Geotechnical, Geological and Earthquake Engineering

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Earthquake Geotechnical Engineering Design

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Foreword

Earthquake Geotechnical Engineering has developed greatly in the last 30 years since the First International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics that was held in St. Louis in the year 1981. During the opening address of the conference given by D. E. Hudson, he said: "I began to wonder if Geotechnical Earthquake Engineering is in fact any different from Earthquake Engineering. Even for the detailed problems of steel and concrete structural design, the importance of soil-structure interaction may be a critical matter. Geotechnical Engineering is indeed the foundation on which the whole subject is built."

The importance of the soil characterisation in the local site seismic response was outlined some years before in 1974 by H. B. Seed, who grouped 104 earthquake recordings in four soil categories – rock, hard soil, alluvial sandy soil and soft clay – showing the significant amplification of the records on the rock going from hard soil to soft clay.

Following the first conference in St. Louis in 1981, some other International Conferences devoted to Earthquake Geotechnical Engineering and Soil Dynamics were held in many parts of the world. Among these, recently, three International Conferences have been held; two in Italy, one of the UE countries more prone to seismic risk and one in Japan. In 2008, an International Conference commemorating the 1908 Messina and Reggio Calabria Earthquake was held in Reggio Calabria by the Italian Geotechnical Society (AGI). During the conference, K. Ishihara in its inaugural lecture showed that the peak ground design acceleration has been increased from 0.2 to 0.3 g in the 1970s up to 0.6–0.8 g at the present time. Because of that there is a need to shift from pseudo-static approach to performance based design. This topic has been debuted in the International Conference on Performance Based Design in Earthquake Geotechnical Engineering held in Tokyo in 2009. Following this conference, the Second International Conference on Performance Based Design in Earthquake Geotechnical Engineering was held in Taormina (Italy) last year, organised by the TC-203 and ETC-12 of the ISSMGE and by AGI.

Earthquake geotechnical engineering design is progressing very well in the last 5 years. This design is made in several steps. The first one is the evaluation of the site amplification, which is reported in Part I of this book. The second one is related to the evaluation of the soil foundation stability against natural slope failure and liquefaction (Part II). Following these two steps, the volume is devoted to the design of geotechnical works under earthquake loading. Part III is devoted to the design of levees and dams (including natural slopes). Part IV is devoted to the design of foundations and to soil structure interaction analysis; Part V is devoted to underground structures and Part VI is devoted to the new topics, i.e. to the design of reinforced earth retaining wall and landfills.

Part I is subdivided in two chapters and is related to the evaluation of site characterisation and site amplification.

Chapter 1 deals with the site characterisation, based on in situ measurements of shear wave velocity. A new, reliable shear wave velocity model is presented as a prerequisite for the assessment of seismic site response at regional and local scale. The model is based on surface wave test because of their cost effectiveness and efficiency. Three case histories, with pseudo 2D/3D shear waves velocity models, in different geological settings and with different characteristics of the experimental dataset are reported and discussed.

Chapter 2 reports a global dataset of more than 3,000 ground motion records from 536 sites from Greece, Italy, Turkey, USA and Japan, used to propose a new site classification system and soil amplification factors for elastic acceleration response spectra. The new classification system incorporates parameters such as the thickness of soil deposits, the average shear wave velocity to the seismic bedrock and the fundamental period of the site. The dataset is also used to derive soil amplification factors and to compare it with the soil classes amplification of Eurocode 8 (EC8).

Part II is subdivided in three chapters, all devoted to the liquefaction that occurred extensively during the recent earthquakes of 2011 Tohoku-Pacific Ocean earthquake in Japan.

Chapter 3 reports on the liquefaction that occurred in the reclaimed land in Kanto area, located more than 200 km away from the earthquake fault, in soil containing more 50 % of non-plastic fines. Also almost all sand deposits along the Tokyo bay area reclaimed in 1960s or later liquefied, while in good contrast, those older than that did not. To investigate the ageing effect on liquefaction strength of sands containing fines, a series of basic laboratory tests combining innovative miniature cone penetration and subsequent cyclic undrained loading were carried out in a modified triaxial apparatus on sand specimens containing fines.

