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GEO-DATA MODELLING AN ENGINEERING TOOL AS GUIDELINES FOR ESTIMATING NEAR-SURFACE SEISMICE EFFECTS

Elena-Andreea CALARASU[1], Cristian ARION[2], Cristian NEAGU[3]

ABSTRACT

Significant damages of built environment recorded during past seismic events have led to consideration of Romania's capital city as one of the major earthquake-prone urban area worldwide. Strong historical ground motions have outlined that variability and specific parameters of layered unconsolidated sedimentary young deposits represents one of key component in site-response analysis. To predict seismic effects of near-surface soils, comprehensive surveys are needed for the estimation of dynamic behavior and site characterization.

A large number of shallow and deep boreholes, standard penetration tests and non-invasive field techniques as down-hole and MASW have been carried out in Bucharest sites by CNRRS (now https://ccers.utcb.ro) and UTCB. Shear wave velocities (V_S) and penetration resistance (N-SPT) have been set as main indicators in quantifying seismic properties. Empirical correlations to predict V_S from N-SPT test values were developed by using statistical methods. The accuracy analysis of proposed correlations is compared with regression equations suggested in technical literature for assessing parameters performance with previous studies and to set out a good fit correlation for analyzed soil conditions. A comparative method between basic soil dynamic indexes determined by in situ investigation and the ones predicted by applying existing numerical models have been performed. The end-results can be considered as efficient guidelines to predict the potential effect of site conditions on similar soil types, layer sequences and properties, and might be useful for evaluation of buildings safety and optimization of seismic risk management strategies.

Keywords: sedimentary layers, Bucharest, geo-data

1. INTRODUCTION

The consequences of amplification effects induced by near-surface geological site conditions, associated with damage patterns and significant changes in amplitude and variation on certain frequencies of ground shaking, have been documented starting with historical 1891 Mino-Owari, 1906 San Francisco and 1923 Great Kanto earthquake. Initial investigations of site effects were primarily concerned on predicting an overall regional seismic response, without special attention of site behavior estimation. Over the years, worldwide destructive seismic events occurred during 20th century: 1940 El Centro (Mw=6,9), 1964 Niigata (Mw=7,6), 1971 San Fernando (Mw=6,7), 1985 Michoacan (Mw=8,0), 1989 Loma Prieta (Mw=6,8), 1994 Northridge (Mw=6,7), 1995 Hyogoken-nanbu (Mw=6,9), 1999 Kocaeli (Mw=7,6) and 21st century: 2003 Tokachi-Oki (Mw=8,3), 2008 Sichuan (Mw=7,9), 2010 Christchurch (Mw=7,1), 2010 Chile (Mw=8,8), 2011 Tohoku (Mw=9,0) are demonstrated that distribution of severe structural building damages in a specific area is more or less controlled by surface geology and the effect of local soil conditions. A large number of studies focused on the importance of site conditions in characteristics of seismic motion at ground surface have been carried out in the last decades (Borcherdt, 1970; Seed et al. 1987; Idriss, 1991; Bard, 1995). Different effects of shallow layers on ground motion are linked to topographical terms (Faccioli, 1991;

[1]PhD, National Institute for Research and Development in Construction, Urban Planning and Sustainable Spatial Development “URBAN-INCERC”, Bucharest INCERC Branch, Romania, andreea.calarasu@gmail.com
[2]Assoc. Prof., PhD, Technical University of Civil Engineering, cristian.arion@utcb.ro
[3]PhD, eng., Dublin City Council, cristi.neagu@dublincity.ie

Chavez-García et al. 1996) and geological and geotechnical setting (Aki, 1988, Ansal, 1994), which explained the variability of ground accelerations and response spectra values as a result of local site conditions.

Bucharest city is assigned as the most affected area by Vrancea subcrustal earthquakes, with a high concentration of building damages, casualties and economic loss due to its relative proximity to the epicentre and specificity of surface geology structure. Major historical seismic events generated by Vrancea source (1802: Mw=7,9; 1940: Mw=7,7 and 1977: Mw=7,4) have indicated the great influence of particular characteristics and geometrical features of soil layers on seismic motion parameters. The November 10th, 1940 Vrancea earthquake (Mw=7,7) was largely investigated and represents the starting point of earthquake engineering in Romania. The damage pattern in Bucharest and in Romania was explained by the effect of site geology on ground motion. The earthquake triggered liquefaction at many sites in South Moldavian Plain and in Romania Plain including Bucharest. At many sites in Romanian Plain and South of Moldova the earthquake produced ground cracks along river meadows. The majority of these cracks were accompanied by liquefaction.

The surface geological deposits from Bucharest area are composed from unconsolidated alluvial layers with variability in thickness and spatial distribution of cohesive and cohesionless soils. The relative heterogeneity of young formations in an alluvial basin explains the peculiar behavior during Vrancea strong motions imposed by local geology to seismic response. Concerning the assessment of near-surface site effects during 1977 Vrancea seismic motion, Ishihara and Perlea (1984) provide the first scientific detailed research regarding the liquefaction-associated ground damage of Dambovita river sandy deposits, based on extensive in situ site investigation.

