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A COMPARISON STUDY BETWEEN 1D AND 3D SITE RESPONSE ANALYSES BASED ON OBSERVED EARTHQUAKE ACCELERATION RECORDS…

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Abstract

The characteristics of the site conditions have a very significant influence on the variation of building damage during earthquakes, thus, it is essential to evaluate and analyse the effects of site conditions. One option is to conduct site-specific response analysis to calculate the response of the soil layers by using estimated acceleration records on rock outcrop, shear wave velocity profiles, shear modulus reduction, and damping ratio curves as inputs for the encountered soil layers. The objective of the present work is to evaluate the necessity of 3D site response analysis based on the comparison among the peak ground and spectral accelerations recorded by Istanbul Rapid Response Network and Istanbul vertical array stations during the Mw=6.5 24/05/2014 Gökçeada and M_l*=5.7 26/09/2019 Silivri earthquakes with the calculated accelerations by 1D and 3D site response analyses. The shear wave velocity profiles determined based on in-situ geophysical and geotechnical measurements and laboratory tests within the Istanbul Microzonation Project are revaluated adopting an optimization scheme to obtain the best fits between the recorded and calculated accelerations by 1D site response analysis. These modified shear wave velocity profiles are later used for 3D site response analyses performed taking into consideration the three components of the recorded acceleration time histories in all three directions at the bedrock level to model peak ground and spectral accelerations on the ground surface.*

Keywords: 1D and 3D site response analysis, effect of site conditions, vertical strong motion arrays, Istanbul Rapid Response network.

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1 INTRODUCTION

It is widely accepted that a part of dynamic behavior of structures is affected by soil-foundation system during an earthquake. These structures should withstand to a desirable level to future earthquakes in all directions, while considering the designs only for one direction of ground motion may lead to limited results on the ground surface. The primary goal of site response analysis (SRA) is to evaluate the effects of site condition concerning all direction of input motions, magnitude, shear wave velocity, method of analysis and fault type, for reducing the damage of structures and improving life safety during and after earthquakes. Within all these parameters and recent strong earthquakes in Türkiye (Kahramanmaraş 2023 with Mw=7.8, and Izmir 2020 with Mw=6.5), demonstrated the importance of local site response analysis. It was showed by the authors that fault type did not have significant effects on the results of SRA at the ground surface [1]. Throughout the other possibly options, generally 1D wave propagation SRA are suggested for estimating the ground motions [2]. In this study, the importance of considering all the three earthquake acceleration time histories (3D) were investigated as input motions and capturing the behaviour of soil at ground level comparing 1D analysis. Considering that Türkiye is generally in high seismic zones and recent devastating earthquakes, concerns will increase about capability of models for anticipating future earthquakes and local designs. Besides, with respect to nonlinear behaviour of soil, it is important to start analysis with appropriate soil constitutive models. Although equivalent linear methods due their flexibility were widely used, but their accuracy with respect to nonlinear model for case studies especially in high-risk seismic zones to be sure about the reliability of the calculated results should be checked. Moreover, a recent study was showed the significancy of including models in SRA with nonlinearity of soil in case of strong ground motions [3].

The main purpose of this study is to investigate efficiency of directions of applying earthquake concerning East-West (EW), North-South (NS) and Vertical (V), at the bedrock level in Ataköy located in Istanbul with considering nonlinearity of soil to predict ground motions at surface to evaluate the capability of the model based on recorded motions by Istanbul Rapid Response Network (IRRN). To do so, multi directional components acceleration time histories of earthquakes observed with accelerometers at 140-meter bedrock level will be applied to model earthquake conditions at the site. In accordance with this goal, 3D Nonlinear site response analysis were done in PLAXIS3D[4] for Ataköy Vertical array considering multi directional input motions for Gökçeada (Mw=6.5) and Silivri (M_l=5.7) earthquakes. The nonlinearity of soil was modelled with elasto-plastic hysteretic model of Hardening soil available in library of PLAXIS3D code. This advanced model, is capable to model different soft and stiff soil behaviour [5] and capture the seismic ground motions under monotonic and dynamic loads as well [3].

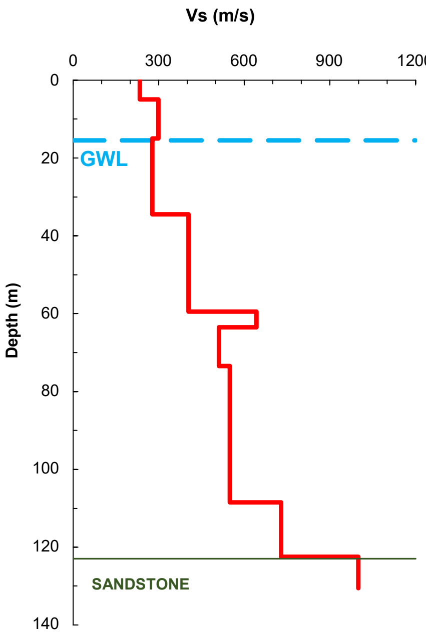
Finally, by evaluating the results obtained on the ground surface in 1D and 3D models with Nonlinear and Equivalent linear behaviour, are compared with respect to the recorded acceleration time histories to evaluate the effects of applying multi directional components of earthquake accelerations in site-specific response analysis.

