4th International Conference on
Earthquake Geotechnical Engineering
June 25-28, 2007
Paper No. 1349

GEOTECHNICAL IN SITU INVESTIGATION USED FOR SEISMIC DESIGN OF BUILDINGS

Cristian ARION[1], Masahito TAMURA[2], Elena CALARASU[3],Cristian NEAGU[4]

ABSTRACT

The present process of harmonization of Romanian seismic codes with European standards requires that the effect of local site conditions be included through the soil factor, S, which must be included in the National Annex of Eurocode 8. The results of the SPT, down-hole prospecting, surface-wave method and CPT tests from the only one available Romanian site (Bucharest Tei) will be presented. The borehole data and the experimental research performed in the last years revealed a new series of elements regarding the stratification and soil characteristics in Bucharest. The evaluation of the soils liquefaction resistance based on in situ tests and the use of the earthquake records will be presented.

Keywords: seismic investigation, SPT, liquefaction, earthquakes, Bucharest

INTRODUCTION

The characterization of local soil conditions using in situ prospecting for establishing the superficial geology and to determine the values of dynamic parameters is an essential element for seismic design of constructions and urban planning. The use of those prospecting techniques represents an important stage in the implementation in Romania of modern codes for seismic design (EC8, EC7, ASCE and UBC). The present paper contains data obtained from geotechnical and seismic investigations at Bucharest Tei, situated in the north-eastern part of Bucharest. Technical University of Construction and National Centre for Seismic Risk Reduction specialists together with the colleagues form Building Research Institute, Japan and Tokyo Soil Research, Japan performed the tests.

The Bucharest metropolitan area is located in the Romanian Plain, along the Colentina and Dambovita rivers. The main source of earthquakes for Bucharest is the Vrancea seismic zone. Some distinct sedimentary complexes, with distinct peculiarities and a large interval of thickness characterize the geology of the city of Bucharest. Those superficial geological complexes were identified as Quaternary alluvial deposits.

The characterisation of ground conditions from the seismic point of view requires the knowledge of local geology and, if possible, of the dynamic soil properties, especially of the shear wave velocity that is used by many codes for ground type classification.

IN SITU PROSPECTING METHODS USED AT VARIOUS SITES IN BUCHAREST AREA

[1] Dr. eng., Technical University of Civil Engineering, Bucharest & National Center for Seismic Risk Reduction, Bucharest, Email: arion@utcb.ro
[2] Chief research Engineer, International Institute of Seismology and Earthquake Engineering (IISEE), BRI, JAPAN, Email: tamura@kenken.go.jp
[3] Eng., National Institute for Building Research, Romania & National Center for Seismic Risk Reduction, Bucharest, Email: celena@gmail.com
[4] Eng., National Center for Seismic Risk Reduction, Bucharest, Email: cristi@cnrrs.ro

In situ P and S-wave measurements
Probably the only direct method to know the elastic properties in depth is borehole logging using elastic waves. A relatively new technique, the suspension PS logging method, is used. Field results of P and S wave velocity measurements using this down-hole method are discussed for the present site investigation. The equipment used for the measurement of compression (P) and shear wave (S) velocities versus depth is a donation from Japan International Cooperation Agency (JICA).

The dynamic response of a site depends strongly on the dynamic properties of the soil. Researches into the dynamic characteristics of soil have been carried out using laboratory soil testing and in situ tests, including geophysical methods. The down-hole technique has become indispensable for determining values of dynamic parameters and Poisson's ratio of soils at relatively small strain levels.
Low-strain tests operate below the strain specified above and are based on the theory of wave propagation in the materials. One of the low-strain field tests is PS Logging, a seismic down-hole technique. In the down-hole method the sensors are placed at various depths in the boring and the source of energy is above the sensors - usually at the surface. This technique does not require as many borings as the cross-hole method, but the waves travel through several layers from the source to the sensors. Thus, the measured travel time reflects the cumulative travel through layers with different wave velocities, and interpreting the data requires sorting out the contribution of the layers. Since S and P wave velocities are calculated from the slope of a depth/travel time curve, the velocities are obtaining not for each incremental interval but for a velocity layer that has a certain thickness including many measuring points as an average values. The P-wave is generated by hitting a wooden pile with a large wooden hammer (as shows in Figure 1), and S-wave is generated by hitting the end of a plank horizontally with the same hammer (as shows in Figure 2). In most of borehole loggings, only the initial phase's data, especially the travel-time data, are used to obtain the velocity profiles. The analysis of travel-time data coordinated with the site stratigraphy revealed the seismic velocity profiles and other related parameters as Young's modulus (E_{din}), shear modulus (G_{din}) and Poisson's ratio (υ_{din}).