Chapter 4 reports also on liquefaction in Tokyo Bay and Kanto Region. The Tone River along the Tokyo Bay suffered the liquefaction-associated damage, despite being located at a distance of about 450–500 km from the epicenter of the earthquake. As a measure to estimate its destructiveness, the ground settlements resulting from liquefaction were calculated based on volume decrease characteristics of sandy soils and their outcome was compared with the settlements actually observed on the ground surface.

Chapter 5 is devoted to settlement as inclination of buildings caused by the earthquake. In Tokyo Bay area, the very long duration of the main shock and an aftershock 29 min later probably caused serious settlement and inclination of houses. The maximum inclination in Urayasu City was about 6 %; it is difficult to live in these buildings after the earthquake though no damage to walls and windows were observed. Tilting of buildings are due to differential settlements. Several factors affected the non-uniform settlement. Among differential factors affecting the differential settlement, the effect of adjacent houses was dominant.

Part III is subdivided in two chapters, devoted to river levees, dams and related artificial slopes.

Chapter 6 analyses the damage caused to river levees by the 2011 Tohoku-Pacific Ocean earthquake in Japan. To mitigate the internal liquefaction inside the levees, not only the field investigation technique but also numerical analysis for performance prediction has to be newly developed.

Chapter 7 is devoted to earthquake performance design of dams using destructive potential factors. The seismic performance design of dams is based on good estimates of sliding displacements and crest settlements. Theoretical result has shown a good correlation between sliding displacement of slope and destructiveness potential factor PD. Crest dam vertical settlement recorded from seismic performance in real Chile earthquakes by destructive potential evaluation confirms the good forecast of the theoretical values obtained in terms of PD compared with PGA.

Part IV is subdivided in three chapters, devoted to foundations and soil-structure interaction.

Chapter 8 deals with an interesting performance-based design, related to the macro-element concept which seems to be very promising. The macro-element theory in its different versions (elasto-perfectly plastic, elasto-strain-hardening plastic, bounding surface plastic and hypo-plastic) is first introduced and the mechanical response of shallow foundations under monotonic/cyclic loading, as it results from experimental tests, is outlined.

Chapter 9 is devoted to large-scale modelling of ground and soil-structure earthquake response. A strategy to incorporate ground response and soil-structure interaction (SSI) is implemented based on the domain reduction method (DRM) for three-dimensional earthquake simulation. Vibration properties and seismic response behaviour for the connector and the soil domain are examined. Different scenarios of bridge response are considered and compared, including fixed-base uniform excitation, and multiple-support excitation with and without the full ground/foundation soil domain.

Chapter 10 outlines the relevance of soil structure interaction in seismic displacement based design of structures. A brief summary of the seismic design method known as "direct displacement–based design" (DDBD) is presented, with some discussion of the appropriate seismic design input to be used, on the applicability to retaining structures and on the relevance of including nonlinear soil-structure interaction in the DDBD and the tools to account for it, with reference to shallow foundations.

Part V is devoted to the performance and seismic design of underground structures. Chapter 11 analyses the seismic performance during past earthquakes of underground structures, tunnels, subways, metro stations and parking lots. A general presentation of the methods used for the seismic design of underground structures is presented and discussed. The main issues discussed herein cover the following topics: (i) force based design against displacement based design, (ii) deformation modes of rectangular underground structures under seismic excitation, (iii) seismic earth pressures on underground structures, (iv) seismic shear stresses distribution on the perimeter of the structure, (v) appropriateness of the presently used impedance functions to model the inertial and the kinematic soil-structure interaction effects, (vi) design seismic input motion, taking into account the incoherence effects and the spatial variation of the motion and (vii) effect of the build environment (i.e. city-effects) on the seismic response of underground structures.

Part VI is subdivided in two chapters and it is related to the new topics reinforced earth wall and landfills.