2 SITE CONDITION

Ataköy Vertical Array Site is located on south of European side of Istanbul in Türkiye (Figure1). Measurements for this site were performed in four boreholes for strong motion recorders with approximate depth of 25, 50, 70 and 140 meters with distance of 5 meters from each other.

Figure 1: Ataköy Vertical Array Site location

Shear wave velocity profile (Figure 2) was obtain based on Suspension PS Velocity Logging test and Measurements were made in fluid-filled boreholes [6] according to OYO Corporation of Japan method [7]. Moreover, for 140-meter depth borehole, standard penetration tests (SPT) and sampling were performed. (Figure 3)



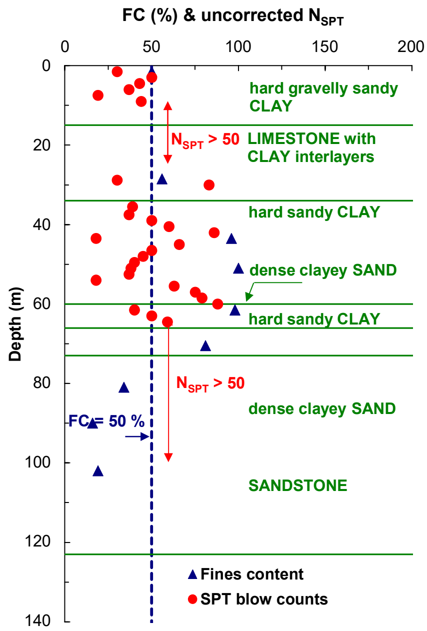


Figure 2: Variation of shear wave velocity with depth.

Figure 3: Fines content (%), uncorrected N_{SPT} (bpm).

Based on information observed from shear wave velocity profile and SPT test, simulation of Ataköy Vertical Array Site was performed.

3 ACCELERATION TIME HISTORIES

With respect to the site response analysis, calculated acceleration time histories on the ground surface may be used for future analysis of super structures [8]. In the conducted parametric study, two recorded earthquakes of Gökçeada and Silivri by Istanbul Rapid Response Network and Istanbul vertical array stations were chosen with magnitudes of M_w=6.5 (24/5/2014) and M_l=5.7 (26/09/2019) respectively. Acceleration time histories were recorded in East-West, North-South and Vertical directions at bedrock and ground surface level as well, and site response analysis with applying motions at the bedrock level were performed in 3D (EW, NS and V at the same time with nonlinear method) and 1D (just EW/NS in equivalent linear method) directions and calculated acceleration time histories at ground surface were plotted. In accordance with the available recorded acceleration time histories available at the ground surface level, and higher similarities between recorded and calculated 3D analysis, it seems 3D calculated acceleration time histories are more suitable for using in structural time history analysis. (Figure 4)

