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Effects of local ground conditions on site response analysis results in Hungary

Titre en français. Instructions aux auteurs (inverser les titres pour un article en français)

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ABSTRACT: Ground conditions play an important role for both seismic hazard assessment and structural design for seismic actions. Generally, 1D site response analysis is the first step toward evaluating local conditions. Often the process is simplified by applying a single reference peak ground acceleration general response spectrum based on soil category. Seismic waves are amplified selectively by near-surface soil deposits that possess strain dependent stiffness and damping parameters that vary with each layer as well as with depth. In order to take these local ground conditions into account, field investigations were carried out for this study. Seismic CPT and MASW measurements were used for determining in situ small strain stiffness profiles at different locations in Hungary. Results of the investigations were used as input data for ground response analyses. Results are presented to show benefits of the detailed investigations as compared to simplified analysis methods based on estimated soil parameters and to EC-8 design spectra.

RÉSUMÉ: Les conditions géo-mécaniques du sol jouent un rôle important tant pour l'évaluation des risques sismiques que pour la conception structurelle des actions sismiques. Généralement, l'analyse de la réponse du site 1D est la première étape vers l'évaluation des conditions locales. Souvent le processus est simplifié en appliquant simplement un spectre de réponse d'accélération pour un sol de référence codifié. Les ondes sismiques sont amplifiés de maniéré sélectives par des dépôts de sols proches de la surface dont les paramètres d'amortissement et de rigidité dépendent de la déformation et de la profondeur de chaque couche constituant le site d'essai. Afin de tenir compte des conditions locales, des essais in situ ont été effectués pour cette étude. Des mesures sismiques CPT et MASW ont été effectuées à différents endroit en Hongrie pour déterminer les profils des rigidités et des déformations des sites étudiés. Les résultats de cette étude ont été utilisés comme paramètres initiaux pour l'analyse de la réponse des sols. Les résultats obtenus des études détaillés effectué sont présentés dans cet article. Ils montrent un avantage certain par rapport aux méthodes d'analyse simplifies basées sur les paramètres estimés des sols et des spectres de conception EC-8.

KEYWORDS: local site effect, 1D site response analysis, seismic CPT, MASW, seismic hazard evaluation

1 INTRODUCTION

Local soil conditions have a profound effect on the expression of earthquake motions at the surface. While general zonation maps and soil profile categories may be sufficient for preliminary design, more detailed 1D site response analysis is often necessary. This is true even for moderate seismic zones such as those found in Hungary. This paper examines the application of 1D site response software to several sites in Hungary compared to EC-8 standard soil-based spectra. Results indicate that there may indeed be significant differences in seismic actions determined by these two methods. Results from 1D site response are very dependent on accurate representation of soil properties, ground motions, and decisions regarding variability of these input properties. The sections that follow address these issues based on our experience.

There is a great deal of literature concerning effects of soils on the amplification or attenuation of seismic shaking. Seed and Idriss (1971) presented a summary of soil effects as observed from damage patterns during the 1964 Alaska, 1964 Niigata, and 1971 San Fernando earthquakes. While liquefaction was a primary focus of their work, much of the performance data demonstrated the influence of soil properties on building damage as well. A dramatic example of the influence of soil conditions was presented by Zeevaert (1986) on the 1985 Michocán Mexico City Earthquake. Similar work on the Loma Prieta-San Francisco earthquake (NRC 1994) reinforced the concept of soil amplification.

The effects of topographic irregularities and alluvial basin geometry on ground motions can also be significant. Ridges, canyons and ground slopes tend to shake differently from horizontal ground because seismic energy can be focused within their physical boundaries. While these issues are worth studying, the focus of this study was primarily on effects of different soil profiles.

There are several methods to investigate the behavior of soft sedimentary structures under seismic wave excitation. Dynamic characteristics of a site can be represented by a variety of parameters such as dominant period, amplification factor and average shear wave velocity, which is the most applied parameter in microzonation, used in several international projects, such as SHARE (Lemoine, et al. 2012), Risk-UE (Faccioli 2006), and ROSRINE (Nigbor, et al. 2001).

Researchers use different techniques to estimate the dynamic soil properties: 1) experimental methods, such as standard spectral ratio, H/V noise ratio or "Nogishi-Nakamura" technique, borehole data, and microtremor techniques; 2) numerical methods, such as one-dimensional or two-dimensional response analysis. These methods have their advantages and disadvantages, experimental methods require large financial support and manpower, while numerical methods are very sensitive to initial soil data. Those methods achieving a higher accuracy are more time consuming. The main advantage of numerical models rest in their flexibility to assess the uncertainty in the seismic response of a site, given the imperfect knowledge regarding the mechanical and geometrical characteristics of the considered site.

