are the results of a subjective interpretation. The velocity spectrum shows the superposition of fundamental and higher modes therefore an erroneous picking of modal dispersion curves necessarily leads to meaningful results. Therefore we have also performed Full Velocity Spectra (FVS) inversion in every measurement location. The results of the FVS inversion performed on a MASW measurement in Városliget can be seen in Figure 14. The resulted V_S profile is very similar to the profile of Figure 13c; a low velocity layer (less than 150 m/s) can be seen above 5 m which probably indicate the existence of a low strength peat layer. Nonetheless the values of V_{S30} were 285 and 290 m/s in the two cases so the soil category is "C" according to the classification of Eurocode 8.

From the near surface seismic methods based on surface wave dispersion, the MASW and ESAC usually gave quite reliable velocity-depth profiles. Reliability of velocities increased by joint inversion of different type of dataset. But we could not find one exclusively preferable methodology that would be the best in every circumstances. In case of mode jumps often the Full Velocity Spectra (FVS) inversion gave the most realistic results but in other cases picking of dispersion curve gave better results. One of our experiences was that the value of V_{S30} was quite stable even if the different processing methods resulted different V_S profiles.

Our other experiences was that even if the engineering geological maps indicated unfavorable subsoil conditions at the measurement points, the soil category was always "C" on the basis of V_{S30} value (this can be regarded as an "average" soil type in Hungary).

ELTE students have taken part in the measurements. One BSc dissertation (Timkó, 2015) and one TDK paper (Timkó, 2015) was written from the results. The results were presented in IUGG conference in Prague (Győri et al. 2015) and in the ESC conference in Trieste (Győri et al. 2016).

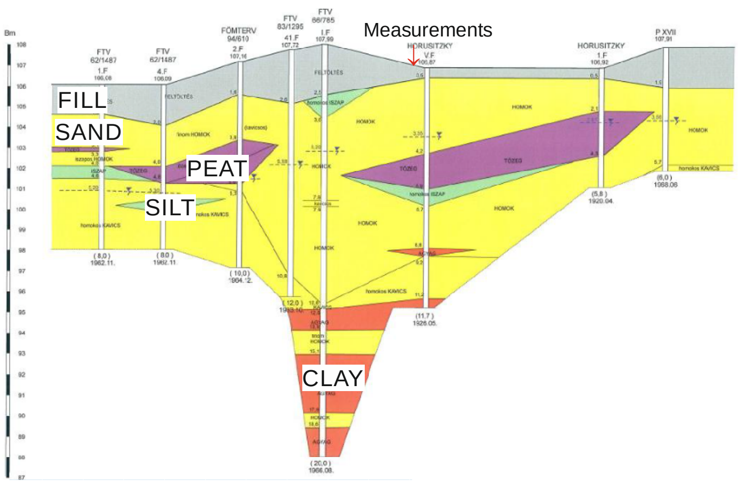


Fig. 11. Geological profile at the location of surface wave measurements carried out in Városliget

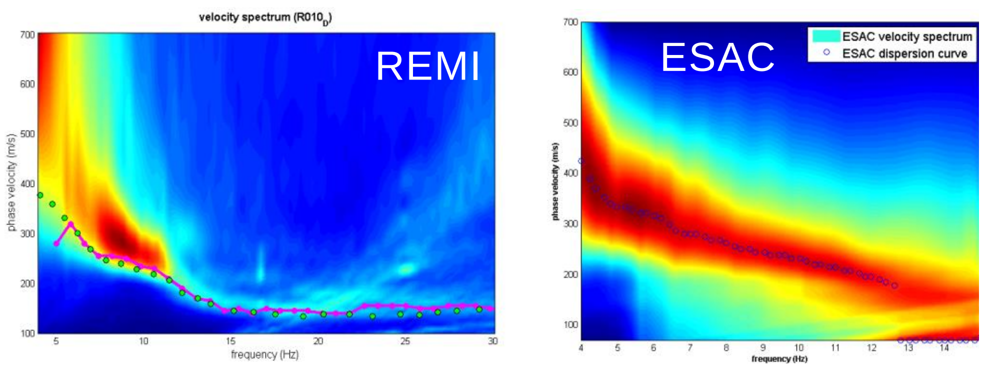
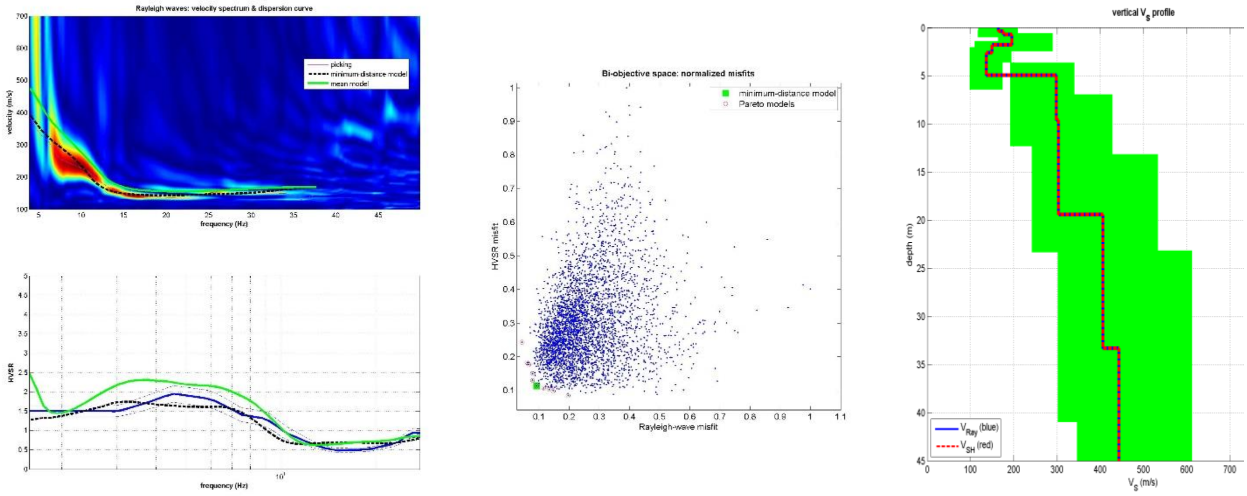


Fig. 12. Geological profile at the location of surface wave measurements carried out in Városliget



a) b) c)

Fig. 13. a) Rayleigh wave velocity spectrum computed from MASW measurement (up) and the H/V curve (down). The picked dispersion curve was determined using the velocity spectrum of all three types of measurements (MASW, REMI, ESAC). b) bi-objective space with a cloud of misfits of the models c) the resulted V_S profile with the search space