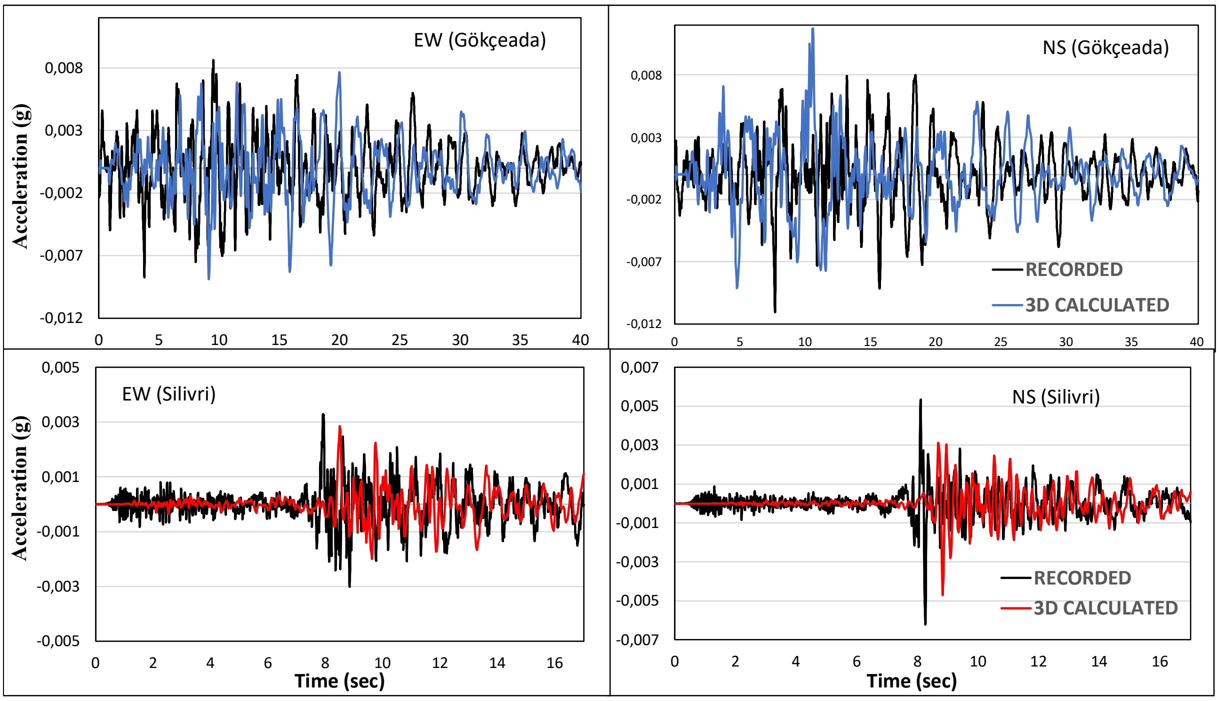


Figure 4: Recorded and calculated acceleration time histories in EW and NS directions for Gökçeada and Silivri earthquakes on the ground surface

4 METHODS AND MATERIALS

In the scope of this study, two types of analysis were selected to perform site response analysis as equivalent linear and nonlinear methods for predicting ground surface movements. Equivalent linear analysis which first suggested by Seed and Idriss [9]consider modulus reduction and hysteretic damping curves by performing iteratively adopting the soil shear modulus and damping to a particular strain level for each soil layer. In spite of the fact that soil properties remain constant during the iterations, but in compassion to the linear analysis the shear modulus is decreased and damping ratio is increased. The equivalent linear method represents adequate results for relatively stiff sites with medium levels of strain (less than 0.1%) [10][5]. Due to compounded behaviour of soil originating of being a multi-phase material, the Nonlinear method of analysis including elasto-plastic nonlinearities also were selected as the second solution to capture soil behaviour instantly with level of load changing in dynamic applications in order to compare to equivalent linear method's estimations on the ground surface. As the type of Nonlinear model, Hardening Soil was chosen for this study which designed first by Schanz [5] in order to model basic macroscopic phenomena illustrated by soils like soil stress history and plastic yielding. Hardening soil model uses three types of stiffness as E_{50} (Secant stiffness in standard drained triaxial test), E_{ur} (Unloading / reloading stiffness) and E_{oed} (Tangent stiffness for primary oedometer loading) as soil input parameters which leads to high accuracy of prediction of soil deformation's magnitude[11]. PLAXIS recommended default values of E_{50}=E_{oed} and E_{ur}=3E_{50} as average values for different soil types. According to available N_{spt} data for Ataköy site, E_{50} was estimated. Based on the PLAXIS Library documents, in hardening soil model, hysteretic damping of the soil depend on the input soil properties can simulate damping at strains larger than 10^{-4}-10^{-2}%, so in order to do dynamic analysis with mentioned model and simulating soil damping during application, using small amount of Rayleigh damping was suggested for damping of lower strains in PLAXIS3D [12]. To do so, the target damping ratio of ζ_1, ζ_2 and related frequencies of f_1 and f_2 should be selected. Based on suggestions, for energy dissipation at low strains it's recommended to keep magnitude of ζ_1 and ζ_2 equally and in a range of 0.5-2% [9] [13], so for the scope of this study $\zeta_1 = \zeta_2 = 1\%$ were selected respectively. f_1 as the fundamental frequency of the whole soil profile for Ataköy site was calculated as 0.97 Hz, and f_2 estimated as $f_2 = nf_1$ based on Hudson (1994) research, which n refers to the closest odd number of ratios of fundamental frequency of ground motion to the fundamental frequency of the whole soil profile[14], so in this way f_2 was calculated and introduced to the program respectively. Geometry of Ataköy profile was simulated as $1x1m^2$ cross section area with depth of down to the engineering bedrock. For studied site, size of mesh as very fine was selected with 2.65-meter size in dimensions which met the requirements of mesh guidelines (average element size should be less than $1/8^{th}$ of the wavelength) recommended by Kuhlemeyer & Lysmer [15] and appropriate absorbing boundary conditions due to wave transfers during application was also chosen.