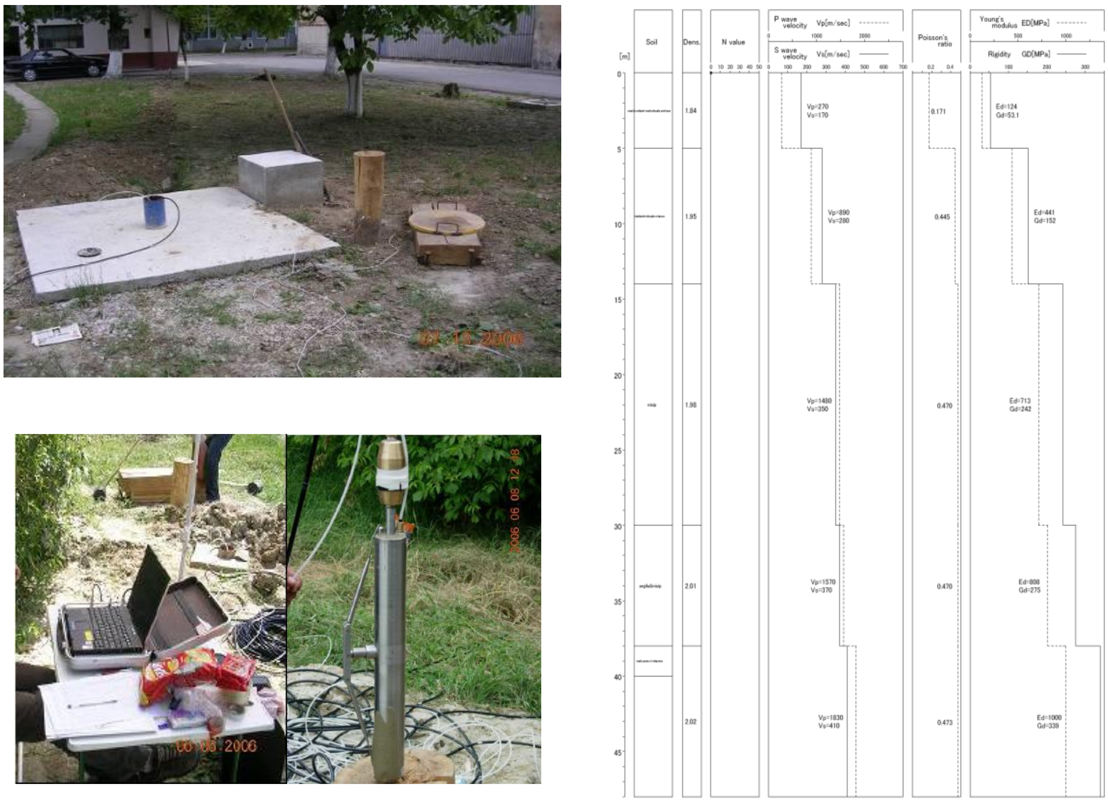
Modern seismic codes (Uniform Building Code, 1997; International Building Code, 2009; Building Standard Law in Japan, 2000 and Romanian P100-1/2013) and other significant regulations and standards (NEHRP 2003, SR EN 1998-1: 2004) are included provisions regarding site response. In mentioned codes, site effects are either quantified by seismic response coefficient linked to soil category and seismicity level or through different spectral shapes specific for defined soil types. Generally, ground conditions refers to soil classes differentiated by qualitative criteria as layers sequences in lithological profile and quantitative ones as shear wave velocities and penetration resistance values. Recently, the studies concerning local site effects assessment on Vrancea strong ground motions have substantially increased (Lungu et al. 2000, Aldea et al. 2003, Arion et al. 2007, 2012, Bala, 2013), as a result of upgrading and extending of seismic networks, modern equipment used for data recording, storage and real-time transmission, development of specialized software for scenarios and seismic response modelling, as well as improvement of ground investigation techniques. The present paper will contribute to this research topic by providing data obtained from detailed surveys performed on different Bucharest areas and empirical correlations of specific indicators (V_S and N-SPT) for site characterization of near-surface sedimentary to be further integrated in seismic response studies.

2. METHODS USED FOR INVESTIGATION OF SURFACE GEOLOGY

2.1 Basic ground parameters and applied methodologies

To assess the seismic effects of near-surface layered structures on ground response, an accurate determination of soil characteristics beneath a target site is required. Usually, site characterization in calculating seismic hazard is governed by shear wave velocities values (V_S), being considered as one of the most important components defining ground motion and soil-structure interaction. The application of V_S has the advantage of being based on an objective measure which affects ground motion in a way that can be modelled. Conventional criteria used for earthquake engineering design purposes (Borcherdt, 1994) are typically based on the distribution of shear wave velocities with depth in the upper 30 m of surface soil structures ($V_{s,30}$). Considered as reference index of dynamic behavior at small-strain levels, $V_{s,30}$ is used to classify sites according to the soil class. Although there is a widely application of this basic elastic property, it can be noticed that there is no complete agreement of using V_{s30} as single parameter in seismic amplification. Recent studies have highlighted additional input factors in ground response assessment, as vibration fundamental period of soil column by referring to thickness, topography and source directivity (Mucciareli and Gallipoli, 2006). Complementary, the number of blow counts gathered from Standard Penetration Test (N-SPT) can be used for seismic classification of soils.