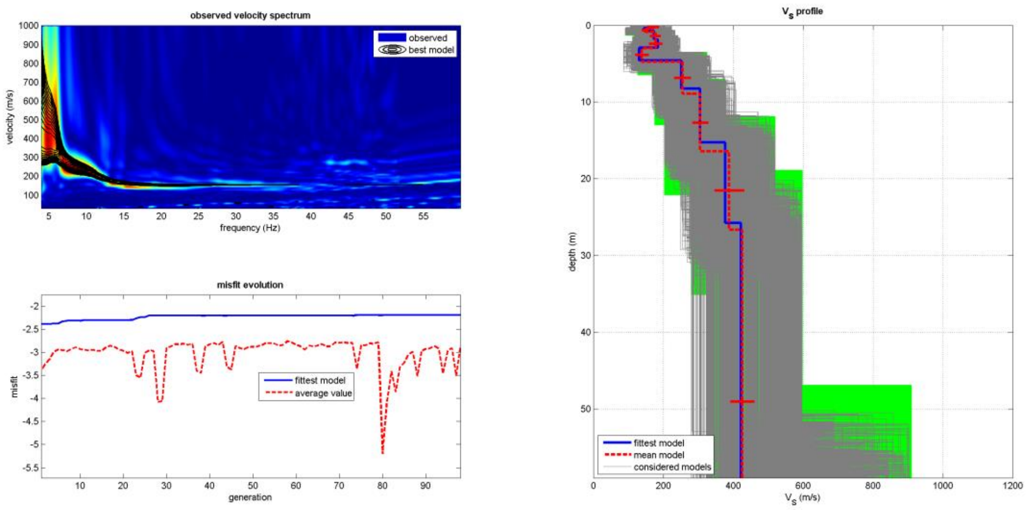


Fig. 14. Results of full velocity spectrum inversion in Városliget.

4.3.2. Ambient noise correlation method

Ambient noise correlation method (Shapiro & Campillo, 2004) uses the cross-correlation of two, simultaneously recorded seismograms to infer the impulse response of the medium between the two receivers. The cross-correlation function is used to generate dispersion curves, which can be inverted for S wave velocities. The application of the noise correlation method has been spreading rapidly because of its numerous advantages. Besides studying the structure and velocities of Earth's crust and mantle, microseismic noise tomography can also be applied for S wave velocity determination of shallow surface layers.

First we have applied the method on regional scale and investigated the Rayleigh wave velocity structure of the Pannonian basin with the ambient seismic noise tomography method using the data of the permanent seismological stations deployed in Hungary and in the surrounding countries. The obtained results have been published in a journal paper (Szanyi et al., 2013).

We have examined the applicability of the method in local scale and carried out noise measurements at all sites where the seismic measurements of GGI were performed (Fig.9b). In addition, measurements were done in Angyalföld too. The interstation distance between the simultaneously recording instruments varied from 40 m to 1.2 km. The measurement time was between 30 minutes and 2 hours depending on the interstation distance (the shorter measurement times belonged to the shorter distances). In a typical measurement setting we used three seismometers at the same time. This arrangement provided three station pairs for which we could determine the cross-correlation functions (CCFs).

The cross-correlation functions were used to obtain the dispersion curves and estimate surface wave group velocities. In order to retrieve the dispersion curves, the processing procedure of ambient noise data consists of four main steps (Bensen et al, 2007): 1) data preparation, 2) cross-correlation and stacking, 3) measurement of dispersion curves and 4) quality control.

Different methods were tested for the processing steps of correlation analysis and stacking and the best combination of them was selected to retrieve the cross-correlation functions and the dispersion curves. Data preparation begun with removing the mean and trend followed by frequency filtering. For time-domain normalization the one-bit normalization technique was applied.

The second phase is the cross-correlation computation and stacking of correlation functions. We have tested the conventional correlation method and the phase cross-correlation (PCC) method (Schimmel, 1999) as well. PCC improves the SNR of the cross-correlation function. It is more sensitive to waveform similarity and less sensitive to large amplitude phenomena than the conventional cross-correlation and it does not require time-domain normalization. Therefore we omitted the normalization step when PCC was applied. Two types of stacking techniques have been tested: the standard linear stacking, which is used in most of the ambient noise tomography studies and time-frequency phase weighted stacking described by Schimmel and Gallart (2007), which has been applied in some recent ambient seismic noise tomography studies. Various combinations of the previously described processing steps have been used to calculate the cross-correlation functions. We've compared the SNR ratio of the obtained cross-correlation functions and concluded that phase correlation with phase weighted stacking leads to the highest SNR.

We have determined group velocity dispersion curves for the CCFs computed from vertical, radial and transversal component of noise recordings. The group velocity dispersion curves determined from vertical and radial component recordings belong to Rayleigh waves, while the ones obtained from transversal noise components correspond to the Love waves. The group velocity dispersion curves were obtained using the frequency-time analysis (FTAN) method.

We computed CCFs for recordings belonging to 50 station pairs. For each pair the cross-correlation functions have been determined for the vertical, radial and transversal components. We found that the quality of the CCFs depends strongly on their type. Under quality we understand the cross-correlation function's suitability for dispersion curve determination. The most significant factors to quality are the signal/noise ratio of the CCF, the lack or presence of high frequency noise in the CCF and the appearance of the FTAN map.

If we consider all of the measurements (regardless of the location within the territory of Budapest), 60 % of the transversal CCFs can be considered of good quality. In the case of vertical and radial CCFs this ratio is much lower, it is around 30 %. Making a distinction between the densely and sparsely built/populated areas we can find a significant difference between ratios of good quality CCFs. E.g. if we examine the results based on the measurements performed in the territory of Városliget, the ratio of good quality CCFs is around 85 % for transversal component and 40 % for the vertical and radial components. Whereas in the Lágymányos region of Budapest, near the river Danube, between large buildings and in the presence of significant traffic, we haven't found good quality CCFs in the case of vertical and radial components and the ratio of the good quality transversal component CCFs was only around 10 %.

The results of measurements that were performed on the same place as the active and passive seismic measurements in the Városliget can be seen in Figure 15. Figure 15a shows the CCF that was computed from vertical components of two seismometers which were in 309 m distance from each other. So group velocity dispersion curve of Rayleigh-wave was determined from cross correlation function (Fig. 15b). On the left side of Figure 14c the red lines show the best fitting velocity-depth functions while on the right side their misfit values with the picked group velocity curve can be seen. Although the resolution of the depth-velocity function determined using noise cross correlation method is lower than the resolution given by seismic methods, it could give information about the velocities of larger depths.