Chapter 12 is devoted to the behaviour of reinforced soil walls during the 2012 Tohoku earthquake in Japan. Approximately 1,600 case histories on the seismic performance of such walls during the 2011 Great East Japan Earthquake were collected and analyzed. Statistical data on the seismic damage revealed that all types of reinforced soil walls performed well during the 2011 earthquake. A case study closely investigated was discussed in terms of economical solution and in terms also of performance required.

Chapter 13 deals with the performance based seismic design of geosynthetic barriers for waste containment. A performance-based methodology for seismic analysis and design of the geosynthetic elements of waste containment systems, including landfills and heap leach pads, has been developed. The methodology offers a rational alternative to the current state of practice for seismic design of geosynthetic containment system elements in which a decoupled Newmark-type displacement analysis is used to calculate a permanent seismic displacement. This calculated displacement is generally considered to be an index of the performance of the containment system during an earthquake. However the Newmark-type design methodology does not gives explicit evaluation of the stresses and strains in the geosynthetic elements of the containment system. So, a finite difference model of waste-liner system interaction has been developed using the computer code FLACTM. This analysis provides a basis for direct performance based seismic design of geosynthetic elements not only in waste containment systems but in a variety of other civil structures that employ geosynthetic elements wherein earthquake ground motions cause relative displacement between the geosynthetic element and the surrounding soil.

The contents of the chapters have been presented as state of art (SOA) papers or keynote (KN) papers at the Second International Conference on Performance Based Design in Earthquake Geotechnical Engineering in Taormina. To the topic of performance based design in earthquake engineering will be also devoted a special number of *Bulletin of Earthquake Engineering* with some others SOA and KN delivered during the Taormina Conference.

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Catania, Italy — Michele Maugeri
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Part I
Site Characterisation and Site Amplification

Chapter 1
Spatially Constrained Inversion of Surface Wave Data to Build Shear Wave Velocity Models

Sebastiano Foti and Laura Valentina Socco

Abstract A reliable shear wave velocity model is a prerequisite for the assessment of seismic site response at regional and local scale. 2D or 3D velocity models can be obtained by interpolation of tests at different locations. Surface wave tests are often used in this context because of their cost effectiveness and efficiency. As any characterization method based on the solution of an inverse problem, surface wave analysis suffers from solution non-uniqueness. Laterally constrained inversion provides a robust framework for the interpretation of surface wave data in the perspective of building pseudo-2D/3D shear wave velocity models. In the chapter three case histories in different geological settings and with different characteristics of the experimental dataset are reported and discussed.

1.1 Introduction

Accurate predictions of seismic site response and soil-structure interaction are particularly important for performance base design. Modern computational tools allow advanced numerical simulations to be performed. Indeed, efficient codes have been established for the simulations of wave propagation at the basin scale. At a different scale, a direct evaluation of the soil-structure interaction under seismic loads is required for assessing the performance of a single construction. In both cases, the reliability of the result is strongly dependent on the availability of an accurate shear wave velocity model, which has to be obtained with geophysical tests.

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Surface wave methods are appealing for the characterization. Indeed they are very cost effective and flexible as they do not require drilling of boreholes and they can be performed with light and portable equipment. Moreover they allow a significant volume of the subsoil to be tested, which is a prerequisite for the construction of a representative model. On the other side it has to be considered that the interpretation of surface wave data is quite complex as it requires advanced signal processing tools and the solution of an inverse problem. The latter is inherently ill-posed from a mathematical point of view. The main consequence is the non-uniqueness of the solution as different profiles may honor equally well the available experimental information, i.e. they are equivalent solutions of the inverse problem. The consequences of solution non-uniqueness for seismic site response in the simple case of horizontally layered media have been studied by Foti et al. (2009). To reduce the uncertainties associated to solution non-uniqueness, it may be useful to introduce additional constraints, such as a-priori information from borehole logs or from other geophysical methods (Socco et al. 2010a; Foti 2013).