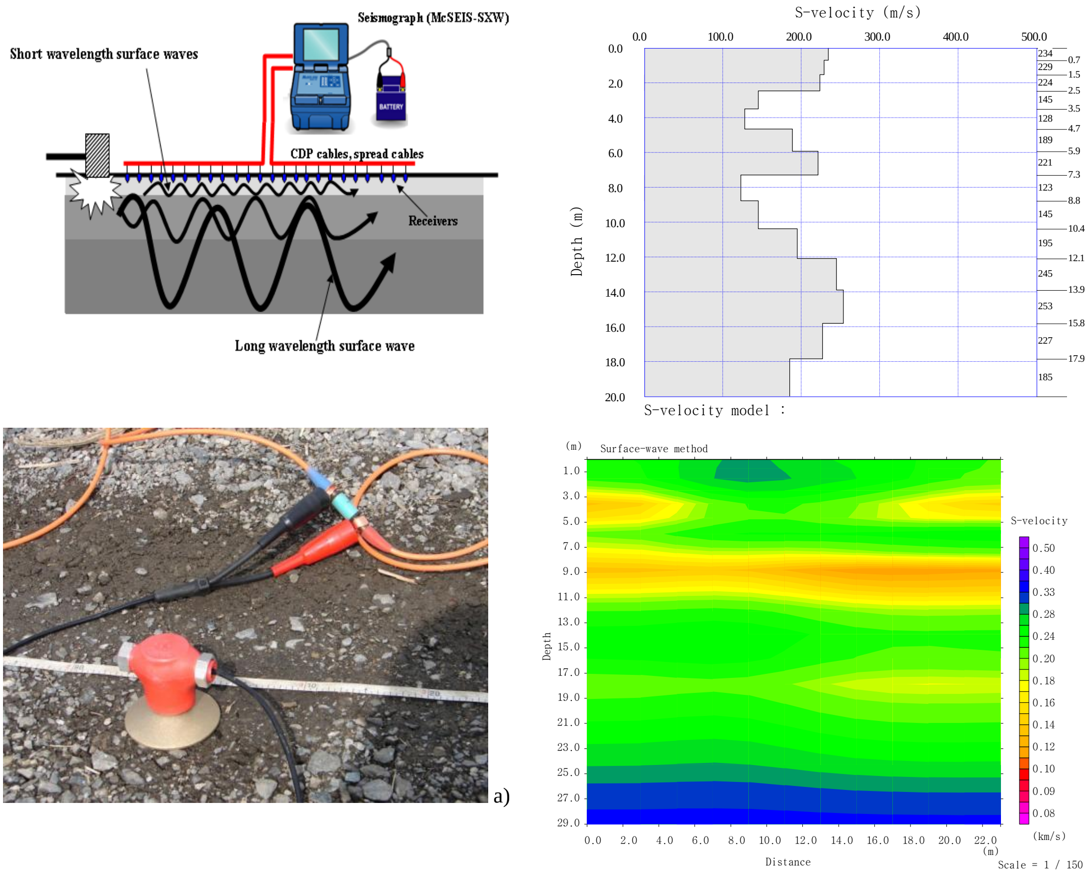
According to global concerns for a more reliable strong motion prediction, comprehensive geophysical and geotechnical investigations have to be conducted in various sites of Bucharest during JICA project by the NCRRS team. Down-hole PS Logging have been used as simple and non-invasive geophysical technique for measurement of seismic waves velocities in more than 20 sites, with a depth investigation ranging from 30 m up to more than 100 m. The impulse source of energy is generated at the ground surface, shear wave records (SH and SV) being obtained by striking a wood plank horizontally and in opposite direction, while compression wave by dropping a wood hammer on the ground. The velocity sensor is composed by three geophones (2 horizontal and 1 vertical). During down-hole measurements, sensor was lowered in borehole up to a predetermined depth investigation, being blocked on boring wall for detecting the waves generated by the surface source at 1m interval of soil column. The equipment system (see Figure 1a) used for velocity measurements is composed from GEODAS acquisition station and PS Logging sensor. Based on the records collected from down-hole techniques on various sites, measured travel time reflects cumulative travel through layers with different wave velocities. Since P and S wave velocities are calculated from the slope of a depth/travel time curve, wave velocities are obtaining for a velocity layer that has a certain thickness including many measuring points as an average values. Specialized software PsLog has been used for data acquisition and software application PS Start for recorded data processing. The 1D velocity profiles of sites (Figure 1b) are also including a description of soil layer type identified by borehole sampling, which can be considered as a boundary index when dealing with sensitive differences of recorded velocities. It is widely recognized the utility of shear modulus (G_d), Young modulus (E_d) and Poisson's ratio (ν), which represents the key characteristics in predicting soil response and soil-structure system to dynamic load actions. Considering P and S-wave velocity values, elastic soil properties of each soil layer from investigated profile were computed.



a) b)

Figure 1. a) PS Suspension Logging system (down-hole technique); b) 1D velocity profiles

An alternative technique to obtain S-wave velocity profile at near-surface soil structure is multi-channel analysis of surface waves (MASW) method, in which the dispersion character of experimental Rayleigh waves is analyzed, was also conducted for Bucharest sites. Recently, the method is applied to engineering problems for microzonation and site response studies and geotechnical characterization of shallow sediments (Park et al. 2001). The MASW method developed to estimate Vs profile is considered as a non-intrusive technique, cost effective, easy procedure and less time consuming as compared to other seismic methods used for shallow deposits. The MASW system for measuring short wavelength of surface waves consists in an impact source to generate energy (sledge hammer), 12-48 geophones placed in a linear array at 3 m intervals, with 4.5 Hz frequency and data logger (Figure 2a). By using data recorded during MASW method, measurements of phase velocity of Rayleigh waves of different frequencies have been used to determine Vs profiles. After calculating dispersion curve, it was built an initial Vs model (1D model), followed by inversion algorithms to look up for an optimum Vs profile model that best fits dispersion curve of experimental data (2D model), as in Figure 2b.



