Site characterization for site response analysis in performance based approach

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Abstract. The local seismic hazard analysis would yield probabilistic uniform hazard acceleration response spectrum on the engineering bedrock outcrop. Thus, site-specific response analyses need to produce a probabilistic uniform hazard acceleration response spectrum on the ground surface. A possible performance based approach for this purpose requires a probabilistic estimation of soil stratification and engineering properties of encountered soil layers in the soil profile. The major uncertainties in site-specific response analysis arise from the variabilities of (a) local seismic hazard assessment, (b) selection and scaling of the hazard compatible input earthquake time histories, (c) soil stratification and engineering properties of encountered soil and rock layers, and (d) method of site response analysis. Even though the uncertainties related to first two items have primary importance on the outcome of the site-specific response analyses, the discussion in this article focuses on the observed variability and level of uncertainty in site conditions, related to soil stratification, thickness and type of encountered soil layers and their engineering properties, depth of ground water table and bedrock and properties of the engineering bedrock. Thus, one option may be conducting site response analyses for large number of soil profiles produced by Monte Carlo simulations for the investigated site to assess probabilistic performance based design acceleration spectra and acceleration time histories calculated on the ground surface based on 1D, 2D, or 3D site response analysis with respect to different performance levels.

Keywords: soil stratification, site response analysis, uniform hazard acceleration spectrum, performance based design

1 Introduction

Site characterization for geotechnical earthquake engineering applications involve many variables and related uncertainties [1,7]. These uncertainties may include soil and rock properties, as well as measurement errors and statistical uncertainty in a very large domain. Therefore, it may be suitable to narrow the approach and focus on the site specific response analysis to evaluate the uncertainties to achieve a probabilistic methodology in defining a performance based approach [13,17]. One of the controlling issues in the performance based design involves the definition of performance objectives. In the case of site response analysis, the performance objectives may be considered as the probabilistic definition of the uniform acceleration hazard spectrum and acceleration time histories calculated on the ground surface.

The general purpose of site response analysis is to calculate the uniform acceleration hazard spectrum and acceleration time histories on the ground surface based on the probabilistic uniform acceleration hazard spectrum on the rock outcrop calculated considering the local seismicity and source models for the region. For the calculated uniform hazard acceleration response spectrum on the ground surface, the major uncertainties are due to (a) local seismic hazard assessment, (b) selection and scaling of the hazard compatible input earthquake time histories, (c) soil stratification and corresponding engineering properties of encountered soil and rock layers, and (d) method of site response analysis.

The uncertainties related in the selection and scaling of the hazard compatible input earthquake time histories was reviewed previously [1]. The discussion in this manuscript will start with the uncertainties related to variabilities in site conditions and engineering properties of soil layers. For a probabilistic methodology, the additional challenge involves probabilistically acceptable definition of soil profiles. One option is to conduct site response analyses for large number of soil profiles generated using Monte Carlo Simulations to assess effects of variability with respect to different performance levels [3].

2 Probabilistic evaluation of site response analysis

Important factors controlling site response analyses are soil stratification with respect to soil types, layer thickness, shear wave velocity for each soil layer and the depth of engineering bedrock. Monte Carlo simulation scheme has been adopted to study the effect of variability of assigned shear wave velocities and layer thicknesses for all soil layers encountered in 209 soil borings in the Zeytinburnu microzonation project [4]. The effect of variability is studied by generating Monte Carlo simulations (MCS) for soil profiles assuming that initially measured shear wave velocities are mean values with the range of possible variation is ± 20% of the mean and observed layer thickness are mean values with the range of possible variation is ± 10% of the mean, thus 100 soil profiles were generated for each 209 soil profiles.

Total of 459,800 site response analysis for 100 Monte Carlo simulations for 209 soil profiles and for 22 acceleration records were conducted. Based on the observed discrete distribution approach, the 90% percentile value for each period level for acceleration spectra is calculated corresponding to 10% exceedance in 50 years or for 475 year return period and 98% percentile spectrum for corresponding to 2% exceedance in 50 years or for 2475 years return period as shown for two soil profiles in **Fig. 1.** ~~**Fig. 1.**~~