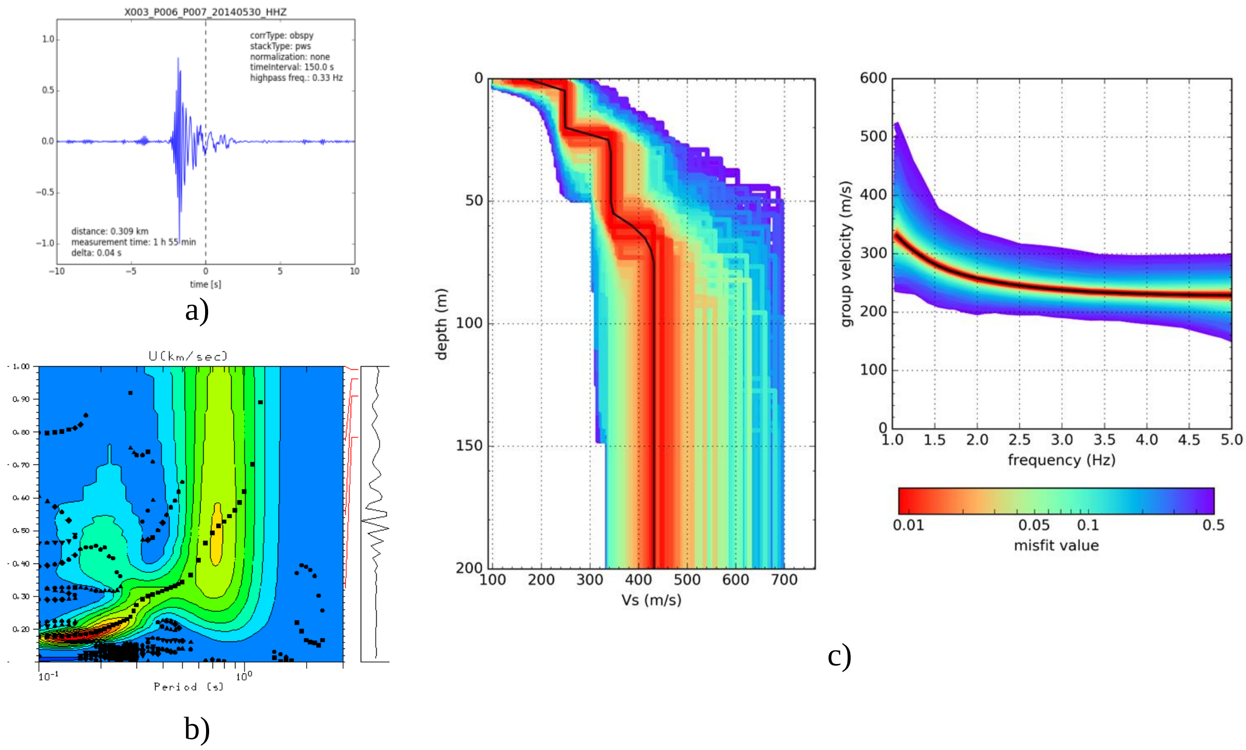


Fig. 15. Determination of velocity profile using ambient noise cross correlation method in Városliget: a) cross-correlation function, b) group velocity curve of Rayleigh wave and c) the results of inversion

Based on the above results we can conclude that the quality of the results of the ambient cross-correlation method depends strongly on the location of the measurements. We can expect better quality CCFs in more quiet environments, far from strong seismic noise sources. This phenomenon however unfortunately limits the applicability of the method in urban environments.

To make an experiment in a location with lower background noise, we have performed microseismic noise measurements in the loess high bank at Dunaszekcső. Our aim was to map the Rayleigh wave group velocity distribution on the area, because it can help to image intact and creviced areas. The measurements were performed in 31 points at an approximately 100 m x 80 m area on the Castle Hill which is a landslide prone area. Interstation distance between simultaneously recording instruments varied from 11 to 101 m. The instruments and the data processing method were the same as in Budapest. The obtained CCFs were rarely symmetric, indicating that the sources of ambient noise are non-uniformly distributed azimuthally. Out of 136 cross-correlation functions 62 yielded an acceptable dispersion curve. Despite the less than 50% acceptable curves, the measurements were successful. We have found low velocity areas which might indicate a previously unknown loosened domain.

The results were presented in ESC conference in Trieste (Szanyi et al. 2016), and published in a journal paper (Szanyi et al. 2016).

4.4. Resonance of surface sediments

Soil category maps based on solely on V_{S30} values doesn't explain entirely the damage distribution caused by earthquakes. These don't give information about the resonance of the subsoil, the possible topographic and 2-3D focusing effects. Resonance can be expected in case of large impedance contrast i.e. where large velocity hard rock is covered by loose sediments. Resonance frequency depends on the thickness and the average shear wave velocity in the upper loose layers while the strength of the resonance depends on the impedance contrast. A special soil class "E" in Eurocode 8 earthquake safety standard marks this type of subsoils.

We have performed microseismic noise measurements on the area to identify and delineate the areas where resonance can occur. We have determined the resonance frequencies and the strength of the resonance by computing horizontal-to-vertical spectral ratio (H/V) curves (Nakamura, 1998).

Because of the size of the studied area, we have to restrict the measurements to those areas where large impedance contrasts are expected on the basis of geological maps or where the damages during Dunaharaszti earthquake were larger than the average. So we have carried out microseismic noise measurements in 275 points within the boundaries (Fig. 10a) of the city using three Le3D/5s type mobile seismographs and Güralp datalogger. Arrival of instruments delayed for one year so we could begin the measurements in summer of 2014. Data processing were performed using WinMASW software (Dal Moro, 2014). The number of measurements also was limited some degree of the weather because the wind cause very strong variation in low frequency range (mainly below 1 Hz). This phenomenon could be decreased by burying of the sensor but it is not feasible in urban environment.

We carried out measurements among others in Városliget, Rákospalota, Angyalföld, Kőbánya, Lágymányos, Csepel Island, Gazdagrét, Hűvösvölgy, Óbuda, Vérmező, Districts XI and XXII. We could identify resonance in Kőbánya in Pest side and in the northern part of Csepel Island, near Budafok. But areas prone to resonance can be found mainly in the valleys and hill-side areas in Buda side. So we have identified some areas in Hűvösvölgy, Óbuda, Vérmező, Districts XI and XXII where soil resonance can occur during earthquakes.

Figure 16 shows the resonant frequencies determined from the measurements performed in Óbuda. Diameter of the points is proportional with the amplitude of resonance peak while their color shows their frequency. Large amplitude resonance peaks can be observed at the areas of hill-sides.