a)
b)

Figure 2. a) Data acquisition system and geophone for MASW method;
b) 1D and 2D shear wave velocity profiling

Additionally to seismic methods, more than 30 applications of standard penetration tests have been performed, with depth investigation ranging from 20-50 m in order to assess penetration soil resistance of shallow layers. Standard Penetration test (SPT) represents one of the oldest, popular and common geotechnical method for in situ investigation used in geotechnical and earthquake engineering projects because of simplicity of equipment and efficiency of test procedure. Standard Penetration Test is used to determine soil type, strength and deformation characteristics, with special applications in cohesionless soils, being generally recommended for geotechnical investigations of shallow deposits. In particular SPT method are widely used for seismic site characterization, site response and liquefaction studies towards seismic microzonation due to large data availability (Dobry et al. 2000, Arion et al. 2015). Penetration resistance values have to be used as a supplementary parameter or combined with V_s for defining soil categories and seismic site characterization. The resistance to penetration was obtained by counting the number of blows required to drive a steel tube of specified dimensions into the subsoil to a specified falling height using a hammer with standardized weight. The disadvantage of method consists in limited shallow depth investigation up to 40-50 m and soil disturbance, being considered an invasive geotechnical technique.

2.2 Geo-data analysis and seismic site characterization

From geotechnical point of view, based on observational and testing results, investigated sites consists in the following layer sequences from the top to bottom of soil profile: (1) loess-like deposits with clayed and sandy silts, silty and sandy clay, medium to high plasticity and high porosity; (2) poorly-graded fine to medium gravel with fine to coarse sands, loose to medium dense state; (3) clays and intercalation of silty and sandy clays, medium to high plasticity, stiff consistency state; (4) well-graded medium to coarse sands, with intercalations of sandy clay and silt, medium dense to very dense state;

(5) clays and marl clay, very stiff to hard consistency state, high plasticity. Soil characterization based on specific characteristics in profiles was emphasized lateral and vertical inhomogeneity of soil layers, reflected in thickness variability on sites. Furthermore, for a comprehensive site characterization, results of field investigation are integrated. According to modern seismic code provisions, the average shear wave velocity of the upper 30 m can be calculated with the Equation 1:

$$V_{s,30} = 30 / \sum_{i=1}^{n} (d_i / V_{si}) \tag{1}$$

where: d_i and V_{si} denote the thickness (m) and shear wave velocity of the *i*-th layer from the upper 30 m. By processing field data measurements and developing V_s profiles, $V_{s,30}$ values were calculated in accordance with Equation 1 ranging from 219m/s to 316m/s, as illustrated in Figure 3. The sites are classified in soil class S, which correspond to a stiff soil profile ($V_{s,30}$=180-360m/s) according to UBC 97, IBC 2009 and NEHRP 2003 provisions. Compared to these standards, $V_{s,30}$ values belong to class C corresponding to intermediary soil profile according to EC8 and P100-1/2013, consisting in deep deposits, with thick dense and medium dense sand, gravel and clay.

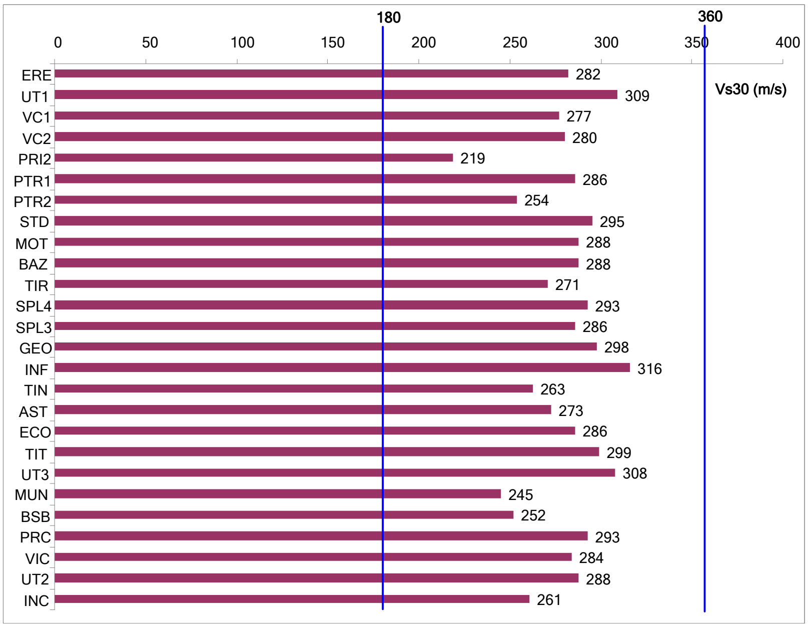


Figure 3. Variability of V_{s30} values on sites

The experimental values of shear-wave velocities gathered from down-hole measurements were grouped and analyzed in several statistical distribution for estimating the factors and relations between parameters for a better understanding of dynamic behavior of soil conditions from engineering point of view. Using power regression type, it can be observed a strong correlation of V_S values calculated for each depth interval in the upper 30 m and maximum depth investigation, reflected by coefficient correlation of about R^2=0.78, respectively R^2=0.80, as represented in Figure 4. V_S values measured up to maximum depth of site investigation are varying from 261 m/s to 361 m/s. Moreover, the comparison of these set of values reveals a relative low increase of S-velocities ranging from 10% up to 15% for a great part of sites. For deep measurements, the increase of V_S values calculated for total investigation thickness of soil layers can reach 20-30%, so it can be mentioned that thickness of sedimentary layers intercepted in boreholes can represents an important factor in velocity profiles, especially in case of deep alluvial deposits.