2 FIELD MEASUREMENTS

Field measurements can capture in-situ conditions and variability quite accurately. Typical measurement resolutions are about 5% for shear wave velocity of soils (v_s) with sampling intervals of about 1 meter. Different field methods offer trade-offs between volume of soil sampled, spatial and temporal resolution, speed of testing, and data processing effort.

Several methods are commonly used for measuring v_s, either from the surface, or at depth. We used multi-channel analysis of surface waves (MASW) and seismic cone penetration testing (SCPT) in this study.

MASW was easier to deploy, required only hand-carried equipment, and was less disruptive in a city environment. We were able to perform tests in public spaces with only minimal redirection of pedestrian or bicycle traffic. Post processing was more intensive, and depth of sampling limited to less than 50m. One may argue that sampling volume for this test is more appropriate for site response analysis when compared to SCPT.

The SCPT tests required more equipment layout space and a more controlled environment as well as access and drilling permits (utility locations). While the profile often has a finer resolution than MASW, the sampling volume is much smaller. An added advantage of the SCPT is the sounding data (q_c, f_s, u) that is produced in addition to the v_s profile. This gives greater confidence in the v_s profile and allow for correlation with nearby standard cone data as well. We've had very good experiences with both testing methods and use them interchangeably. We've had success correlating MASW, SCPT, and standard boring data in local environments as well (Kegyes-B., et al. 2015).

The field data produce shear wave velocity profiles that are directly related to low amplitude shear modulus (G_{max}) and are applied to site response analysis with very little additional evaluation. For this study we used MASW results at the two locations in Győr and SCPT data at the other four locations (Tivadar, Szolnok, Kaposvár, Paks).

2.1 *MASW measurements*

The MASW method uses the conventional seismic refraction mode with an active seismic source (hammer, weight, explosive) and an array or receivers deployed along a line at regular intervals. The maximum depth of investigation is around 30 m depending on site and source conditions and is dictated by the longest wavelength made by the impact source. Greater impact power translates to longer wavelengths and deeper sampling depths.

Vertical low-frequency geophones (<4.5Hz) are recommended as receivers. The length of the receiver spread usually limited to 50-100 m and it is directly related to the longest wavelength detected while receiver spacing (distance between receivers) relates to the shortest wavelength detected. The source and receiver spread distance is one of the variables that affect the horizontal resolution of the dispersion curve.

Different types of waves are recorded through multichannel array. The dispersive nature of different types of waves is imaged through wave-field transformation of seismic record by frequency wavenumber (*f-k*) or slowness-frequency (*p-f*) transform. From the dispersion image, a dispersion curve of the fundamental mode of Rayleigh waves is selected, which is then inverted for a v_s profile.

2.2 *Seismic CPT*

The cone penetration test involves advancing an instrumented cone penetrometer into the ground and measuring the cone tip resistance (q_c) and sleeve friction (f_s) at selected intervals (typically 1 to 5 cm). CPT systems used for geotechnical site investigation are the conventional CPT, the Piezo-CPT (CPTu), and the Seismic CPT (SCPT or SCPTu). The SCPT is performed in the same manner as the CPT with the addition of usually two geophones or accelerometers located in the CPT tip. The v_s is measured at selected intervals (typically 1 to 2 m) by striking a steel or wood beam pressed firmly against the ground and calculated based on the difference in travel time of the shear wave between the consecutive geophones at a given depth.

The benefit of the SCPT is that regular CPT data can be used for general soil classification, typically based on interpreted Soil Behavior Type, and determining other related parameters which are important for modeling such as ground water table, density etc.

3 RESPONSE ANALYSIS

Seismologists and engineers divide the problem of seismic wave transmission into four stages: source, geologic path through rock layers, near surface path through soil and surficial rock layers, and interaction between shallow soil and structure. For risk assessment, all of these stages are important; however, this study will focus on the near-surface path through soil and surficial rock. This segment of the problem is commonly called site response analysis. It normally involves estimating an input motion at “bedrock” and computing the resulting surface ground motion.

