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Effect of soil depth on inelastic seismic response of structures

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ABSTRACT

Effect of depth of soil stratum on estimated inelastic displacement of three typical structures, *viz.* a four storey building, a continuous bridge, and a tower, is studied and adequacy of the site amplification models of the current design codes and available empirical relationships is examined. The structures are assumed to be located on well-defined sites with varying bedrock depths, and effect of depth on elastic response spectrum, site amplification factor, displacement modification factor and inelastic displacement is studied, numerically, for two values of PGA. It is observed that soil depth has a significant effect on elastic as well as inelastic response of the structures; however, the effect of soil amplification on inelastic response is not as pronounced as in case of elastic response. Therefore, use of empirical site amplification models based on elastic response may be too conservative, for estimating inelastic response.

1. Introduction

The effect of soil on seismic ground motion, and consequently on seismic performance of structures, is well recognized. Characteristics of ground motion on the soil surface are quite different from the motion at the rock-outcrop or at the bedrock. In design codes, the effect of soil stratum is considered by using amplification factors for different site classes. The site classification in codes, is mainly based on average shear wave velocity ($V_{S,30}$) in top 30 m of stratum. Depth of soil stratum is still not included in the criterion for site classification in most of the national codes, except a few, like the German seismic code DIN 4149:2005 [1,2]. The use of $V_{S,30}$ for site classification for the purpose of ground motion amplification, has also been questioned by many researchers [3–6], suggesting that the single parameter is not able to represent the site amplification characteristics, fully. Some design codes, *viz.* the New Zealand code, NZS 1170.5:2004 [7] and the Japanese code (as referred in [8]) consider the natural site period (T_o), in addition to $V_{S,30}$, to classify sites, which indirectly takes into account the effect of soil depth. Zhao [9] in his study based on KiK-Net (http://www.kik.bosai.go.jp) dataset, reported that for sites with predominant periods over 0.6 s, period is a better site parameter than $V_{S,30}$, for estimating amplification factor.

Recently, effect of soil depth on seismic response has been a topic of interest to many researchers. Rodriguez-Marek et al. [10] indicated that soil depth is an important parameter in site response, and proposed a scheme for geotechnical characterization of sites, which included soil depth and stiffness. Pitilakis et al. [8] identified soil type, stratigraphy and thickness, fundamental site period, and the average shear wave velocity up to bedrock, as the key parameters governing site response. Sun et al. [11] have shown that the site coefficients specified in the Korean seismic design code (adopted from UBC and NEHRP provisions) underestimate the amplification factor in the short period range, overestimates the amplification factor in the mid-period range; and are not applicable to the Korean Peninsula due to the large difference in the bedrock depth and the soil stiffness. Hashash [12,13] has reported that the soil depth plays a very significant role in the ground motion estimation and that the NEHRP site coefficients are not applicable for deep deposits. He has proposed 'NEHRP-style' depth-dependent site coefficients for the upland and lowland regions of the Mississippi embayment. The developed short period site coefficients (F_a) show increasing dependence on the embayment thickness as the soil becomes stiffer, whereas, the developed long period site coefficients (F_v) show higher dependence on the embayment thickness as the soil becomes softer. The calculated site coefficients for the upland and the lowland are lower at short periods and greater at long periods, than the existing NEHRP site coefficients. Recently, a detailed empirical study for estimating site effects has been carried out by Cadet et al. [14,15]. The KiK-net surface-downhole strong motion recordings have been used, and the site amplification factors (ratio of surface to downhole response spectra) have been evaluated, empirically. Cadet et al. [14] have proposed a methodology to normalize the site amplification factors with respect to a standard outcropping rock site in line with the present

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design codes, by applying two correction factors, namely, the depth correction factor and the impedance contrast normalization factor. Cadet et al. [15] then used the so obtained 'homogeneous site amplification factors' to analyze the correlations between site response and various site characteristics, and proposed a set of new 'site amplification prediction equations (SAPE)'. The developed empirical relations consider the effect of bedrock depth (or total soil thickness) implicitly, in terms of the fundamental site frequency, f_0. Lately, Pitilakis et al. [16] have extended their previous work [8] and proposed a new site classification scheme for EC8, which takes into account the depth of soil stratum along with other parameters. They have also proposed amplification factors for the proposed site classes, using a worldwide strong ground motion database.

In the past few decades, there is a paradigm shift in the design philosophy from conventional 'force-based' design to 'displacement-based' design [17], where inelastic (total) displacement of the structures is the governing design criteria and a prerequisite to design. Historically, the displacement based design methods have been developed primarily in context of seismic evaluation and rehabilitation of existing structure. However, now these methods are being used for performance based design (PBD) of new structures, as well [18,19]. A number of methods have been developed in the last two decades to estimate inelastic displacement using the elastic response spectrum of design codes. Use of inelastic displacement ratio (C_μ, also known as 'displacement modification factor' [20]), which permits estimation of maximum deformation demand of inelastic system, from the peak deformation of corresponding elastic system [21], has become quite popular in performance based earthquake resistant design. Some researchers [22,23] have pointed out that soil conditions have a significant effect on C_μ. However, the effect of soil depth on C_μ is yet to be explored.