Figure 1. Generation of P-waves


Figure 2. Generation of S-waves

The modern codes for earthquake resistant design, including Eurocode 8, classify the soils based on qualitative indicators (description of stratigraphy, soil type, layer thickness etc.) and quantitative indicators (average shear wave velocity, Standard Penetration Test results, plasticity index etc.). Eurocode 8 specifies that the influence of local ground conditions on the seismic action shall generally be accounted for by considering the five ground types A, B, C, D and E, described by the stratigraphic profiles and parameters: average shear wave velocity over the top 30 meters, number of blows in the first 30 meters using standard penetration test or dynamic penetration, shear strain of undrained soil samples.

Standard Penetration Test (SPT)
The geotechnical method used for soil prospecting in different sites in Bucharest area consists in Standard Penetration Test (SPT). Starting to 2003, NCSRR received, as a donation from JICA, drilling equipment FRASTE Drilling Rig Type Multidrill XL, which has as attachments an automatic device used for Standard Penetration Test.

The purpose of the Standard Penetration Test is to identify the soil stratification, the layer thickness in order to estimate the geological and hydrogeological conditions and other engineering properties of soil layers as relative density of sands, the resistance and rigidity soil characteristics to penetration. During the drilling, it was possible to take disturbed and undisturbed samples (using double core barrel-sampler), which were used for further laboratory tests.

The resistance to penetration is obtained by counting the number of blows required to drive a steel tube of specified dimensions into the subsoil to a specified distance using a hammer of a specified weight (mass). The results of the SPT measurements are quantified in the number of blows required to affect that segment of penetration, N_{SPT}. The relative firmness or consistency of cohesive soils or density of cohesionless soils can be estimated from the blow count data. The SPT equipment, SPT split-barrel sampler and the drill rods used for soil penetration test are shown in Figure 3, and the soil sampling is presented in Figure 4.

Figure 3. Standard Penetration equipment

Figure 4. Soil sampling using SPT

In many countries, Standard Penetration Test remains the subsurface investigation technique of choice for geotechnical engineers. The test is well established in practice, provides a soil sample, and a vast amount of local experience and correlation data have been collected by researchers. The testing procedure varies in different parts of the world. Therefore, standardization of SPT was essential in order to facilitate the comparison of results from different investigations. Figure 5 present distinct items specifications included in the SPT standards of several countries. SPT standards used in different countries are as follows: Japan – Japanese Industrial Standard (JIS A 1219-2001), United States of America (USA) – American Society for Testing and Materials (ASTM, D 1586-2000), United Kingdom (UK) – British Standard (BS 5930:1981 – Code of Practice for Site Investigations), European Standard – CEN ISO 22476-3:2002 „Standard Penetration Test”, EUROCODE 7 (ENV), Part 3 „Design assisted by field testing”, 1997, revised in 1999, Romania – Romanian Standard for Soil Foundation „Soil investigation using standard dynamic penetration in drilling”, STAS 1242/5-1988, International Reference and Technical Papers on Penetration Testing, J. De Rutier – „Penetration Testing”, 1988.