The main parameters involved in the analysis are the intensity and duration of the input base motion and the dynamic properties of the soil layers leading up to the surface. Earlier sections discussed the measurement of dynamic soil properties, mainly shear wave velocity, but other soil properties, and a method to select appropriate input base motions are still necessary.

Simplifications to site response analysis often reduce the problem to one dimension and a single type of wave: horizontally-polarized vertically-propagating shear wave. This corresponds to the most damaging wave for buildings. The horizontal motion imparts lateral inertia loads on the building which are generally more difficult to resist than vertical loads. The vertical propagation is a reasonable approximation as well since the pathway for seismic waves becomes more vertical as it moves through material that is less stiff (lower v_s, G_{max}) as it moves toward the surface.

3 .1 *Rexel software*

The method chosen to select base motions was a magnitude scaling technique implemented in the software package REXEL. Strong motion records are selected from a database (European Strong-Motion Database) and compared to a desired set of criteria. If the record meets the criteria it is copied into a “bin” of motions that will be used later. For many typical low to moderate seismic actions, the database will contain many suitable records. However, if the criteria are not met, REXEL will scale the earthquake motion (increase or decrease acceleration amplitude) so that it will meet the criteria. While amplitude scaling has some disadvantages, especially with frequency content, records that are nearly the same magnitude will be accurate enough. Other parameters affect the suitability of an earthquake for scaling and relocation. Distance from epicenter, and type of faulting that initiated the motion all have an significant impact on the final behavior in the response analysis.

The most common set of criteria are those described by Eurocode 8 or other building code standards. Design spectra from these codes are easily input to the program and default values of allowed variability are often enough to produce a bin of 7 earthquake records that are subsequently used in the soil response analysis program as input motions on the bedrock. Therefore it is common to use records which were obtained at locations where the layers close to the surface are rock-like, i.e. quite stiff, dense because these layers will modify (filter or amplify) the base rock motion the least. Such sites are usually classified into class A by Eurocode 8. For this study three bins of seven earthquake records were selected; two that match EC 8 Type 1 and one for the Type 2 spectra, all of them for a site class A.

3.2 *Strata software*

The program Strata was used to compute 1D response at the six sites. The dynamic properties of soil (shear modulus, *G*, and damping ratio, *D*) vary with shear strain, and thus the intensity of shaking. This software uses an equivalent-linear approach, meaning nonlinear response of the soil is approximated by modifying the linear elastic properties of the soil based on the induced strain level, and then iteratively calculate them based on the computed strain. A transfer function is used to compute the shear strain in the layer based on the input motion.

Equivalent-linear site response analysis requires that the strain dependent nonlinear properties (i.e. *G* and *D*) be defined. The initial small strain shear modulus ($G_{\max}$) is calculated by:

$$G_{\max}=\rho\ v_s^2 \tag{1}$$

where ρ is the mass density of the layer, and v_s is the measured shear wave velocity. Characterizing the nonlinear behavior of *G* and *D* is achieved through modulus reduction and damping curves that describe the variation of $G/G_{\max}$ and *D* with shear strain. Shear modulus values correspond to secant modulus and damping is equivalent viscous damping.

The computational method of Strata is very efficient; a large number of soil profiles, earthquakes and soil nonlinear conditions can be examined. Soil profiles can be varied by specifying mean and standard deviation values of $G_{\max}$ and *D* for each soil layer. Since most sites had more than one set of field measurements available, we used them to estimate the variation of the v_s and $G_{\max}$ for each soil layer in STRATA. Many earthquake motions can be specified initially and the software will collect all the results and compute profile data, response spectra, transfer functions, and time histories with median, high and low percentile or log standard deviations. Therefore, the impact of the variability of input data on site response can be quantified. For this study we used the standard variation options (vary layer thickness, soil dynamic properties) in Strata to generate 100 different soil profiles based on the actual profile for each site and applied the mentioned 3 bins of 7-7-7 earthquakes as input. Three levels of base acceleration were considered (a_{gR}=0.09g, 0.12g and 0.21g) for all sites. Altogether, nearly 40,000 realizations were calculated.

3.3 *Investigated sites*

Response analyses were performed at six locations in Hungary, where in-situ measurements were available (MASW, SCPT). For Eurocode 8, the top 30m of the surface-near soil layers are classified (A-E) based on average shear wave velocity (v_{s30}). Together with PGA, given in the Annex of EC8, the elastic design spectrum is constructed. The chosen sites were all classified as "C" (Table 1). For site response however, the soil profile had to go beyond the 30m depth to "bedrock"; usually defined as the base layer with $v_s \geq 800$ m/s. Based on available geological data, depth to bedrock was 50-150m (Table 1). Since measured v_s data was only available for the upper 30-50m, an estimated profile was calculated assuming $G_{\max}$ varied with the square root of effective confining stress.