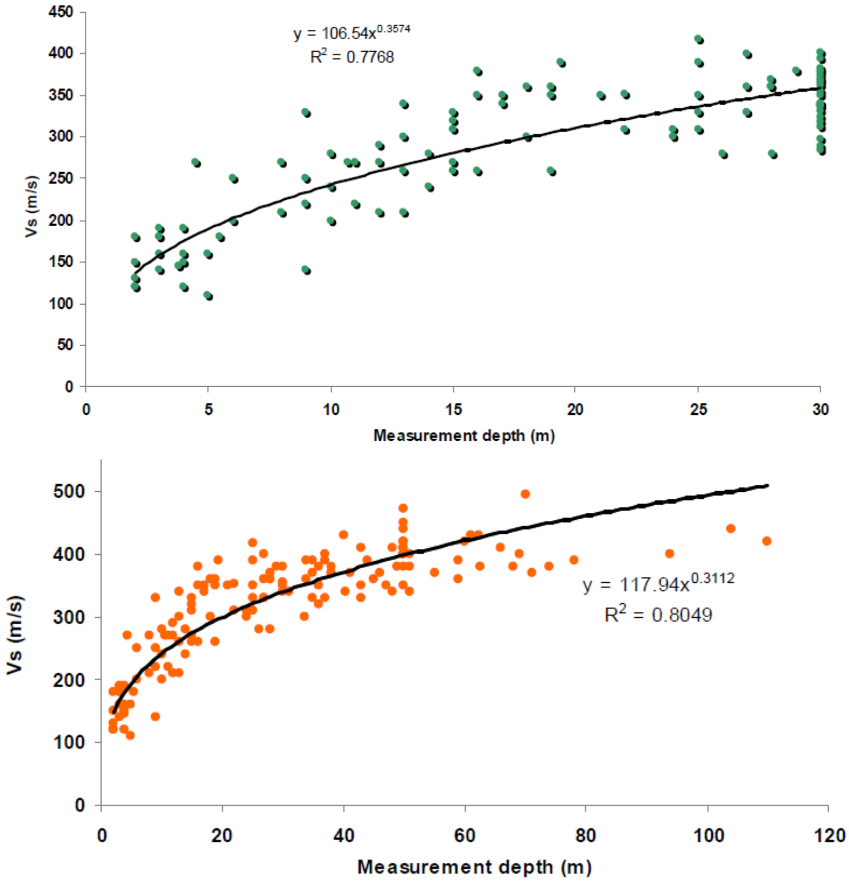


Figure 4. Distribution of V_s values in the upper 30 m and maximum depth investigation

An important issue in site effects assessments is to estimate characteristic period of site, defined as period of vibration corresponding to the fundamental frequency. The vibration period of soil layers in the upper 30 m ($T_{s,30}$) is calculated using the Equation 2 specified in P100-1/2013:

$$T_{s,30} = 4h / V_{s,30} \qquad (2)$$

where: *h* is soil depth and $V_{s,30}$ is average S-wave velocities on the first 30 m. The minimum value of $T_{s,30}$ was 0.38s and the maximum value was 0.55s for investigated sites. The elastic natural period of a specific site have to be taking into account in relation with vibration period of structure in order to estimate amplification effects of soft soils known as resonance and furthermore building vulnerability.
For several sites where ground survey was conducted by both down-hole and MASW methods, a comparative analysis of $V_{s,}$ values corresponding to each depth interval in soil profile and average $V_{s,30}$ has been performed, as shown in Figure 5. $V_{s,30}$ data obtained from MASW are ranging from 189 m/s to 302 m/s, which can indicate that sites are included in soil class C, similar to soil type defined trough down-hole seismic method. It can be observed that data collected from MASW application are grouped in a constant interval velocity 150-250 m/s comparing to a larger and gradually increase one obtained from down-hole technique. Differences between $V_{s,30}$ values obtained in down-hole and MASW surveys are ranging from 15-35%, probably due to constrain of depth investigation limitation, sensors sensitivity, procedure and equipment specificity and lateral discontinuities of soil profiles.