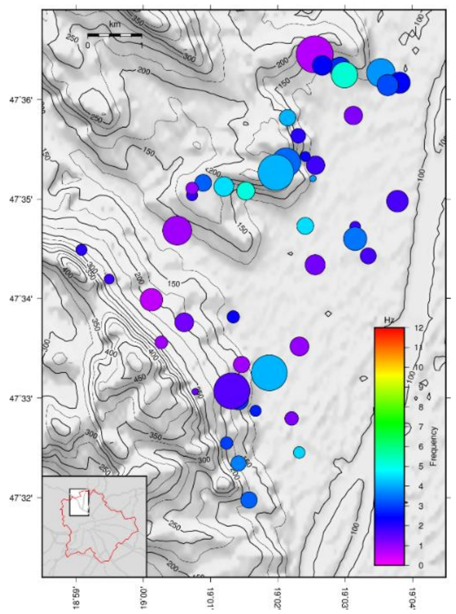


Fig. 16. Locations of measuring points in Óbuda plotted on the topographic map of the studied area. Diameter of the circles is proportional with the amplitude of resonance peak while their color shows their frequency

An interesting phenomena was found in Lágymányos where two peaks could be seen on H/V curves. The peaks indicated both the Oligocene-Triassic and the Quarter-Oligocene boundaries with less than 1 Hz and around 4 Hz respectively. It has to be note here that resonance of subsoil can be dangerous only in that case if the resonance frequency of subsoil and the buildings located there is coincident.

We show the results of microseismic noise measurements of a smaller area, called Hűvösvölgy in Figure 17-18. Hűvösvölgy is one of the areas where damages during Dunaharaszti earthquake were larger and the residents report stronger shaking during nearby earthquakes than the average. The area is located in a tectonic valley which is filled with Holocene sediments of variable thickness. We have computed the average H/V (Horizontal-to Vertical) spectral ratio curves (Fig. 17) and have determined their azimuthal variations (Fig. 18) which is useful for the recognition of site response directivity. We have found strong resonance in some locations but their frequencies are coincident with the resonance frequencies of the buildings only in the SE part of the area. Probably this soil-building interaction appears in the relatively large number of felt reports (Fig. 4b) that have arrived into the Observatory during recent earthquakes. Drawing the polarity diagrams onto a topographic map, amplification of topography moreover the effect of the valley edge could be also detected.

A BSc dissertation was made from the Hűvösvölgy microseismic noise measurements (Timpfel, 2015)

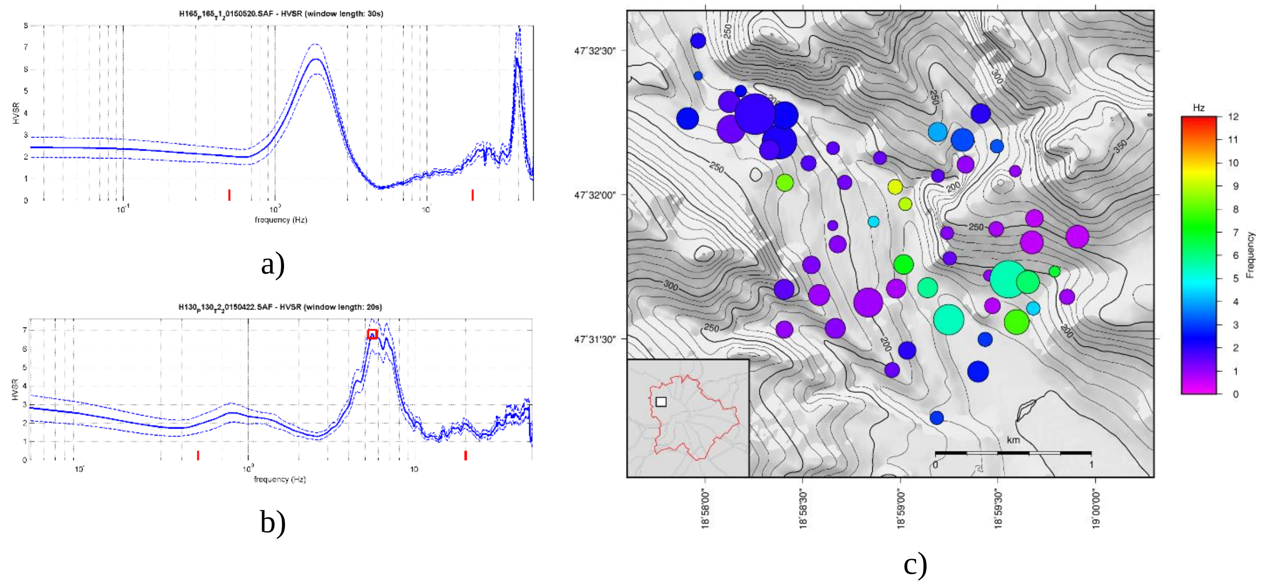


Fig. 17. Examples of H/V curves (a, b) and measurement points plotted on the topographic map of the studied area (d). The colors show the resonance frequencies while the size of the circles is proportional with the amplitude of resonance peaks. The high frequency peaks in the valley show the 1D resonance of the quaternary stream sediments while the low frequency ones arise from deeper structures or from lateral amplifications.

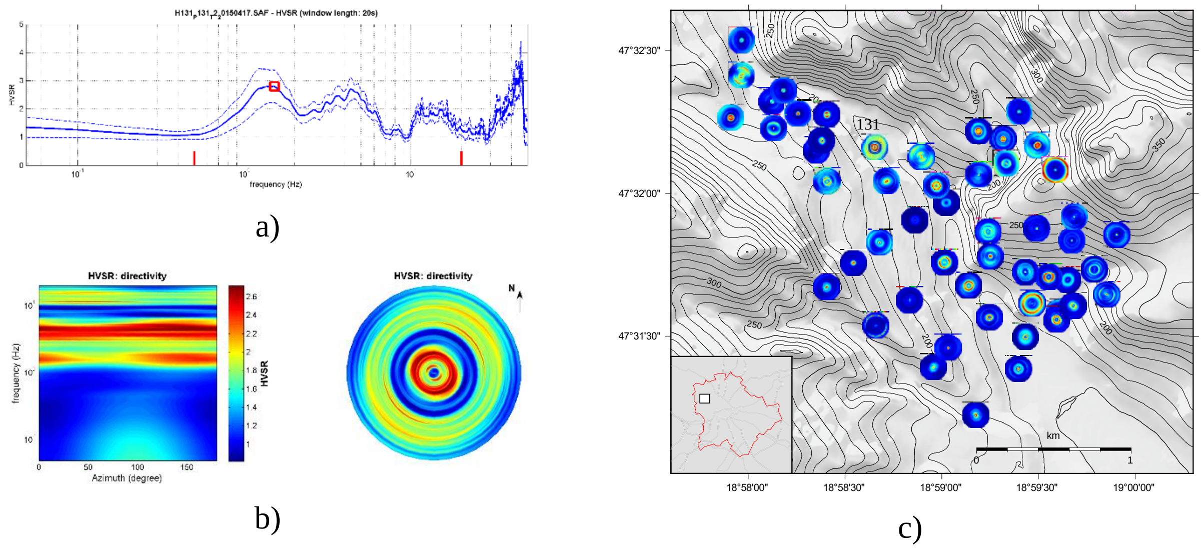


Fig. 18. a) Multiple resonance peaks on H/V curve and b) the directivity plot indicate the directional amplification. The computations were made for point 131. (The maximum frequency on the directivity plots is 20 Hz. The frequency axis on the polar plot is linear.) c) Directivity diagrams plotted on the topographic map of the studied area

4.5. Soil-building interaction

Heavy damages can occur during earthquakes even in newer buildings if the resonance frequencies of the soil and the buildings or structures are equal or very close to each other. Soil type ***E*** in Eurocode 8 standard indicates exactly the same kind of soil. According to the definition, this is a soil profile consisting of a loose surface alluvium layer with thickness varying between about 5 m and 20 m, underlain by stiffer material. The resonance frequencies of such layers are approximately between 2 Hz and 18 Hz. The resonance frequencies of usual one to ten story buildings, moreover the stiffer structures fall within this range.