The interpretation of surface wave data is typically based on a horizontally stratified model with linear (visco-)elastic homogeneous layers. The obtained solution is a 1D profile of shear wave velocity versus depth. Most attempts to obtain a 2D or 3D shear wave velocity model are based on the fusion of 1D profiles from multiple realizations of the test at adjacent locations. This is easily implemented with moving receiver arrays.

Considering the uncertainties associated to solution non-uniqueness, the possibility of linking adjacent profiles with a constrained inversion can lead to a more robust and reliable model. This strategy, initially proposed for vertical electrical soundings by Auken and Christiansen (2004), has proven to be very effective on surface wave data (Socco et al. 2009). Moreover the Laterally Constrained Inversion (LCI) can also integrate available a-priori information and/or data from other geophysical tests (Wisèn and Christiansen 2005; Garofalo et al. 2012).

More advanced approaches for getting 2D models, as for example full wave waveform inversion, are very promising, but still under development (e.g. Tran and Hiltunen 2012). Issues to be resolved are in particular related to the very high computational requirements and to the need for adequate strategies for the regularization of the solution.

After a discussion on the use of surface wave data for the construction of pseudo 2D-3D shear wave velocity models and an outline of the Laterally Constrained Inversion approach, this chapter reports three applications to site characterization for seismic projects.

1.2 Surface Waves Methods and Lateral Variations

The analysis of the propagation of surface waves has been initially exploited for the characterization of the Earth's crust in seismological studies (Aki and Richards 2002; Romanowicz 2002). First applications in engineering date back to late 1950s

(Jones 1958), but the diffusion of the technique started with the introduction of the SASW (Spectral Analysis of Surface Waves) method (Nazarian and Stokoe 1984). Nowadays surface wave methods have gained a wide popularity, especially in the fields of applied seismology and near surface geophysics. A detailed discussion of the fields of application and of current trends is reported by Socco et al. (2010b).

Active-source methods are typically preferred for shallow applications. Passive methods based on microtremors allow the medium to be characterized at depth without the need for heavy and costly sources. An overview on the various methods for surface wave analysis is provided by Foti et al. (2011).

The propagation of surface waves is influenced by the physico-mechanical properties of a zone of limited thickness close to the ground surface. Monitoring of particle motion on the ground surface can be used for the solution of an inverse problem aimed at the characterization of the subsoil. Although a full-waveform inversion is in principle feasible (e.g. Tran and Hiltunen 2012), most implementations are based on the evaluation of an experimental dispersion curve, i.e. the relationship phase velocity of surface waves versus frequency. The inverse problem is then solved assuming a stack of linear elastic homogeneous layers as reference model. This assumption has strong implications in presence of lateral variations. Indeed in such conditions there is a discrepancy between the model and the actual medium. The latter is eventually represented as a layered medium with fictitious parameters.

In general, the results of surface wave tests are representative of the subsoil below the whole length of the testing array, for a depth which is linked to the maximum available wavelength (hence proportional to the inverse of the lowest usable frequency in the dataset). This aspect has also to be taken into consideration when comparing the results of surface wave methods with those of intrusive methods such has seismic cross-hole or down hole tests. Indeed the latter are local measurements which are representative only of soil behaviour in the limited space between the source and the receiver (or first to second receiver).

A set of surface wave tests for different positions of the array can be used to obtain a sequence of 1D profiles, which can be considered a pseudo-2D/3D model. In practice the subsoil is modeled locally as an horizontally layered medium (Fig. 1.1). Such a procedure can be implemented with different strategies:

- a series of independent acquisitions with conventional arrays at nearby locations;
- a moving array (streamer) towed by a vehicle on land or by a vessel for marine applications;
- subsets of data extracted with a moving spatial window from long seismic surveys.

Land streamers are widely used because they allow data to be collected in a fast and effective manner. A string of geophones is mounted on a rough support that allows it to be towed by a vehicle on land (van der Veen et al. 2001; Vangkilde-Pedersen et al. 2006). The string is moved at different positions and the test is repeated for each position. Typically a certain overlap is used between different