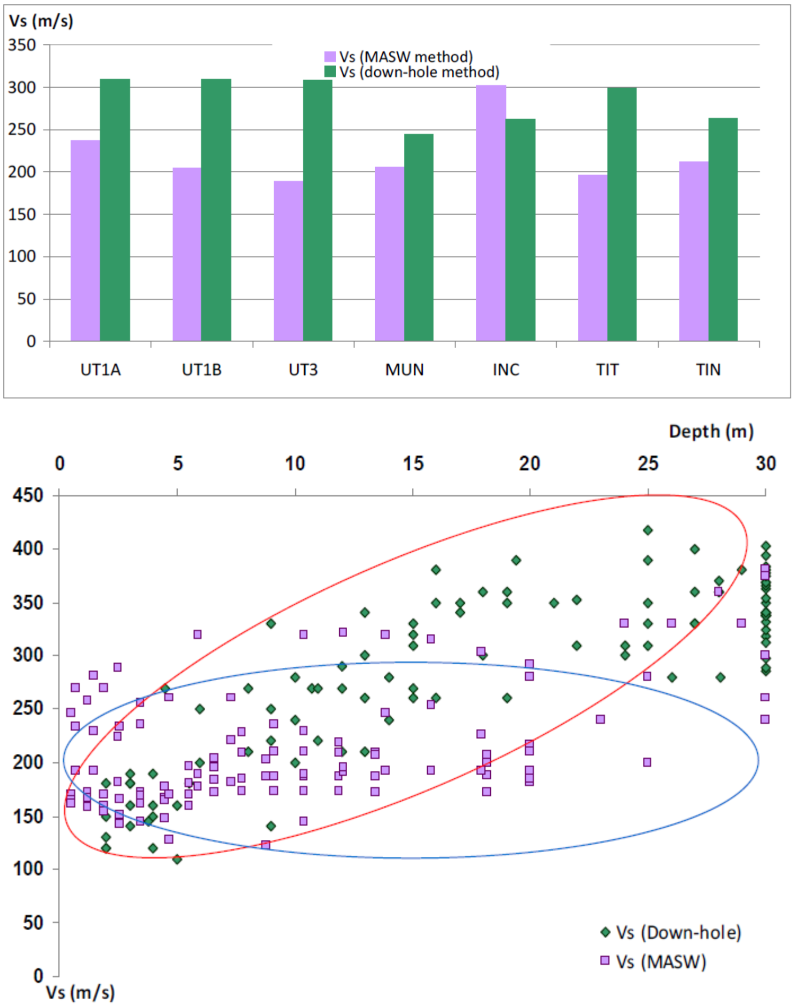


Figure 5. V_S geo-data comparison: down-hole (green) and MASW (magenta)

In order to complete the site characterization survey, invasive geotechnical methods as standard penetration test have been conducted. The sum of data recorded for 150-300 mm and 300-450 mm interval of sampler penetration represents the penetration resistance value called N-SPT at a specific depth. During SPT testing procedure, data regarding identification of soil nature, blow counts and layer thickness are recorded. Based on N-SPT values, representative penetration resistance profiles for each investigation site were performed. The results of standard penetration measurements and their empirical correlations with different geotechnical characteristics (shear strength and deformability) can be used in foundation design as bearing capacity and settlement calculations.

According to international seismic code provisions (BSSC, 2001; IBC, 2006; UBC, 1997 and EN 1998-1), the soil classes are also accounted by average of N-SPT values in the upper 30 m, recommended as supplementary or indirect investigation needed for seismic site classification and calculated with the Equation 3:

$$N_{SPT,30} = 30 / \sum_{i=1}^{n} \frac{d_i}{N_{SPT,i}} \qquad (3)$$

where: d_i and N_{SPT}, i denote the thickness (m) and penetration resistance measured on 30 cm of the *i-th* layer from the upper 30 m. Based on penetration resistance measurements and layer thickness, the average values for each site have been computed. Penetration resistances are varying from 12 blows/30 cm to 34 blows/30 cm and it can be observed that are grouped in class C, with corresponding values between 15-50 blows/30 cm. In terms of relative density, N-SPT values indicate the presence of medium to very dense sands and gravels, with individual values ranging from 15 blows/30 cm to more than 60 blows/30 cm. concerning consistency of cohesive soils, N-SPT values are ranging from soft to hard clay with 8 blows/30 cm up to 30 blows/30 cm.

3. EMPIRICAL CORRELATIONS BETWEEN V_S AND N-SPT

Correlation of shear wave measurements are not always feasible due to time consuming, space constrains in urban areas with high level of noise or unstable soil structures, as well as lack of specialized workers. Therefore, it is necessary to determine Vs values through indirect methods such as SPT. In technical studies, as presented in Table 1, the correlations proposed a power law relationship between V_S and N-SPT, expressed as: $V_s = A \cdot N^B$, where *A* and *B* are constant parameters determined by statistical regression. Several researchers were developed equations for specific soils, depth, geological age or corrected penetration resistance by using data collected from earthquake-prone areas as Japan and Turkey. A significant number of statistical correlations between V_S and N-SPT are based on uncorrected N-SPT values. Recently, various studies have been developed on empirical relationships between corrected N-SPT and V_S data for sand, clay type and for all soils irrespective of soil type. For the present study, there were selected several empirical relations between N-SPT and V_S values from technical literature, presented in Table 1.