We have performed microseismic noise measurements in different types of buildings (brick and panel buildings with different number of floors) and have measured the microseismic noise in different levels of the building. Fundamental mode could be determined from the peak on the H/V curve whose amplitude was increased with the floor number.

Our measurements confirmed the general rules that the resonance frequencies of buildings decrease with increasing number of levels or increasing height of the buildings. The highest studied building was the MTA building in Budaörsi Street with 1 Hz resonance frequency. The usual panel buildings of 8-11 levels have a resonance peak around 2 Hz (buildings of housing estate in Angyalföld, ELTE dorms in Budaörsi, Nagytétényi and Damjanich Street). The resonance frequencies of 2-6 level buildings in Budapest were highly variable, their values depended among others on the shape, width and the type of construction. Their values were typically between 3 and 8 Hz, while the smaller family houses had frequencies larger than 10 Hz.

4.6. Soil categorization

Soil categorization can be made primarily on the basis of soil classes defined in earthquake safety standards. The Eurocode 8 which is valid also in Hungary differentiates 5 standard (***A***–***E***) and 2 specific (***S₁, S₂***) soil categories. The ***A***–***E*** categories are defined by the V_{S30} value. The standard defines soil factor values for ***A***–***E*** categories e.g. multipliers that have to be applied to bedrock acceleration. For sites of the two specific types, special studies for the definition of seismic action are required. During the preparation of soil category map we tried to classify the soils into one of the ***A***–***E*** soil types.

To prepare the soil category map, digital versions of Engineering Geological Map Series (1:40000), Geomorphologic Map (1:20000) of Budapest, extent and thickness of Quaternary formations in Budapest (1:20000) were available. These were supplemented by borehole data, geological and geotechnical profiles, V_{S30} data, moreover P and S wave velocities for different types of formations. We have used Google Earth, GMT and several GIS software to prepare and to visualize the maps.

The prepared soil category map can be seen in Figure 19a.

According to definition of Eurocode 8, ground type ***A*** is rock or other rock-like geological formation, including at most 5 m of weaker material at the surface. The shear wave velocities in them are larger than 800 m/s. Based on the prior velocity information, the Triassic limestones, Fődolomit, Sashegy and Budaörs Dolomite Formations, Eocene Szépvölgy Limestone, Miocene Limestones, Badenian and Carpathian volcanic formations, Pleistocene travertine have been classified into this category. Therefore we considered the subsoil to be category ***A*** where the above listed rocks outcrop to the surface.

Very dense sands, gravels, or very stiff clays can be considered as ground type ***B***, where the average shear wave velocities in the top 30 m are between 360 and 800 m/s. Based on the available velocity information we classified the following rock types into category ***B***: Eocene formations, Buda Marl, Tard Clay, Kiscell Clay, Törökbálint and Hárshegy Sandstone Formations, Oligocene–Miocene formations, Miocene clayey and sandy soils. Usually formations that are older than Quaternary, were classified into soil type ***B***. Consequently, every area was rated as category ***B*** where the above listed formations outcrop to the surface. In addition, those areas where this type of dense sediments or sedimentary rocks are covered by relatively thin Quaternary, looser sands or clays are also included. Therefore based on the uncovered geological and Quaternary thickness maps, formations were classified as category ***B***, where the base is made of ***B*** type rocks and the thickness of the Quaternary layers above it is not more than 5–10 m.

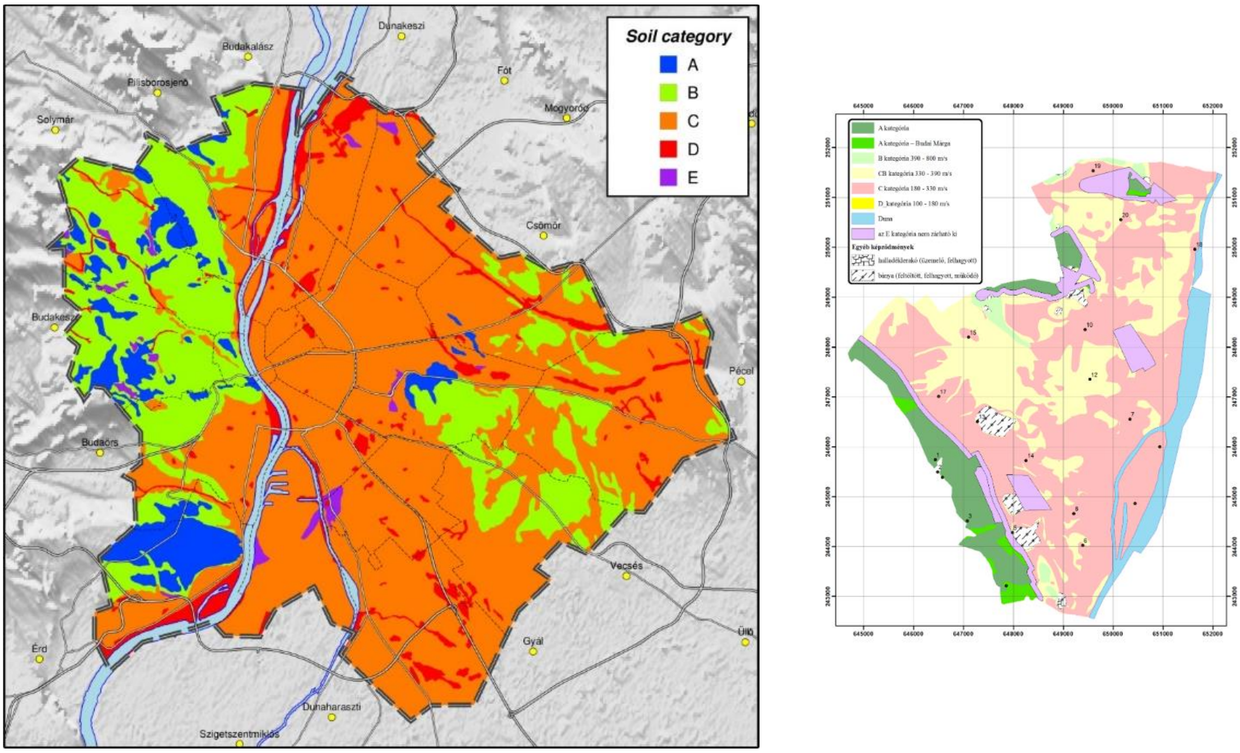
Soil types ***C*** are those of deep deposits of dense or medium dense sand, gravel or stiff clay, whose thickness range from several tens to many hundreds of meters. The average shear wave velocities in the top 30 m are between 180 and 360 m/s. Based on the results of velocity measurements of the previous years and in the frame of present project, most of the Holocene and Pleistocene sediments belong to this category. Such velocities characterize the coarse-grained sandy, gravelly sediments of Danube floodplain, the older, lower Holocene fine-grained silty and clayey soils, slope sediments, Pleistocene loess and creek alluvial fans.