Main items of specification	*JAPAN*	*USA*	*UK*	*ENV 7*	*ROMANIA*	*AUSTRALIA*	*CANADA*	*GREECE*	*MEXICO*	*PORTUGAL*	*POLAND*	*INDIA*
Scope												
- hammer weight (63.5 kg)	*	*	*	*	*	*	*	*	64	64	65	65
- falling distance (760 mm)	*	*	*	*	*	*	*	*	750	750	750	750
Boring restrictions												
- clean hole capability	*	*	*	*	*	*	*	*	*	*	*	*
- hole diameter restriction (mm)	65-150	57-152	<150	<150	min. 75	not specified	57-152	min. 75	57-152	not specified	not specified	55-150
Sampler assembly (lenght – mm)												
- extern diameter shoe (51.1±1)	*	*	50	*	*	*	*	*	*	no details	no details	50.8
- intern diameter shoe (35±1)	*	*	*	*	*	*	*	*	*			*
- sampler diameter 457	535	533	535	525	533	535	533	483	-			675
- solid cone	no	no	yes	no	no	yes	no	no	no			no
Drive rods												
- rod weight (4.33-10.03 kg)	*	*	*	*	*	*	*	*	*	*	*	*
- rod diameter (40.5-60 mm)	40.5	*	*	*	*	*	*	*	*	*	42-51	*
Executing test												
- maximum blows	50 during SPT test	100 50/50 mm	50 during SPT test	50 during SPT test	50 during SPT test	60 during SPT test	100 50/50 mm	50 during SPT test	50/100 mm	100 50/50 mm	-	20/250 mm
Use and practice												
- material range S=sands and silts C=clays G=gravels WR=weak rocks	S,C&G	S,C&G	S,C,G &WR	S,C&G	S,C&G	S,C,G&WR	glacial till	S,C	-	S,C&G drilling mud in loose sand	-	S,C

Figure 5. Standard Penetration Test standards in different countries

Cone Penetration Test (CPT)

The Cone Penetrometer Technology (CPT) provides cost-effective, real-time data for use in the characterization of the subsurface. The cone penetrometer consists of a steel cone that is hydraulically pushed into the ground while in situ measurements are continuously collected and transported to the surface for data interpretation and visualization. The cone penetration test is used for cohesive and cohesionless soils, especially for sandy soils and the maximum depth of the static penetration can be established between 25.00 to 30.00 meters. The purposes of the cone penetration test is to evaluate the soil type, geological and hydrogeological conditions, soil stratification, layers limits, thickness and inclination of the soil layers in the lithological profile, soil density and in situ stress condition, shear strength parameters. During the static penetration, the cone resistance (q_c) and the friction sleeve (f_s) are measured.

In July 2004, the CPT equipment from *Geomil, Holland*, was received as donation from JICA. The Cone Penetration Test equipment from Geomil and the electrical piezocone are presented in Figure 6 and Figure 7.

Figure 6. CPT equipment

Figure 7. Electric piezocone

Surface wave method

The surface-wave method can be carried out from ground surface nondestructively. The shear-wave velocity can be obtained by the surface-wave method. Surface-wave (Rayleigh wave) is elastic waves propagating along the ground surface and its energy concentrates near the ground surface. The surface-wave velocity of propagation strongly depends on S-wave velocity. If subsurface S-velocity vary with the depth, propagating velocity vary with its frequency or its wavelength. This character is called dispersion. Sub-surface S-wave velocity structure can be estimated by analysis of dispersion of the surface-waves. The surface wave method is the seismic exploration method in which the dispersion character of the surface-waves is analyzed.

Figure 8 shows the schematic view of a surface-wave method. Data acquisition and analysis for the surfaces is based on the MASW (Multichannel Analysis of Surface Waves) proposed by Park et al.(1999a, 1999b) and CMPCC (Common Mid Point Cross-correlation) analysis proposed by Hayashi and Suzuki (2004). A 10kg sledgehammer or 50kg weight drops are used as a source. The sources are placed with 1 to 4m intervals. 12 to 48 geo-phones (4.5Hz) are deployed with 0.5 to 2m intervals.