Very few comprehensive studies on the effect of soil depth on seismic response of inelastic structures are available in literature [24]. The effect of soil depth on seismic performance of buildings has been studied by Kamatchi et al. [24] for site specific earthquakes. In this study, artificial ground motions have been generated, using finite fault simulation, for a selected *M–R* pair. The inelastic displacement demand estimated using the generated artificial motions, has been compared with that obtained using Indian seismic design code for the 'comparable seismic risk. As the design code response spectrum represents an envelope (or uniform hazard spectrum) which may be controlled by more than one *M–R* pairs, it is necessary to have some sort of calibration/matching of spectra of the considered motions (on rock outcrop), with the code spectrum to be able to directly compare the inelastic demand from the two methods. Since the spectral shape as well as spectral ordinates, depend heavily on the selected *M–R* pair, the uncertainty in selection of *M–R* pair and the effect of amplification due to soil have been coupled together and it is not possible to differentiate the effect of soil depth *vis-a-vis* other parameters. Further, the study is based on an idealized variation of shear wave velocity in the soil stratum, ignoring the effect of impedance contrast occurring between intermediate layers, whereas many researches [8,9,25] have identified impedance contrast between intermediate layers, also to be an important parameter affecting site amplification. In the present study, effect of soil depth on inelastic seismic response of structures, has been studied for selected soil profiles having well defined material properties. All the selected sites belong to the same NEHRP site class 'D', but have different assumed bedrock depths. One dimensional wave-propagation analysis has been performed using equivalent linear modelling [26] to study the effect of soil depth on pseudo acceleration spectra, amplification factors, elastic and inelastic displacement spectra, and C_μ, for a common target response spectrum on rock outcrop (ASCE 7-05 design spectrum on site class B [27]). The effect of soil depth on inelastic displacement of three representative structures (periods ranging from 0.75 s to 2.23 s) has also been studied using the ASCE 41-06 [20] methodology.

2. Methodology

Site effects can be estimated using experimental (instrumental), empirical, or numerical methods. To study the site effects, instrumental and empirical methods are more reliable. However, sites having different soil depths, but identical site classification based on $V_{S,30}$, with sufficient recordings, and having a nearby reference rock site (for obtaining the amplification factors with reference to rock sites), are rare. In absence of adequate instrumental data, numerical methods provide an attractive alternative to study the site amplification for any desired range of soil and ground motion parameters.

For estimating the response of structures, in the present study, a decoupled analysis approach has been used. In this approach, the free field response of the site is first obtained and then used as input for estimating response of the structure. Several approaches are available for estimating response of soil sites, which is a highly nonlinear material. In the present study, the site response analysis has been performed using equivalent-linear modelling of soil. It is an iterative procedure, in which equivalent shear modulus and damping are evaluated in each iteration, as functions of shear strain. The main issue in this procedure is selection of appropriate modulus reduction and damping curves. Darendeli [28] carried out site response analyses for a 100 m thick silty-sand deposit using his experimentally obtained nonlinear material curves and the average generic curves proposed by Seed et al. [29]. He reported a difference of 30–50% in the spectral accelerations at all periods less than 1 s. Therefore, in the present study, well defined sites have been chosen from literature, for which experimentally evaluated material parameters are available. Ground motions recorded at rock-outcrop and made compatible with the code (ASCE 7-05) design spectrum are used as input in the software DEEPSOIL [26] to perform equivalent linear 1 D wave propagation analysis. The primary objective of the present study is to study the effect of depth and stratification of soil; and the effect of topography and spatial variation of soil properties along horizontal plane has not been considered. This is consistent with the current practice of classification of soil sites based on vertical stratification. The motions obtained at the ground surface, have been used to obtain the elastic and inelastic spectra and response of selected structures, assumed to be located on the chosen sites.

2.1. Sites considered

Five different soil sites, *viz.* region M3, Delhi [24], La Cienega, Los Angeles [30], KGWH02, KiK-net, Japan [30], Lotung, Taiwan [30] and Treasure Island near San Francisco bay area [31,32], have been chosen for the present study. Except the Delhi site, all the four sites considered in the present study are geotechnical array sites. The criterion for selection of these sites was that all the sites belong to the same NEHRP site class 'D' ($V_{S,30}$ in the range of 180–360 m/s) and well documented material properties and engineering models are available in literature, to accurately simulate the ground response. Delhi, the national capital of India, is a rapidly growing city with a number of tall structures, which are particularly susceptible to the ground motions travelling through deep soil deposits. Thickness of the alluvium above bedrock at Delhi varies between 50 m and 300 m [24]. The La Cienega site, KGWH02 (KiK-net network of strong motion stations, Japan) site and Lotung (Taiwan) sites are also natural sites, with extensive instrumentation. The Treasure Island site is a hydraulically filled