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Evidence of complex site effects and soil non-linearity numerically estimated by 2D vs 1D seismic response analyses in the city of Xanthi

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ABSTRACT

This study discusses the effects of local site conditions on earthquake ground motion for city of Xanthi, North-Eastern Greece, focusing on the influence of complex site effects and soil non-linearity. Although city of Xanthi is characterized as a low seismicity area, documented strong earthquake events of past centuries indicate the necessity of an appropriate estimation of ground surface motion of the region. Therefore, a typical 2D cross-section along the city following an E-W direction is constructed, based on the synthesis of available geological, geotechnical and geophysical data of the broader area. 1D and 2D numerical models are generated utilizing the Finite Difference Method and site response is investigated for different seismic scenarios. Wave amplification is captured as a result of 1D resonance phenomena integrated with potential 2D complex wave effects, due to lateral propagation of the locally generated at the discontinuities surface waves. The additional, relatively to 1D, 2D amplification or de-amplification of ground shaking, in terms of its amplitude and its spectral content is quantified. The impact of soil deposits non-linearity on amplification level, as well as, on generated 2D wave fields is considered by implementing both equivalent-linear and non-linear approaches. The results reveal that, across the city, spatial variation of ground surface motion is obvious, attributed primarily to the variation of subsurface soil profiles. 2D wave effects have been generated signifying that, at particular site locations, ground motion is additionally amplified or de-amplified with respect to 1D response. However, 2D versus 1D differentiation has been calculated of $\pm 20\%$ in terms of PGA and spectral accelerations up to 1.0 s, in the majority of the examined sites, implying that site response even though, influenced by 2D resonance phenomena, could be sufficiently captured by an 1D approach. Moreover, it is shown that if soil non-linearity is properly accounted for, it may play an important role on the estimated ground response, since non-linear approach seems to produce lower amplification levels with regard to 1D and 2D equivalent-linear approaches. As a general trend across the investigated site, for the entity of the various scenarios, the numerically calculated response spectra exceed EC8 seismic code provisions.

1. Introduction

The effects of local site conditions on the intensity of ground shaking have been recognized for many years, since they profoundly influence all the important characteristics – amplitude, frequency content and duration- of strong ground motion [1]. The role of “site effects” has been depicted, during various previous earthquakes (Mexico 1985, Loma Prieta 1989, Kobe 1995, Athens 1999, Lefkada 2003, Achaia-Elia 2008, etc.), in a very precise documented way, where observational evidence has been obtained. Their influence could be illustrated in several ways, using experimental and/or theoretical approaches and should be accounted for on a case-by-case basis. More specifically, the ground response analysis in urban regions, characterized by moderate seismicity, with neither strong, nor weak records available, but in the proximity of potentially active faulting is quite challenging and this is exactly the case of the city of Xanthi, in North-Eastern Greece, which is investigated in this study.

The most common method in geotechnical earthquake engineering for modeling wave propagation is the one-dimensional (1D) (linear and/or non-linear) analysis assuming soil layers to extend infinitely in the horizontal direction. The SH-waves propagate vertically from the underlying bedrock and the term “site effects” includes primarily the impedance contrast of surface soil deposits to the underlying bedrock. In many cases, analyses based on 1D assumptions have been proved to estimate the ground response in a reasonable agreement with the recorded one. However, in several cases, (Armenia 1988, Northridge 1994, Aigio 1995

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etc.) the reported spatial variability of the ground surface motion and the distribution of damage could not be sufficiently explained by 1D approaches. Surface topography and strong lateral geological heterogeneities, such as, alluvial valleys and deep basins, have revealed (Bard and Bouchon [2,3]; Aki [4,5]; Faccioli et al. [6]; Raptakis et al. [7]; Makra et al. [8]) additional modification of the characteristics of the incoming wave-field. While 1D soil layer effects have been investigated fairly extensively, surface and subsurface topography effects, implying 2D or 3D phenomena, such as diffraction of body waves and generation of surface waves, fall short in investigation as they are quite complicated, illustrating thus, the need to understand the physical background that governs those complex wave-fields.

For the aforementioned reasons, in this study we will consider the 2D ground response analysis for the city of Xanthi, utilizing numerical models based on the Finite Difference Method (FDM), implemented in the software code FLAC2D [9]. Apart from estimating spatial variability of ground surface motion attributed primarily to 1D resonance of body waves, an attempt will be made to capture potential 2D wave effects that are likely to arise. We will investigate and quantify the additional amplification or de-amplification on the intensity of ground shaking to that predicted by 1D wave propagation theory, in terms of both, amplification of ground motion and its spectral content.