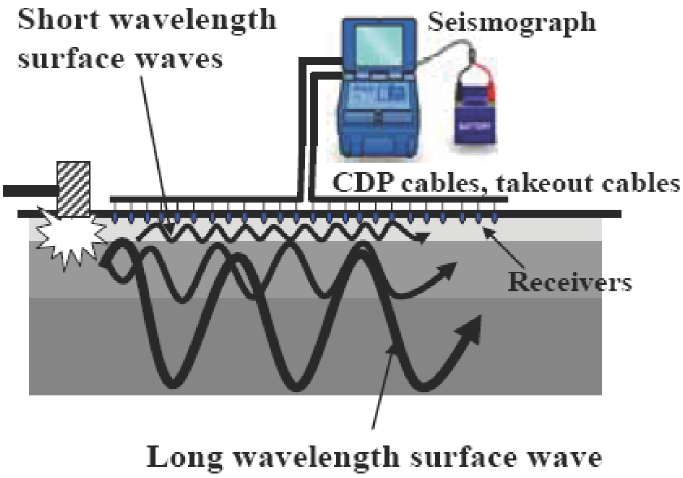

Figure 8. Schematic diagram of a surface-wave method

EVALUATION OF SOIL LIQUEFACTION RESISTANCE USING FIELD DATA

The recent developments in the numerical analyses for the nonlinear dynamic responses of grounds due to strong earthquake motions have increased the demand for the dynamic soil properties corresponding to large strain level.

The most common cause of ground failure during earthquake is the liquefaction phenomenon that has produced severe damage all over the world. The liquefaction of sandy soils and sands with non-plastic fines as a result of earthquake ground shaking poses a major threat to the safety of civil engineering structures. The problem of liquefaction is addressed in EC8, Part 5, § 4.1.3 "Potentially liquefiable soils" as well in the Annex B "Empirical Charts for simplified liquefaction analysis". The current state-of-practice is described by Youd et al. (2001).

Liquefaction resistance: empirical methods based on in situ penetration resistance

At higher range of shear strains, the behavior of soils is elastic-plastic and produce irrecoverable permanent to measure high-strain. Standard Penetration Test and Cone Penetration Test are of particular importance to measure high-strain characteristics of soil.

Many factors govern the liquefaction process for in situ soils and the most important are intensity of earthquake and its duration, location of ground water table, soil type, soil relative density, particle size gradation, particle shape, depositional environment of soil, soil drainage conditions, historical environment of the soil deposit and building additional loads of these deposits. Liquefaction susceptibility is usually expressed in terms of a factor of safety against its occurrence. This factor is defined as the ratio between available soil resistance to liquefaction, expressed in terms of the cyclic stresses required to induce liquefaction, and the cyclic stresses generated by the design earthquake.

Evaluation of soil liquefaction resistance using SPT results

The liquefaction resistance of soil deposits and prediction of the liquefied thickness is based on Standard Penetration Test blow counts in a single boring log. It is widely accepted that only the recent sediments or fills of saturated, cohesionless soils at shallow depth (< 20 meters) will liquefy in a large magnitude earthquake (M_w>7). Starting in the 1970's, H.B. Seed and his colleagues worked to develop a reliable method for assessing the liquefaction potential based on SPT data. Their framework for SPT-based assessments of liquefaction potential was developed in a series of papers that includes Seed and Idriss (1971), Seed et al. (1977), Seed (1979), Seed and Idriss (1981, 1982), Seed et al. (1983), significant contributions were also suggested in the work of Tokimatsu and Yoshimi (1983), Seed et al. (1985).

The empirical method in evaluating the soil liquefaction resistance from Standard Penetration Test blow counts is based on corrected values of $(N_1)_{60}$ and cyclic resistance ratio, CSR.