According to the safety standard, we have to consider ***D*** type those deposits of loose-to-medium cohesionless soils, or of predominantly soft-to-firm cohesive soils, in which the shear wave velocities are less than 180 m/s. This category includes the very young, silty and clayey sediments, casting muds and peaty soils. On the basis of map of suitability for building projects of Budapest, we added to this category the "areas influenced by natural waters and consisting low loading capacity formations" and the marsh and polder areas. But contrary to our prior expectations, V_S measurements have not proved such low V_{S30} values on these areas. We have found very low velocity layers (less than 150 m/s) but the average V_S velocity in the upper 30 m was always above 200 m/s. Therefore ***D*** categories on the map of Figure 19a need to be revised.

The soil profile can be considered as ground type ***E***, which consists 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. Its separation from the other categories is justified by its resonance behavior.

Revision, digitizing and incorporation of Engineering Geological Map Series of Budapest into GIS database were in progress in MFGI during the time of the project. Some of them were completed only in 2015. Partly because of this and partly because of financial reasons we could not use this database in the MTA CSFK GGI.

However soil category map of Óbuda (Fig. 19b) was completed in the MFGI by Péter Tildy (2016) using this database moreover the velocities and geotechnical parameters of the formations found there. The construction of the map was the work of 2-3 years. Comparing this with the Óbuda part of the map in Figure 19a, it can be seen that the former is much more detailed. The main differences are in categorization of ***B*** and ***C*** soil classes but it has to be note that in a lot of cases the values of V_{S30} velocities are approximately at the boundary of the two categories.



a) b)

Fig. 19. a) Soil category map of Budapest using some digitized maps and b) soil category map of Óbuda completed using the GIS database of MFGI

Despite the differences manifested in the two maps, soil category map of the whole city (after some revision) can be used in microzonation for intensity and then in risk estimation. The reason is that differences in soil factors belonging to neighboring soil classes is quite small (In case of Type 2 spectrum, 1.35 and 1.5 at ***B*** and ***C*** categories, respectively) while according to the table in Figure 5, one intensity degree spans large acceleration range. Besides, V_{S30} based soil category is only one from the many factors that determine the experienced intensities.

Probabilistic seismic hazard map of Budapest in Figure 5a was prepared using intensity attenuation equations determined from Hungarian macroseismic data, and it is valid for the average ground conditions, not for a reference rock. Therefore intensity change can be positive or negative too, compared to this average soil.

The V_{S30} velocity of the so called "average soil" according to classification system of Eurocode 8, was computed using the V_{S30} map of Hungary and its vicinity (45.5 to 49° north latitude and 16–23° east longitude), determined from topographic gradient. The map was constructed from 30-arcsec SRTM data. The average of the velocities belonging to the grid points were considered as the average velocity for the country. It was 341 m/s, so we concluded that the average subsoil in Hungary and its immediate vicinity can be classified into category ***C***.

Between the logarithm of maximum ground acceleration (PGA) and intensity there is a linear relation. Therefore we can easily calculate the intensity change compared to average subsoil by soil factors. Using the widely used intensity-PGA equation of Wald et al. (1999) and the soil factors defined for Type 2 elastic response spectrum in Eurocode 8, we can compute the intensity modification of different soil categories with respect to soil type ***C***. (Presently the Type 1 spectrum is accepted in Hungary but the seismicity justifies rather the use of Type 2 spectrum) The calculated values (ΔI_t) are summarized in Table 2.

Table 2
Intensity changes computed for different soil types

Soil type	***A***	***B***	***C***	***D***	***E***
ΔI_t	-0.6	-0.2	0	0.3	0.1

As it is shown, the expected intensity decreases at categories ***A*** and ***B*** while increases at ***D*** and ***E***. It has to be mention here that intensities are expressed only in integer values, so the calculated values have to be round to the nearest integer value.

4.7. Other causes of amplification

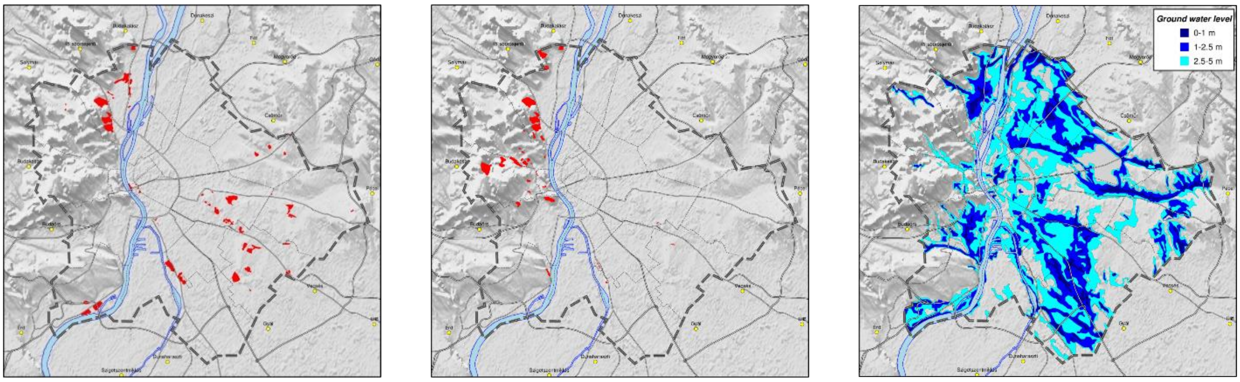
Damages in buildings can be caused by strong shaking and also due to failure of the soil. Low velocity layers amplify the surface motion that can be taken into account by the soil factors belonging to the soil categories. In addition, subsurface lateral inhomogeneities and formation boundaries can cause differential motion so larger damages; but the topography, the focusing effect of basins and valleys, the interferences at basin edges can also cause changes in intensity.