Table 1. Summary of EC-8 v_{s30} and Strata depths for sites

Site	$v_{s,30}$	Strata Depth, m
Kaposvár	266	50
Szolnok	201	150
Tivadar	217	150
Paks	324	50
Győr III	300	100
Győr IV	290	100

Shown in Figure 1 are profiles determined from SCPT compared to empirical formulae (CPT_{est}) from Robertson (2009). Although the two profiles are similar, the better accuracy of field measurements is obvious. Also shown is the extrapolation formula used to extend data to 50m depth. The other profile lines in the figure show mean, minimum, and maximum values for $G_{\max}$ used in developing the realizations in Strata. Profiles of the other sites were similar to this, however space limitations do not allow for further illustration.

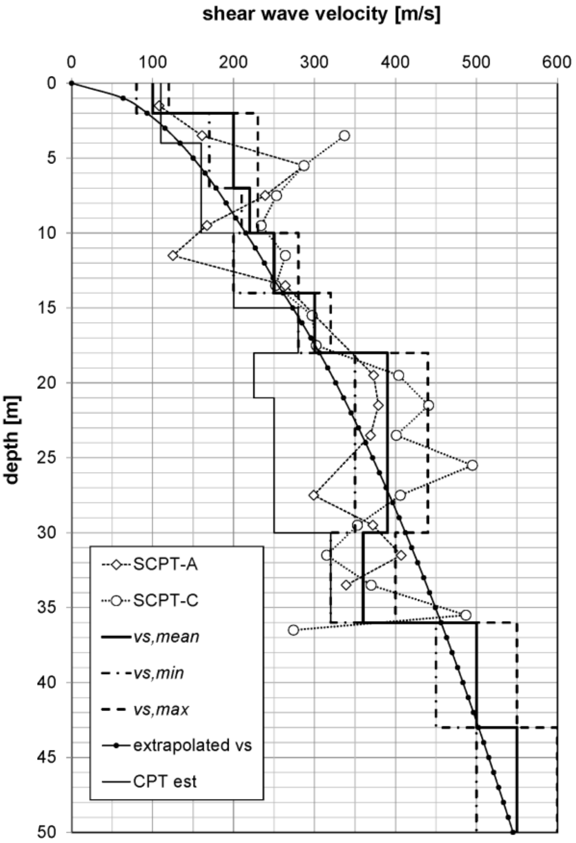

Figure 1. v_s profile for Kaposvár $SCPT_{mean}$ and CPT_{est}

Our results showed consistently higher seismic actions compared to standard EC-8 soil type C spectra. Shown in Figures 2, 3, and 4 are median values of surface elastic response spectra from base input motions corresponding to EC-8 Type I or Type II spectra.

In Figure 2, the surface acceleration spectra show magnifications from 50 to 100% more than predicted by EC-8 soil class C. The base input motions corresponded to Type I spectra (presently used in Hungary for seismic design) but the shifts in amplitude and frequency content are obvious. The spectra from Szolnok and Tivadar show a significant component of high period (low frequency) amplification that is not represented in the EC-8 spectral envelope. This means if a seismic event does indeed match Type I spectra, they will transmit 2-4x stronger actions than predicted by the code spectra in this frequency range.

The influence of input motion bin restrictions is not very large when one views the response in Kaposvár (Figure 3) for both Type I and II input motions. Either way, the code spectra underestimate seismic action by a factor of 2. If one wishes to consider the effect of EC 8 structure importance factor, the issue is further magnified.

Figure 4 shows the impact of importance factor on response spectra for the Szolnok site where standard spectra are compared to lower and higher PGA input motions. The reader should keep in mind that each Strata result line is actually the mean value of over 700 realizations.