The first step in evaluating the soil liquefaction resistance is to correct the measured SPT blow counts N_{SPT}. The measured SPT blow counts is first normalized for the overburden stress at the depth of the test and corrected to a standardized value of $(N_1)_{60}$.

$$(N_1)_{60} = N_{SPT} \cdot C_N \cdot C_E \cdot C_B \cdot C_S \cdot C_R \tag{1}$$

where:
N_{SPT} represents the blow counts necessary for 30 cm soil penetration;
C_N, C_E, C_B, C_S, C_R are the correction factors

The next step in the liquefaction analysis procedure is to find the cyclic resistance ratio (CRR) for the soil based on the computed clean-sand equivalent ($(N_1)_{60cs}$). This is done using the empirical base curve drawn from the liquefaction catalogue for a magnitude 7.5 earthquake. The mathematical expression implemented for determining the cyclic resistance ratio for soil is:

$$100 \cdot CRR_{M=7.5} = \frac{95}{34-(N_1)_{60cs}} + \frac{(N_1)_{60cs}}{1.3} - \frac{1}{2} \tag{2}$$

where:
CRR is the cyclic resistance ration for a M=7.5 earthquake;
$(N_1)_{60cs}$ represents the clean-sand equivalent *SPT* value.

The value of $CRR_{M=7.5}$ must be adjusted for the magnitude of the earthquake under consideration. This is done with a magnitude scaling factor, MSF:

$$CRR = CRR_{M=7.5} \cdot MSF \tag{3}$$

where:
CRR is the cyclic resistance ratio of the soil for an earthquake magnitude corresponding to MSF, which can be considered by assuming that the main effect of different magnitude earthquakes on liquefaction resistance is the number of significant stress cycles generated (Seed et al., 1983).

Once the liquefaction resistance is known at a certain depth, the average cyclic shear stress generated by an earthquake must be estimated. The representative horizontal shear stress is computed with a simplified equation suggested by Seed et al. (1983, 1985) and expressed in terms of the cyclic stress ratio (CSR):

$$CSR = 0.65 \cdot \frac{a_{\max}}{g} \cdot \frac{\sigma_{vo}}{\sigma'_{vo}} \cdot r_d \quad (4)$$

where:

g=9.81m/s^2 is the acceleration due to gravity, σ_{vo} is the total vertical overburden stress, σ'_{vo} is the effective vertical overburden stress at the depth of interest, a_{max} is the maximum horizontal acceleration that would occur at the ground surface in the absence of excess pore pressures or liquefaction generated by the earthquake. The last parameter is the stress reduction factor, r_d, which accounts for soil flexibility as a function of depth. Several researchers have used simple linear equations to approximate these average r_d values, Seed and Idriss (1971), Tokimatsu and Yoshimi (1983), Liao and Whitman (1986) and Kayen et al. (1992).

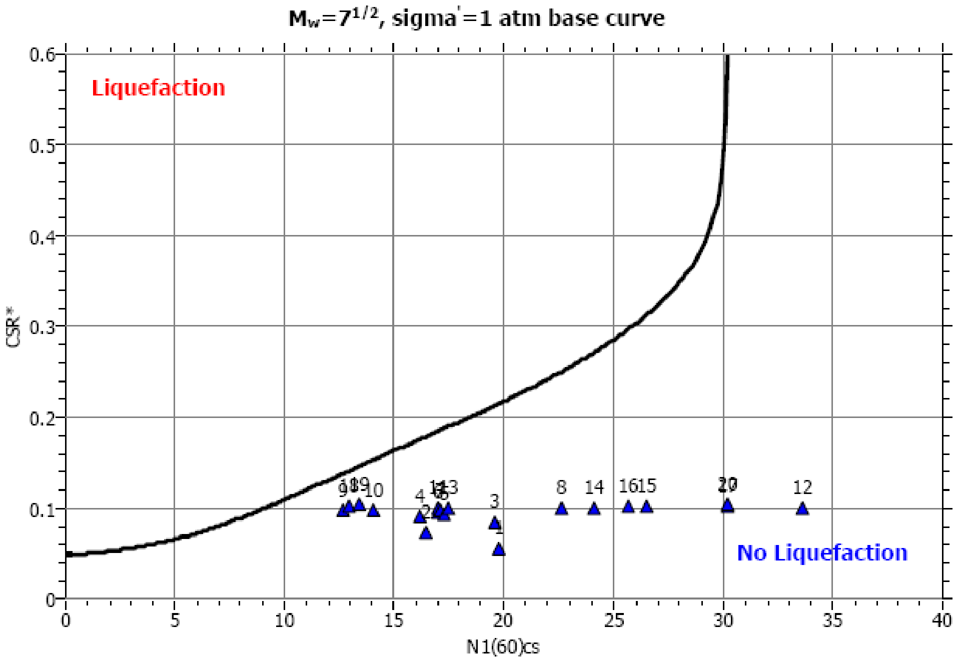

Figure 9. The assessment of soil liquefaction potential from SPT data at UTCB site (applying Eurocode 8 method)