Serious damages can occur on artificial fills and on sloped areas prone to ground movement and sliding. In territories filled by miscellaneous materials of great thickness (Fig. 19a), low velocities and highly variable velocity distributions are often present, which can seriously increase surface motions. Moreover, heterogeneities can cause differences in soil settlements, which further aggravate the level of damages.

In slump-affected slope areas (Fig. 19b) an earthquake can initiate sliding. This can particularly happen if the soils soak through from a larger amount of precipitation. High water content reduces the strength of them, in clayey cohesive soils slip planes can evolve. In this case even a small magnitude earthquake can possibly induce landslide.

Comparing Figures 19a and 19b, we can see overlapping between the two maps in District III along the Bécsi road and on the slopes of Testvérhegy, Táborhegy, Remetehegy. Until the second half of the XX. century, the clay mines of Újlaki, Victoria-Bohn and Drasche brickyards operated here, which were post-mining replenished and cultivated. On the sloping surfaces besides the uneven soil settlements dip-oriented landslides can occur, thus these sites are indicated on both maps.

High groundwater level also can increase damages during earthquakes. Pore pressure increase during strong shaking causes decrease in bearing strength of the subsoil; even liquefaction can occur in loose saturated sandy sediment. Figure 20 shows the areas of groundwater level higher than 5 m in Budapest.



a) b) c)

Fig. 20. a) Areas filled with waste, b) areas prone to surface movements, c) areas of high groundwater level (after Raincsákné 1980)

The above mentioned circumstances increase earthquake damages, however the occurrence and impact of these phenomena cannot be quantified without appropriate geophysical, geotechnical measurements and numerical modelling. The amplification of intensities can be determined only on the basis of experiences gained during past earthquakes.

5. SUMMARY AND CONCLUSIONS

During the project, we have made seismological methodological research in seismic hazard assessment and microzonation of Budapest. We have gained valuable experience, but also new questions have arisen both in acceleration and intensity based determination of seismic hazard.

We have overviewed the earthquake catalogue of Hungary and worked out the methodology of discrimination of earthquakes and quarry blasts. We have renewed the macroseismic data collection which had a great effect to the number of incoming filled in questionnaires. We have found that the earlier intensity attenuation formulas don't describe well the experienced intensity attenuation of recent earthquakes. Therefore we have developed new intensity attenuation equations for the Pannonian Basin that was defined by the crust thickness of 30 km. The formula has described well the attenuation most of the earthquakes but in case of some larger events the epicentral intensity were larger and the attenuation were faster than it was predicted by our formula. It necessitate the overview the quality of primary data and maybe the overview of the applied formula. We have selected attenuation formulas adaptable in Hungary to compute acceleration based seismic hazard maps.

We have collected the observations in Budapest that were gained from past (historical and recent) earthquakes and studied their relationship with the local geology. Because we don't have instrumental information about the shaking strength caused by the 1956 Dunaharaszti earthquake, we have computed the horizontal accelerations in the epicenter, at the identified liquefied sites by "back-analysis" of liquefaction. The results showed very good agreement at the two locations; PGA was 0.18±0.03g at Taksony and 0.20±0.03g at Dunaharaszti.

Methodological research was also performed in microzonation. We have studied the applicability of topographic slope to estimate soil category with collecting and comparing the shear wave velocity data measured in Hungary with the relations determined from measurements of other areas. Correlation developed for tectonically active areas has been found to be more appropriate to use in Hungary but the method is applicable only for mapping on regional scale. We have studied active and passive surface wave methods to determine shear wave velocities that are applicable in urban environment. We have got good results with the joint inversion of dispersion curve determined from velocity spectrum of MASW, ESAC, ReMi measurements and the H/V ratios. In case of mode jumps the full velocity spectrum inversion gave the best results. We have studied the local applicability of ambient noise cross correlation method and have concluded that the quality of the results depends strongly on the location of the measurements. We have got miscellaneous results; the quality of CCFs was better in more quiet environments, far from strong seismic noise sources. Therefore we have made noise tomography measurements in the loess high bank at Dunaszekcső. The measurements were successful and we have found low velocity areas which might indicate a previously unknown loosened domain. We have performed microseismic noise measurements in Budapest and have identified areas prone to soil resonance. In case of some locations soil-building resonance were also manifested.

We have prepared soil category map of Budapest on the basis of Eurocode 8 soil classes using digital versions of Engineering Geological Map series of Budapest and the available velocity, geotechnical, borehole information from the area. This map has to be reviewed yet because the new measurements gave additional information to the categorization. Comparing the Óbuda parts of the map with the new soil category map of Óbuda which was prepared using the GIS database of MFGI (completed during this project) and the detailed available velocity and geotechnical data, it has to be stated that its resolution is much more less and cannot be applied in engineering design. However a microzonation for intensity can be made using it together with the areas of lateral amplification, artificial fills, and areas prone to surface movements, and high groundwater and can form the basis of the estimation of risk.

The lessons learnt from the research is that it is not a simple task to complete a detailed site condition map of the whole Budapest because of the lack of uniform in-situ shear wave velocity data sets similar to the ones in California, Japan, Taiwan, Italy etc. characterized by high seismicity. The costs of an enhanced measurement campaign hardly can be expected by a country situated in moderate seismicity terrain.

However there are some possibilities to finish a soil condition map by using GIS databases and available shear wave profiles that can help in seismic design. Till 2015, almost all of the important geological-geotechnical sheets of the Series of Engineering Geology Maps of Budapest have been digitized and built in GIS data sets. As a first step, these maps together with in-situ shear wave measurement results obtained in the last decade make it possible to complete a site condition map with limited effort within some years. Then the resulted map can be improved by additional in-situ data and correlation relationships depending on the allocated resources.

6. REFERENCES

Akkar, S., Sandıkkaya, M. A., & Bommer, J. J. (2014). Empirical ground-motion models for point-and extended-source crustal earthquake scenarios in Europe and the Middle East. *Bulletin of earthquake engineering*, *12*(1), 359-387.

Allen, T. I., & Wald, D. J. (2009). On the use of high-resolution topographic data as a proxy for seismic site conditions (VS30). *Bulletin of the Seismological Society of America*, *99*(2A), 935-943.

Bán, Z., Gyori, E., & Horváth, T. (2015, April). Back-calculation of surface acceleration from penetration resistances at liquefied sites of 1956 Dunaharaszti earthquake, in Hungary. In *EGU General Assembly Conference Abstracts* (Vol. 17, p. 9390).

Bensen, G. D., Ritzwoller, M. H., Barmin, M. P., Levshin, A. L., Lin, F., Moschetti, M. P., Yang, Y. (2007). Processing seismic ambient noise data to obtain reliable broad-band surface wave dispersion measurements. Geophysical Journal International, 169(3), 1239-1260.