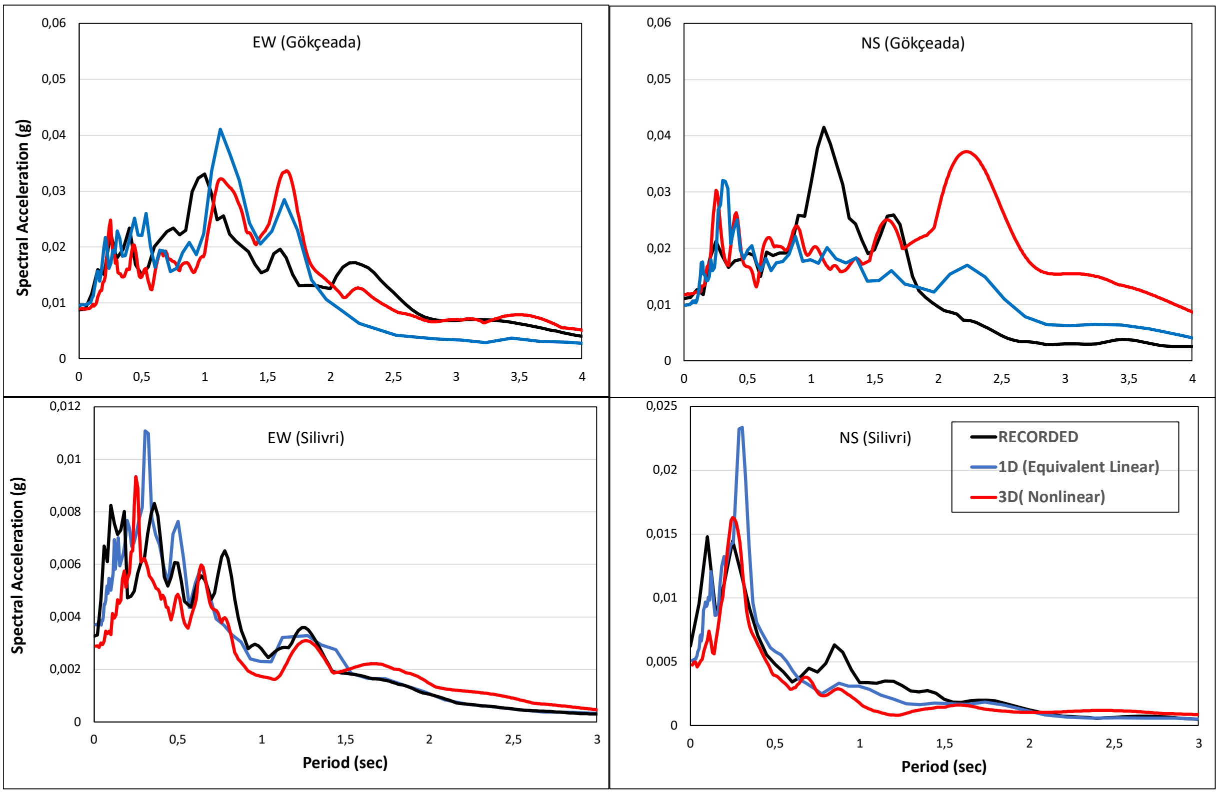


Figure 5: Recorded and calculated spectral accelerations in 1D and 3D directions for Gökçeada and Silivri earthquakes on the ground surface.

5 SITE RESPONSE ANALYSIS

The aim of this study is to compare site response analysis of Ataköy profile by 1D site response analysis using DeepSoil (including EW/NS directions) and 3D (including applying EW, NS and V components at the same time) by PLAXIS3D. The purpose is to evaluate the applicability with respect to 3D nonlinear and 1D equivalent linear methods. As a result of these analysis, time histories (Figure 4) and spectral accelerations (Figure 5) were calculated at the ground surface for both Gökçeada and Silivri earthquakes and compared to the recorded motions.

6 CONCLUSIONS

Multi directional site response analysis on Ataköy soil profile was conducted by applying earthquakes in EW, NS and V directions simultaneously. Results of both 1D and 3D applications show some agreement with respect to recorded motions at ground level. In case of Gökçeada earthquake calculations using 3D model, the acceleration spectra in EW direction appear to model the observed spectra better, however, the calculated acceleration spectra for 1D and 3D are radically different after 1.5 sec period. The acceleration level of observed and 3D calculated are similar with 1sec period difference most likely due higher damping in the 3D nonlinear model. In the case of Silivri earthquake, the 3D calculated acceleration spectra appears also better in modelling the recorded spectra. In these limited applications, it seems 3D model is giving lower spectral accelerations compared to 1D method that agree better with recorded acceleration spectra.

Based on the comparison of 3D calculated acceleration time histories and observed acceleration time histories, 3D calculated time histories may be more suitable to be used as input for structural time history analysis, based on the findings for two different earthquakes with different epicentral distances.

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