The last step in the liquefaction analysis is to compute the factor of safety at each *SPT* location and the liquefied thickness. If the computed cyclic resistance ratio (*CRR*) of the soil is less than or equal to cyclic stress ratio (*CSR*) generated by an earthquake, liquefaction is assumed to occur at that location. The factor of safety against liquefaction, FS_{liq}, is defined with (Ishihara 1985, 1993; Seed and Hardner, 1990):

$$FS_{liq} = \frac{CRR}{CSR} \quad (5)$$

- $FS_{liq} \leq 1.0$ indicates that the soil at the depth of the measured SPT blow counts is predicted to liquefy
- $FS_{liq} > 1.0$ indicates no liquefaction

Evaluation of soil liquefaction resistance using shear wave velocities results

The preferable practice when using Vs measurements to evaluate liquefaction resistance is to drill sufficient boreholes and conduct sufficient tests to detect and delineate thin liquefiable strata, to identify non-liquefiable clay-rich soils, etc.

One method of direct determination of dynamic soil properties in the field is to measure the velocity of shear waves in the soil. The waves are generated by impacts produced by a hammer or by detonating charges of explosives, and the travel times are recorded. This is usually done in or between boreholes. The use of Vs as an index of liquefaction resistance is justified since both Vs and liquefaction resistance are influenced by many of the same factors (void ratio, effective confining pressure, stress history, geologic age).