Table 1. Proposed correlations V_S – SPT values

Researcher	**Proposed correlation**	**Soil type**
Iyisan (1996)	$V_s = 51,5 \cdot N^{0,516}$	All soils
Yokota et al. (1991)	$V_s = 121 \cdot N^{0,27}$	All soils
Hasancebi&Ulusay (2007)	$V_s = 104,79 \cdot N^{0,25}$	All soils
Jinan (1987)	$V_s = 116,1 \cdot (N + 0,3185)^{0,202}$	All soils
Imai & Tonouchi (1982)	$V_s = 96,9 \cdot N^{0,314}$	All soils

One of the aims of present study is focused on development of statistical correlations based on S-wave velocities and N-SPT values corresponding to different sites located in Bucharest area. These soil indicators can be used as input in dynamic site characterization and site response analysis of near-surface deposits. There were selected S-wave velocities values at depth that is nearest to the one where N-SPT value was recorded, being used 78 pairs of data. Empirical correlation between corrected N-SPT and V_s values resulted from MASW measurements has been obtained using power regression type. We obtained the Equations 4, 5 as representing V_s a function of normalized N_{60} and $N_{1(60)}$ values.

$$V_s = 116,8 \cdot {N_{60}}^{0,148} \tag{4}$$

$$V_s = 108,51 \cdot {N_{1(60)}}^{0,188} \tag{5}$$

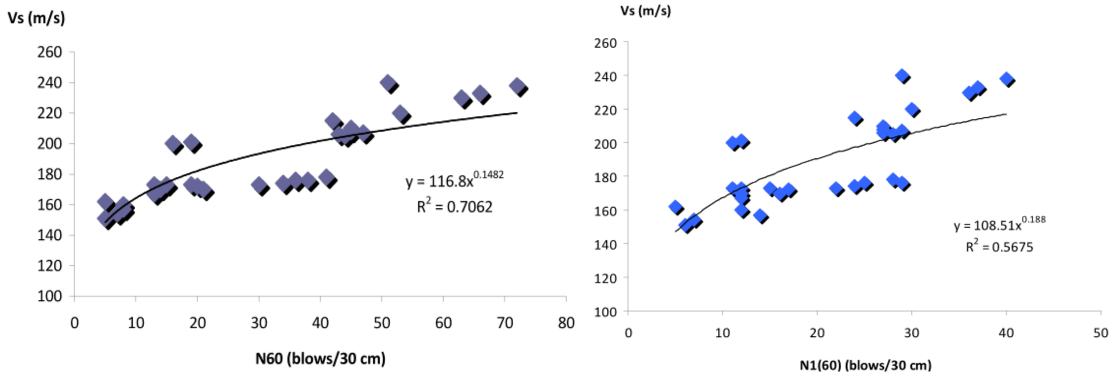


Figure 6. Correlation of V_S values from MASW and corrected N-values

Using the data from MASW method, the results are highlighted an intermediate correlation of V_s and N_{60} values with correlation coefficient R^2=0.71, respectively relative intermediate correlations between V_s and $N_{1(60)}$ values with are R^2=0.57, as shown in Figure 6.

In comparison, V_s values gathered from down-hole measurements linked to corrected N-SPT reveals a better correlation between V_s and N_{60} values with correlation coefficient R^2=0.81, respectively intermediate correlations between V_s and $N_{1(60)}$ values with are R^2=0.66 (see Figure 7). These correlations were obtained by using data of travel time-distance curves of V_s values in order to obtain corresponding data for each N-SPT measurement, as a result of velocity interval averaging, empirically delimited by impedance contrast of layers, thickness and velocity travel time, comparing to high density of point measurements and detection of thin layers during penetration resistance testing. The Equations 6, 7 obtained by power regression type for V_s and normalized N_{60} and $N_{1(60)}$ values were obtained as follows:

$$V_s = 101,07 \cdot N_{60}^{\ 0,255} \tag{6}$$

$$V_s = 88,26 \cdot N_{1(60)}^{\ 0,327} \tag{7}$$

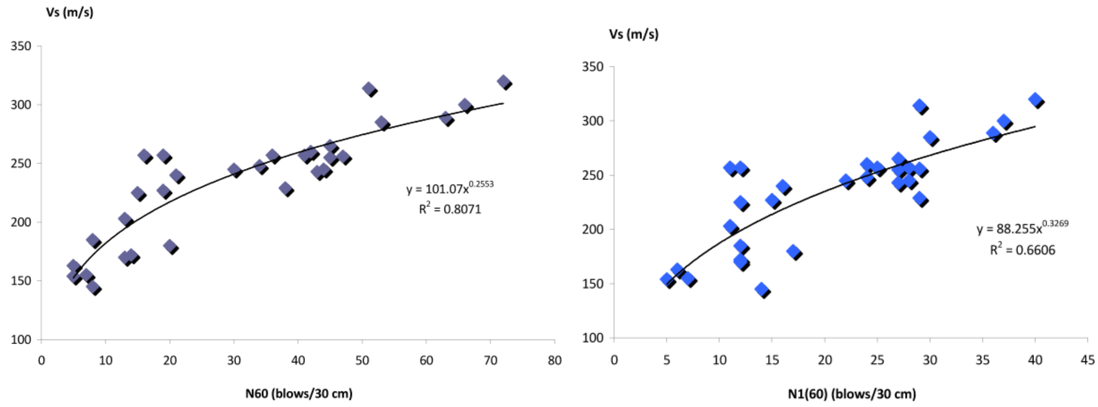


Figure 7. Correlation of V_S data from down-hole and corrected N-values

Measured (by DH down-hole and MASW) and estimated S-wave velocities are compared in order to assess the performance of proposed regression models. Considering the higher correlation coefficient obtained in statistical analysis, accuracy of developed formulas based on V_s and N_{60} values (Equation 4 and Equation 6) was compared with existing empirical ones as are represented in Figure 8. Values of V_S estimated by using equations proposed by Jinan (1987) and Hasancebi and Ulusay (2007) are considered to be in a better correlation with down-hole measured data, with differences that can reach 20% in both positive and negative trend, comparing to 40-50% in case of MASW values.