Moreover, stress-strain behavior of soils under dynamic loading is well known to be non-linear [10], implying that amplification level is decreased compared to a linear elastic soil behavior. Additionally, during strong excitation cases, soil non-linearity, may contribute to a damping effect of the generated surface waves. In this way we reduce the rather large 2D amplification that would have been computed, if soil deposits were to behave linearly (Zhang and Papageorgiou [11]; Bielak et al. [12]; Psarropoulos et al. [13]).

In this study, soil non-linearity will, initially, be investigated by implementing the widely used iterative procedure, referred to as “the equivalent-linear method” [14]. Although this method provides reasonable results in many cases, it remains an approximation of real non-linear soil behavior. Hence, an alternative approach will be also addressed utilizing direct numerical integration in time domain, by implementing an elasto-plastic constitutive model, as an attempt to estimate the actual non-linear ground response of the investigated site.

The goal of this paper is to estimate ground response of city of Xanthi, specifically focusing on 2D generated wave effects integrated with non-linear phenomena, by utilizing numerical methods. Extensive comparisons with results of 1D approach are realized and presented herein; namely, we compare results of 2D versus 1D approach using linear elasticity, equivalent linear approximation and nonlinear approach. The results are also compared with provisions of the seismic code, Eurocode 8 [15], in order to investigate its capacity to capture the theoretically estimated ground motion at city of Xanthi.

2. The case of city of Xanthi and input motions

The main parameters that characterized the investigated site, regarding seismicity, geology, surface topography, taxonomy of formations and the physical, mechanical and dynamic properties of soil and rock materials, have been obtained in the framework of a research project [16].

2.1. Location, historical seismicity and tectonic structure of the broader area of city of Xanthi

Fig. 1 illustrates the location of city of Xanthi, in north eastern Greece, as well as the location of major historical earthquakes (before 1911 for Greece) [17]. According to both Hellenic Seismic Code (EAK) [18] and Eurocode 8 (EC8) [15], city of Xanthi is located in a low seismicity region, classified in the seismic hazard zone I, with a design acceleration on a rock site, $a_{gR}=0.16g$. Albeit seismicity of the investigated region is low, compared to the adjacent areas, especially Northern Aegean Sea, strong earthquake occurrence in the broader region is historically documented, constituting a non-negligible threat for urban areas. Papazachos and Papazachou [19] report that the whole city of Xanthi was almost destroyed in 13 April 1829, by the most recent strong earthquake, as well as, another two devastating seismic events, (Komotini, 1784; M=6.7 and city of Xanthi, 1864; M=7.4) occurred in the broader area, testifying the need for an estimation of the ground

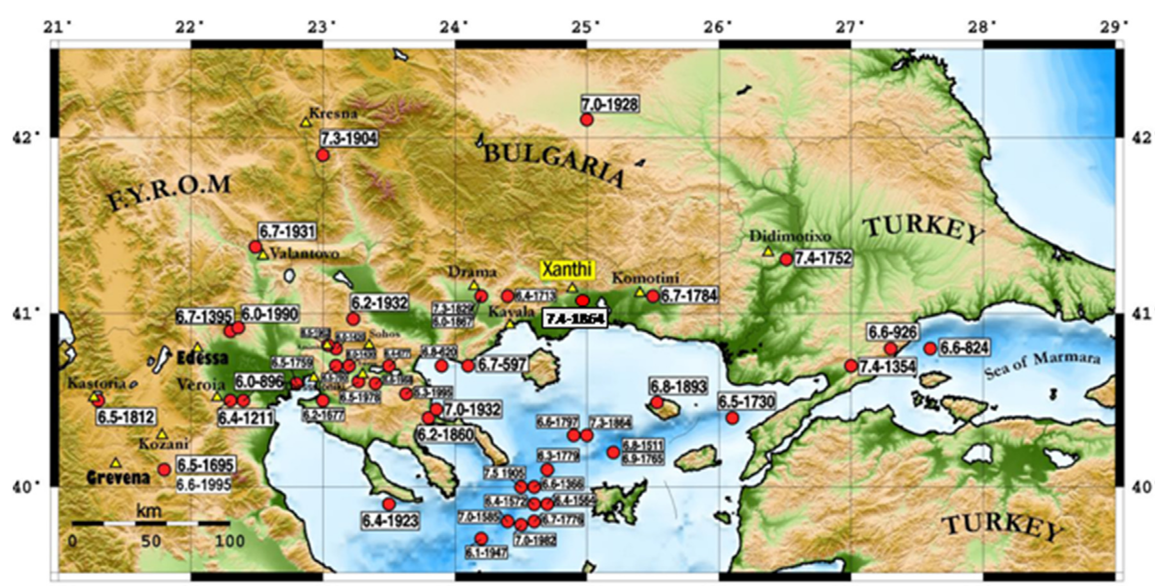

Fig. 1. Location of city of Xanthi and other cities in Northern Greece, affected by strong historical earthquakes. The epicenters of the earthquakes are denoted by red circles; magnitudes and dates of the events are also shown [17]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)