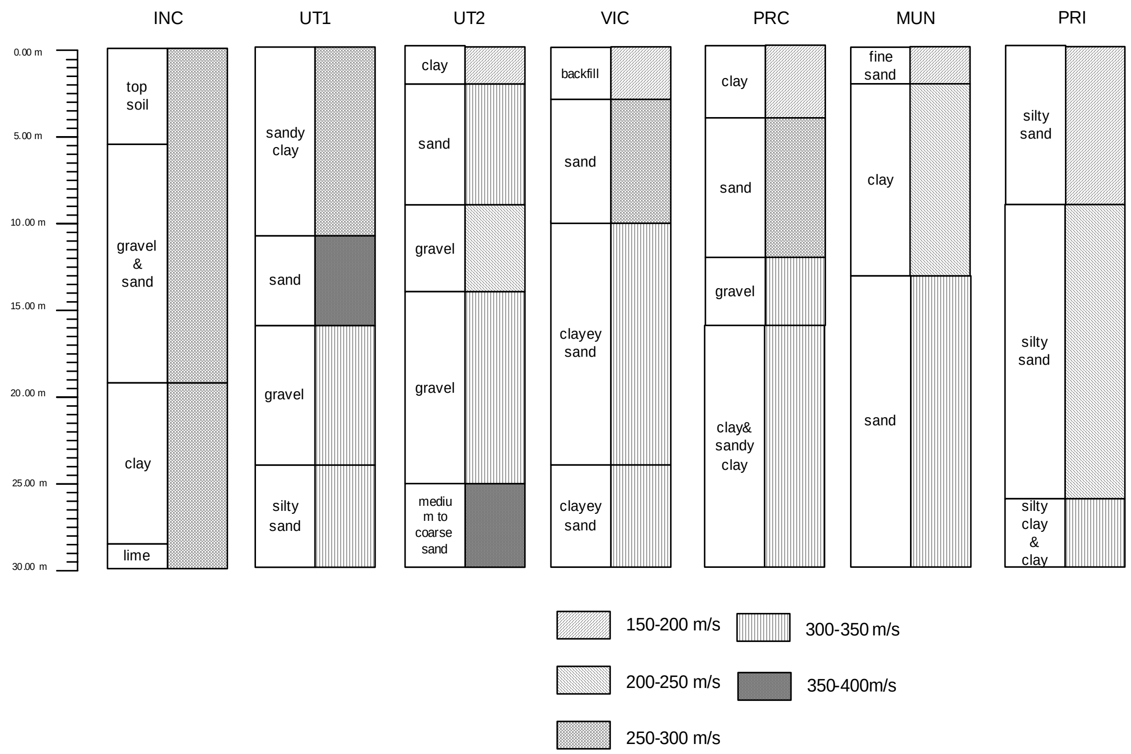

Figure 10. Results of in situ S-wave measurements at various sites in Bucharest area

The resistance of the soil, expressed as the cyclic resistance ratio is generally established by separating liquefied cases from non-liquefied cases in actual earthquakes. Here, following empirical equation defined by Andrus et al. (1999) is used:

$$\mathrm{CRR} = \left\{ a\left(\frac{V_{s1}}{100}\right)^2 + b\left(\frac{1}{c - V_{s1}}\right) - \frac{1}{c} \right\} \tag{6}$$

where:
a,b,c are parameters (a=0.022, b=2.8, c=200~215m/s), V_{s1} is the overburden stress corrected shear wave velocity defined as:

$$V_{s1} = V_s \left(\frac{Pa}{\sigma_v'}\right)^2 \tag{7}$$

where:
V_s = measured shear-wave velocity (m/s), Pa =reference stress (100kPa), σ_v' = initial effective overburden stress (kPa).
The parameter c in the equation (6) represents the limiting upper value of V_{s1} for liquefaction occurrence. Generally, in the SPT based simplified method, a corrected blow count (N) of 30 is assumed as the limiting upper value for liquefaction occurrence.

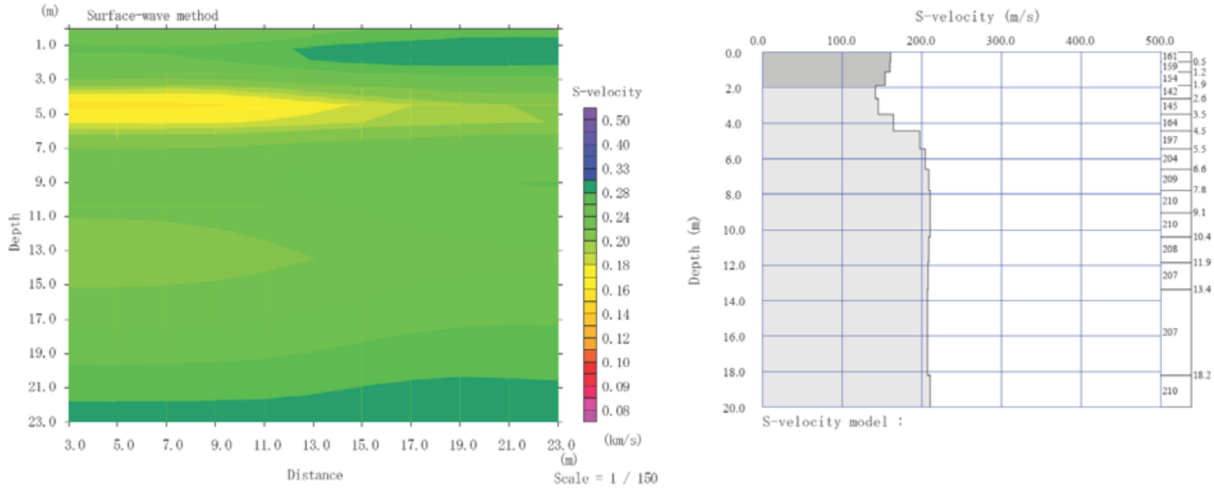

Figure 11. Shear-wave velocity models for the UTCB site obtained through the surface-wave method

CONCLUSIONS

The different local soil conditions in Bucharest area lead to a variability of the soil response at seismic ground motions, which can occur at small distances and can be observed even for the same city area. This is the reason why in the case of the large urban areas microzonation studies must take into account the mapping of the soil profile and the ground parameters.