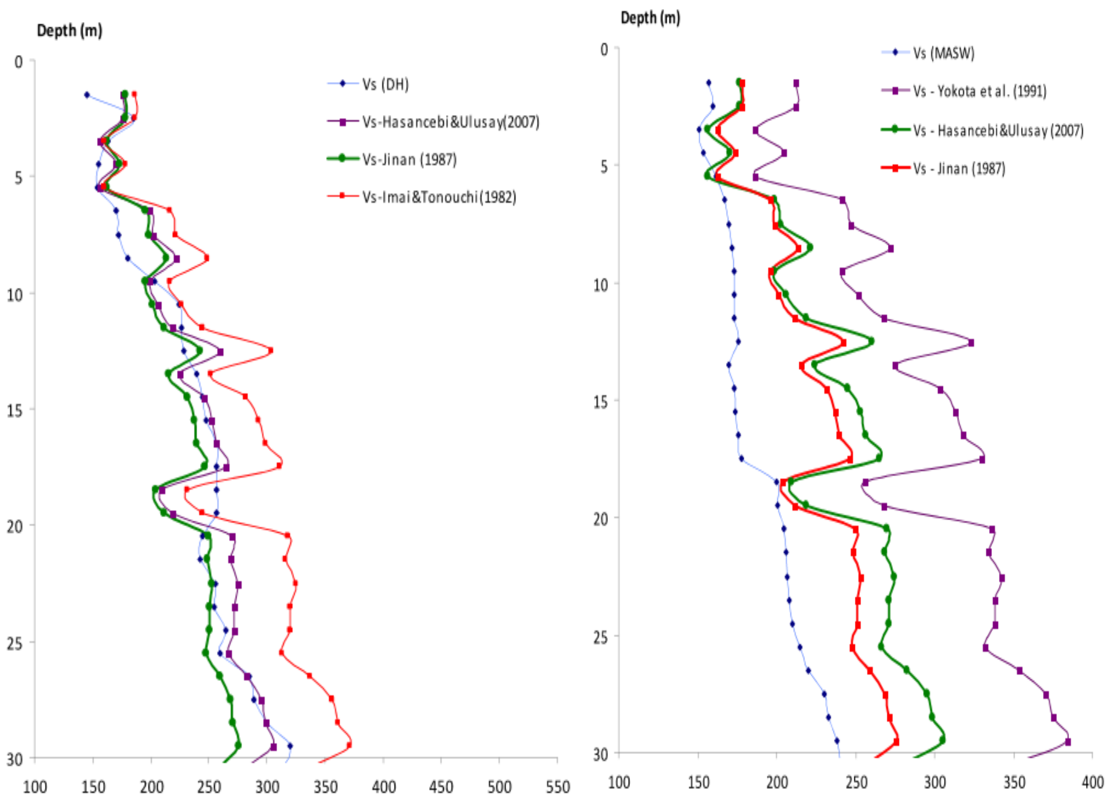


Figure 8. Distribution of experimental and predicted shear wave velocity, V_S based on N_{60} values

4. CONCLUSIONS

For the purpose of near-surface site effects assessment during Vrancea strong earthquakes, it is essential to characterize the sites according to seismic classification. In the present paper, the authors have made an attempt to characterize several sites located in Bucharest earthquake-prone area, according to modern seismic codes provisions, using $V_{s,30}$, in order to obtain a comprehensive database to be used in site response analysis. Based on data recorded from boring logs, sampling, geotechnical and geophysical investigation methods, various key parameters for dynamic behavior analysis have been gathered. Besides soil stratigraphy, layer thickness and other important geotechnical parameters, elastic soil parameters have been obtained by down-hole and MASW measurements, as well as characteristic period of site related to upper 30m of soil. Investigated sites located in different part of Bucharest have been grouped, based on $V_{s,30}$ parameter and N-SPT blow count, on seismic class C "intermediary soil profile". For each investigated site, V_S and N-SPT profiles have been computed for a better structuring of database related to local soil conditions. Geotechnical parameters and elastic properties determined by indirect measurements through correlations from V_S and N-SPT are reflecting the large variability in thickness and surface of stratified alluvial deposits formed by cohesive and cohesionless soils.

A good agreement of down-hole and MASW surveys has been observed for the upper 30 m of ground surface, with small differences due to technical specifications of applied methods. Moreover, it can be concluded that both methodologies used for assessing Vs profiling data can be useful for a more detailed site characterization. Correlations of Vs and N60 values have been proposed using existent empirical equations in simple regression analysis. Correlation coefficients are reflecting a better correlation of V_S data from DH method and normalized N-SPT values, comparing with intermediate correlation observed in case of V_S data from MASW. There is generally a relative scatter of measured data due to different resolutions of velocity measurements and natural variability of soil properties, which can introduce uncertainties in data analysis. It may be useful to select the option of V_S values for maximum depth investigation, which includes larger thicknesses. From this point of view, there are several disadvantages related to measurement depth and deep geological structures that directly influence and limit Vs values. The utility of proposed correlations is to estimate a potential range of values for sites where direct measurements are not feasible due to high costs or space constrains. Information provided can contribute to development of mitigation earthquake disaster strategies and continuous improvement of earthquake-resistant design provisions adjusted to specific ground conditions.

5. ACKNOWLEDGMENTS

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