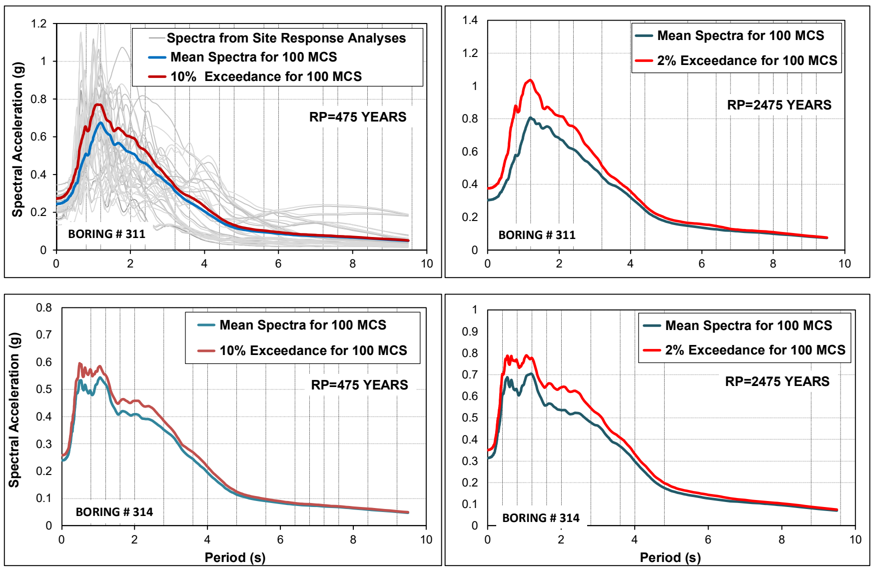

Fig. 1. 10% and 2% exceedance uniform hazard spectra on the ground surface based on Monte Carlo Simulations

3 Acceleration Time histories for Performance Based Design

It appears possible to calculate uniform hazard acceleration spectra on the ground surface that can be adopted in the performance based design of engineering structures. However, in the case of dynamic response analysis using acceleration time histories for the super structures, the question is still remains open for the general performance based design. Thus, the one possibility may involve use of acceleration time histories calculated by site specific response analysis [8, 10, 16].

The state-of-practice in earthquake engineering design has moved toward the use of dynamic non-linear time history analysis. The critical issue in performance based analysis is the selection of acceleration of time histories for nonlinear time-history analysis of engineering structures. One option is to use recorded accelerations in real earthquakes scaled to match design code spectrum or uniform hazard spectra. However, when selecting time history records from the data banks, the effects of site conditions are totally neglected. One possible approach at this stage may be to adopt the calculated acceleration time histories on the ground surface for the nonlinear time-history analysis of engineering structures. In this case the reliability of the calculated acceleration time histories on the ground surface become an important issue.

In a parametric study conducted previously, acceleration spectra and acceleration time histories calculated based on the modified version of Shake91[5] are compared with acceleration response spectra and acceleration time histories recorded by the Ataköy SM station in Istanbul during 1999 M_w=7.4 Kocaeli Earthquake as shown in **Fig. 3** and **Fig. 4**. The higher frequency motions are more dominant during the whole duration in comparison to the recorded time histories. In the light of the similarities between recorded and calculated acceleration response spectra (**Fig. 2**), and the similarity between recorded and calculated acceleration time histories, it is acceptable of the calculated acceleration time histories as an input to structural analysis.

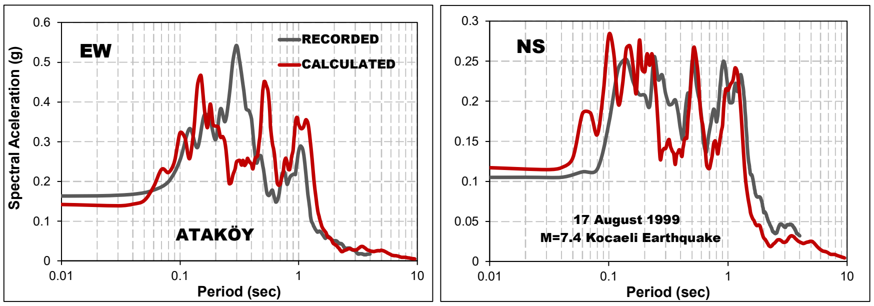

Fig. 2. Calculated and recorded acceleration spectra at Ataköy SM station for the 17/8/1999 Mw= 7.4 Kocaeli Earthquake