Boore, D. M., Stewart, J. P., Seyhan, E., & Atkinson, G. M. (2014). NGA-West2 equations for predicting PGA, PGV, and 5% damped PSA for shallow crustal earthquakes. *Earthquake Spectra*, *30*(3), 1057-1085.

Boulanger, R. W., & Idriss, I. M. (2014). CPT and SPT based liquefaction triggering procedures. *Rep. No. UCD/CGM-14*, *1*.

Campbell, K. W., & Bozorgnia, Y. (2014). NGA-West2 ground motion model for the average horizontal components of PGA, PGV, and 5% damped linear acceleration response spectra. *Earthquake Spectra*, *30*(3), 1087-1115.

Cetin, K. O., Seed, R. B., Der Kiureghian, A., Tokimatsu, K., Harder Jr, L. F., Kayen, R. E., & Moss, R. E. (2004). Standard penetration test-based probabilistic and deterministic assessment of seismic soil liquefaction potential. *Journal of Geotechnical and Geoenvironmental Engineering*, *130*(12), 1314-1340.

Chiou, B. S. J., & Youngs, R. R. (2014). Update of the Chiou and Youngs NGA model for the average horizontal component of peak ground motion and response spectra. *Earthquake Spectra*, *30*(3), 1117-1153.

Dal Moro, G. (2014). *Surface wave analysis for near surface applications*. Elsevier.

Gráczer, Z., Czifra, T., Kiszely, M., Mónus, P., & Zsíros, T. (2012). Hungarian national seismological Bulletin 2011. *Kövesligethy Radó Seismological Observatory, MTA CSFK GGI, Budapest*, *336*.

Gyori, E., Gráczer, Z., & Szanyi, G. (2015, April). Intensity attenuation in the Pannonian Basin. In *EGU General Assembly Conference Abstracts* (Vol. 17, p. 4059).

Győri, E., Tóth, L., & Mónus, P. (2015). Secondary effects generated by earthquakes: liquefaction occurrences in and around Hungary. *Acta Geodaetica et Geophysica*, *50*(1), 79-95.

Juang, C. H., Fang, S. Y., & Khor, E. H. (2006). First-order reliability method for probabilistic liquefaction triggering analysis using CPT. *Journal of Geotechnical and Geoenvironmental Engineering*, *132*(3), 337-350.

Kiszely, M., & Gyori, E. (2013, April). Discrimination of earthquakes and quarry blasts in the Vértes Hills, Hungary. In *EGU General Assembly Conference Abstracts* (Vol. 15, p. 10596).

Kiszely, M., & Győri, E. (2015). Separation of quarry blasts from the aftershock sequence of the Oroszlány (Hungary) January 29, 2011 (ML= 4.5). *Acta Geodaetica et Geophysica*, *50*(1), 97-107.

Marótiné Kiszely, M., & Bánné Győri, E. (2014). Az Észak-középhegységben és Szlovákia déli területein kipattant földrengések és robbantások összehasonlító elemzése. *MAGYAR GEOFIZIKA*, *54*(4), 185-203.

Marótiné Kiszely, M., & Győri, E. (2014). A robbantások és földrengések elkülönítése különböző paraméterekre számolt Mahalanobis-távolságok segítségével. *GEOMATIKAI KÖZLEMÉNYEK*, *17*, 101-120.

Moss, R. E., Seed, R. B., Kayen, R. E., Stewart, J. P., Der Kiureghian, A., & Cetin, K. O. (2006). CPT-based probabilistic and deterministic assessment of in situ seismic soil liquefaction potential. *Journal of Geotechnical and Geoenvironmental Engineering*, *132*(8), 1032-1051.

Schimmel, M. (1999). Phase cross-correlations: Design, comparisons, and applications. Bulletin of the Seismological Society of America 89(5), 1366–1378.

Schimmel, M., Gallart, J. (2007). Frequency-dependent phase coherence for noise suppression in seismic array data. Journal of Geophysical Research: Solid Earth 112(B4).

Shapiro, N. M., Campillo, M. (2004). Emergence of broadband Rayleigh waves from correlations of the ambient seismic noise. Geophysical Research Letters, 31(7).

Sørensen, M. B., Stromeyer, D., & Grünthal, G. (2009). Attenuation of macroseismic intensity: A new relation for the Marmara Sea region, northwest Turkey. *Bulletin of the Seismological Society of America*, *99*(2A), 538-553.

Stromeyer, D., & Grünthal, G. (2009). Attenuation relationship of macroseismic intensities in Central Europe. *Bulletin of the Seismological Society of America*, *99*(2A), 554-565.

Szanyi, G., Gráczer, Z., & Győri, E. (2014). Macroseismic intensity data of the 22 April 2013 Tenk (Hungary) earthquake. *Acta Geodaetica et Geophysica*, *49*(3), 283-294.

Szanyi, G., Gráczer, Z., Győri, E., Kaláb, Z., & Lednická, M. (2016). Ambient Seismic Noise Tomography of a Loess High Bank at Dunaszekcső (Hungary). *Pure and Applied Geophysics*, *173*(8), 2913-2928.

Szanyi, Gy., Gráczer, Z., Győri, E. (2013). Ambient seismic noise Rayleigh wave tomography for the Pannonian basin. Acta Geodaetica et Geophysica 48(2), 209–220.

Tildy P. (2014) 9.1 Földrengés veszélyeztetettség — mérnökszeizmológiai térképezés, Kézirat, MFGI, Budapest

Tildy P. (2016) Talajmechanikai és a földrengések helyi hatásának vizsgálatához szükséges paraméterek meghatározása geofizikai módszerekkel, PhD értekezés, NyME, Sopron

Timkó M. (2015) Felszínközeli rétegek S-hullám sebességének vizsgálata MASW módszerrel. Szakdolgozat, ELTE TTK,

Timkó M. (2015) Lágymányoson végzett sekélyszeizmikus mérések együttes kiértékelése, TDK DOLGOZAT, GEOFIZIKUS MESTERSZAK

Timpfel G. (2015) Földrengések során bekövetkező rezonancia jelenségek és vizsgálatuk. Szakdolgozat, ELTE TTK, Geofizikai és Űrtudományi Tanszék

Völgyesi, L., Tóth, L., Győri, E., & Mónus, P. (2014). Seismic safety of the old buildings in Budapest downtown. *Építés-Építészettudomány*, *42*(1-2), 1-22.

Wald, D. J., & Allen, T. I. (2007). Topographic slope as a proxy for seismic site conditions and amplification. *Bulletin of the Seismological Society of America*, *97*(5), 1379-1395.

Zsíros, T. (1996). Macroseismic focal depth and intensity attenuation in the Carpathian region. *Acta Geod. Geoph. Hung*, *31*(1-2), 115-125.