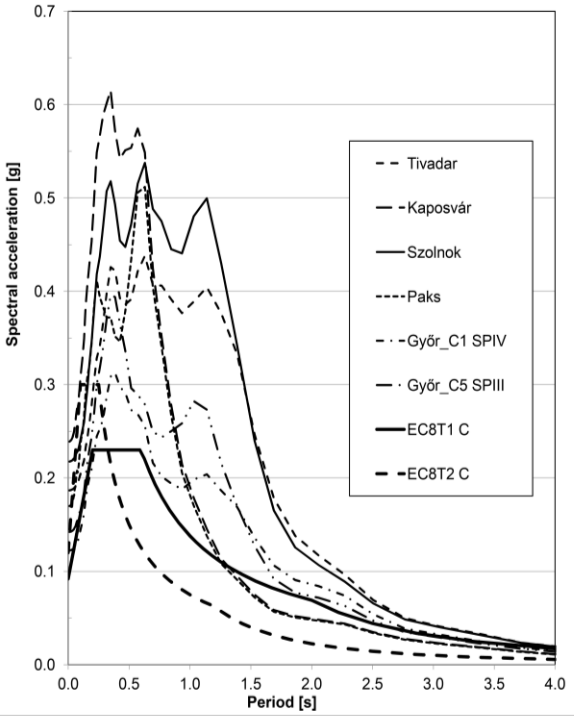

Figure 2. Response spectra - all locations (a_{gR} = 0.12g, T1a bin)

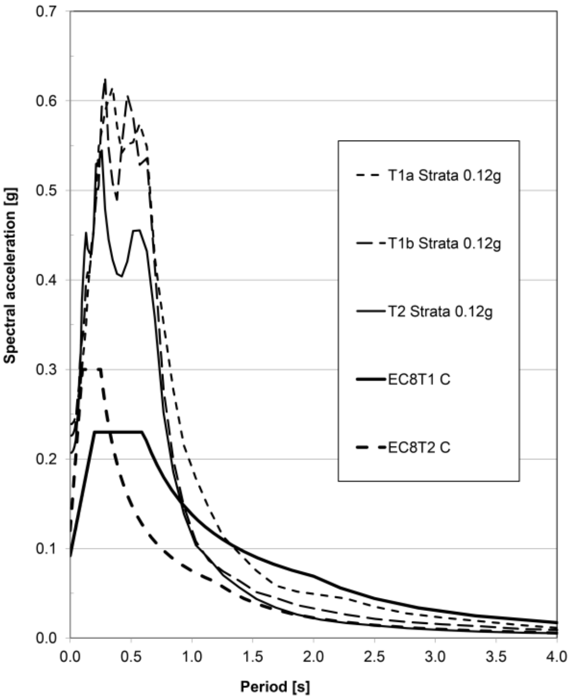

Figure 3. Kaposvár site, T1a, T1b and T2 base excitations vs. standard surface spectra for type C soil profile (a_{gR} = 0.12g)

5 CONCLUSIONS

The local soil profile has a profound influence on seismic action. If the profile is not homogeneous or nearly so, a substantial degree of amplification can be expected. Frequency content can also cause significant modification. As part of an ongoing research effort, we have analyzed 1D response at six locations throughout Hungary using field data gathered for this purpose. Future efforts will be directed toward refining our ability to predict likely spectral maxima with less effort to help make preliminary exploration and design decisions. Refining the base input spectra, nonlinear soil properties for typical profiles and cross verifying response computations with multiple software models are future goals.

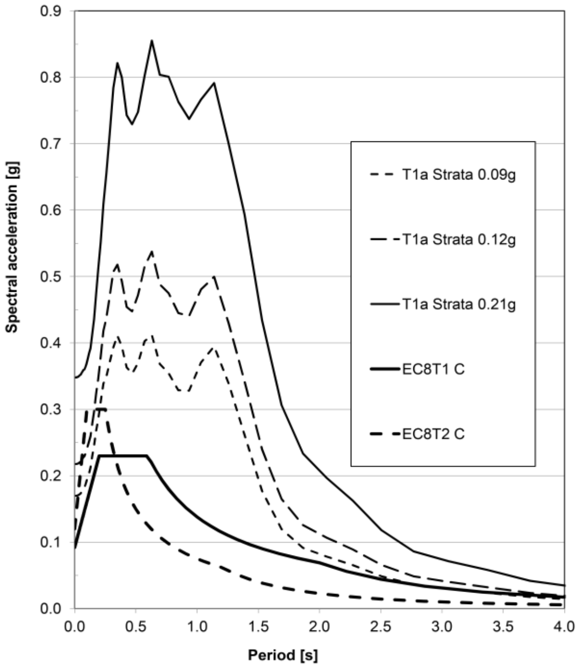

Figure 4. Effect of importance factor on acceleration response spectra (Szolnok, a_{gR} = 0.09g, 0.12g, 0.21g)

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