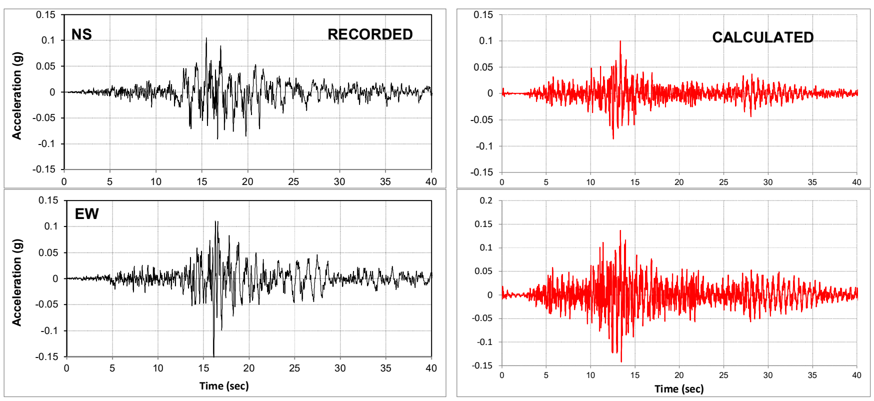

Fig. 3. Calculated and recorded acceleration time history at Ataköy SM station for the 17/8/1999 Mw= 7.4 Kocaeli Earthquake.

4 2D Site Effects

When considering site conditions, it is very clear that everything is 3D, the variation of soil stratification, and properties of soil layers, as well as 3D effects of the earthquake induced seismic source and seismic wave action. Therefore, one performance criteria for geotechnical earthquake engineering may need to be considered in comparison to 1D and 2D site characterization and response analysis [9, 12, 14].

The horizontal variations of the layer thickness and soil properties in 1D site response analysis cannot be modelled accurately. 2D site response analyses may be used to account horizontal variability to have a better estimate of the 2D earthquake characteristics on the ground surface. There have been significant number of studies reported in the literature that used different methodologies to evaluate 2D site analysis and site amplification. Within this framework, Kaklamanos et al [11] evaluated the critical parameters affecting site response results. They observed that 1D site response in general may yield lower spectral accelerations excluding the short period range, however, within the range of maximum shear strain $\gamma_{max} \approx 0{:}1\%$ to 0.4%, the accuracy of equivalent-linear site response analysis may be realistic.

In a previous study conducted by the authors [2,17], it was observed that topographic irregularity of the ground surface and the thickness of the soil layers, the difference between 1D and 2D may be significant. As shown in **Fig. 4** and **Fig. 5**, the variation of soil stratification along the south-north profile in the European side of Istanbul indicate significant variations in the thickness of the soil layers, thus 1D and 2D results are not similar.

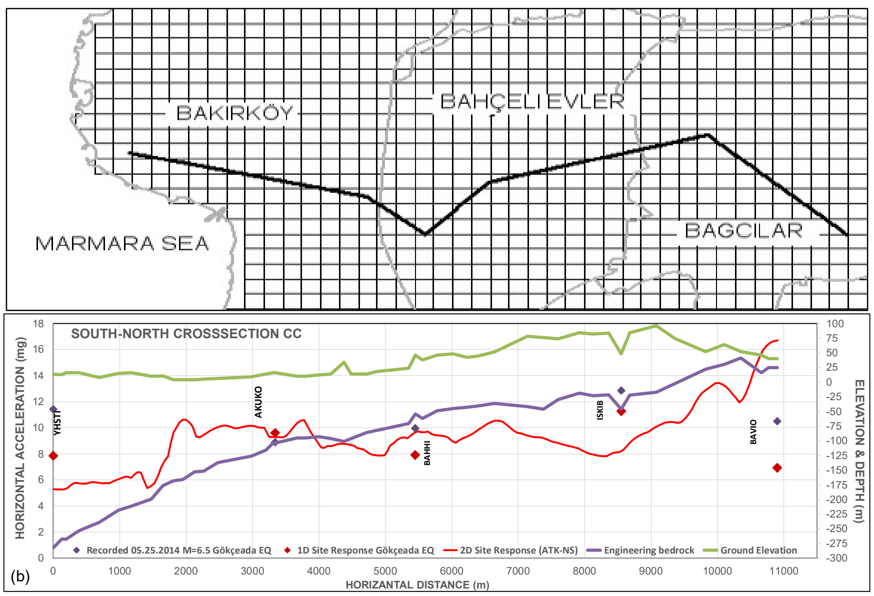

Fig. 4. 2D Soil profile (a) in map view (b) as soil cross-section for calculated PGA by 1D and 2D site response analysis at IRRN stations on the ground surface.

As shown in **Fig. 5**, The thickness of the soil profile from south to north increases continuously introducing a 2D effect that may not be modelled by 1D site response analysis that is also reflected in **Fig. 6**(b).