We have applied seismic investigation to evaluate the liquefaction potential of the site.

Creating an informational database concerning the characteristics of superficial geology of Bucharest is the basis for determining the correlation between seismic velocities, SPT and CPT results and soil parameters at seismic motions. The corroboration of resulted information is useful for the characterization of local site conditions from the geological and geotechnical point of view. The database will set basis for the requirements of Romanian seismic codes, harmonized with the European and international codes.

The extended soil investigation by using those equipments will provide valuable data correlated with prior studies concerning seismic data processing, should be analyzed in the future in order to establish the microzonation parameters to be used for urban planning and earthquake risk reduction.

AKNOWLEDGEMENTS

The authors would like to acknowledge the funding provided by Japan International Cooperation Agency (JICA).

REFERENCES

American Society of Civil Engineers (ASCE, 7-98): „Minimum Design Loads for Buildings and Other Structures”, section 9 ”Earthquake Loads”.

Architectural Institute of Japan, 1993: “Earthquake Motion and Ground Condition”. In commemoration of the 20th anniversary of the Research Subcommittee on Earthquake Ground Motion.

Arion, C., 2004: „Report on soil tests and investigations (laboratory and field experiments)”, JICA/CNRRS/BRI.

Arion, C., 1999:„Soil amplification factors", Bulletin of the International Institute of Seismology and Earthquake Engineering IISEE, Tsukuba, Japan, Vol.35, p.307- 320.

Boulanger, R.W., R.B. Seed., 1995: „Liquefaction of Sand Under Bidirectional Monotonic and Cyclic Loading", Journal of Geotechnical Engineering 121(12):870-878.

Building Standard Law of Japan (BSLJ), 2000.

California Division of Mines and Geology (CDMG), 1997: „Guidelines for Evaluating and Mitigating Seismic Hazards in California". Special Publication 117, California Department of Conservation.

Department of the Navy (1997): "Soil dynamics and special design aspects".

Eurocode 8 (2003): „Design of structures for earthquake resistance", Part 1: General rules, seismic actions and rules for buildings.

Ferritto, J. , 1997: „Seismic Design Criteria for Soil Liquefaction", Technical Report TR-2077-SHR, U.S. Naval Facilities Engineering Services Center, Port Hueneme, CA.

Hayashi, K, and Suzuki, H(2004). "CMP cross-correlation analysis of multi-channel surface-wave data," Exploration Geophysics, Vol 35, pp7-13.

Ishihara, K. 1982: „Evaluation of soil properties for use in earthquake response analysis" Proc., Int. Symp. on Numerical Models in Geomechanics, Zurich: 237-259.

Ishihara K., 1996: „Soil Behaviour in Earthquake Engineering", Department of Civil Engineering Science University of Tokyo, Oxford Science Publications, 1996, 350 pg.

Lungu, D., Arion, C., Aldea, A., Vacareanu R., 2004: "Representation of seismic action in the new Romanian code for design of earthquake resistant buildings P100-2003", 13th World Conference on Earthquake Engineering, Vancouver, Canada, 15p., CD-ROM

Park, CB, Miller, RD, and Xia, J(1999a). "Multimodal analysis of high frequency surface waves," Proceedings of the symposium on the application of geophysics to engineering and environmental problems '99, pp115-121.

Park, CB, Miller, RD, and Xia, J(1999b). "Multichannel analysis of surface waves," Geophysics, Vol 4, pp.800-808.

PHRI, 1997: „Handbook on Liquefaction Remediation of Reclaimed Land".A.A. Balkema Publ., Brookfield.

Uniform Building Code, 1997: International Conference of Building Officials (ICBO), Whittier, California.

Youd, 1998: " Screening Guide for Rapid Assessment of Liquefaction Hazard at Highway Bridge Sites".