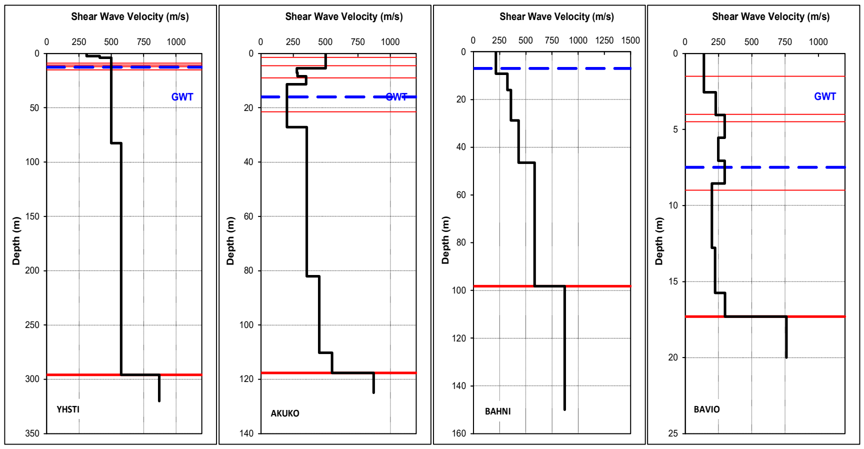

Fig. 5. Soil profiles along the cross section

For some SM stations, PGAs as well acceleration response spectra calculated by 1D and 2D as in **Fig. 6**(a) the match between all seems almost perfect however, as in **Fig. 6**(b) 2D results compared to 1D appears slightly better in modeling the recorded results.

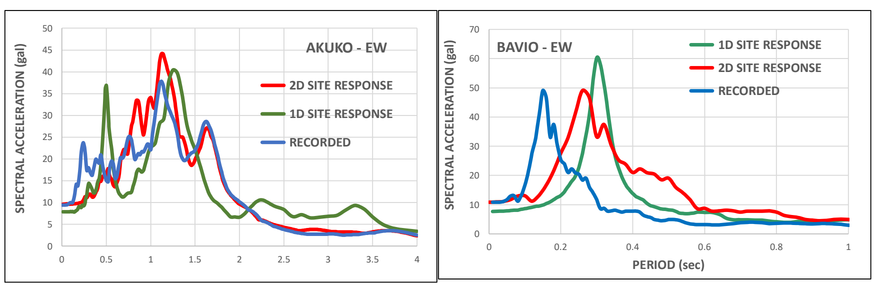

Fig. 6. Acceleration response spectra for calculated by 1D and 2D site response analysis in comparison to the recorded acceleration response spectra

In a study conducted by Bonilla et al. [6] for a basin structure, it was observed that amplification from 2D analysis is higher than 1D that was observed in similar studies. However, in the case of 2D analysis conducted by the authors [2] where there no basins, such effects were not observed, justifying 1D to be sufficient to model or estimate possible earthquake characteristics on the ground surface.

For sites with complex and irregular stratigraphy, two-dimensional (2D) and three-dimensional (3D) ground response is preferred over 1D wave propagation for more realistic evaluation of ground response under seismic load.

Unidimensional analyses are a standard procedure in practical SRA, however these analyses do not involve the effects of the topography and existence of surface and underground structures, so two or three-dimensional models provide an adequate alternative to perform the same analysis with the advantage to include more complex conditions as well the possibility to include the three components of the seismic input motion.

5 Conclusions

Site characterization for a geotechnical earthquake engineering application involves many variables and uncertainties. One of the controlling issues in the performance based design involves the definition of performance objectives. In the case of site response analysis, the performance objectives may be considered as the probabilistic definition of the uniform acceleration hazard spectrum and acceleration time histories calculated on the ground surface.

The variation of peak ground and spectral accelerations recorded on the ground surface by some of the Istanbul Rapid Response Network (IRRN) stations are assessed with respect to soil stratification, ground surface and bedrock topography. 1D and 2D site response analyses were conducted to model the observed PGAs recorded during the M_L=6.5 Gökçeada 24/5/2014 earthquake for the soil profile along south-north direction to see the effect of two dimensional modelling with respect to 1D and 2D site response analysis and recorded acceleration records. It is observed in this preliminary investigation to specify the performance base objectives for site response analysis may require at least 2D site response analysis to be on more realistic approach for performance based approach.

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