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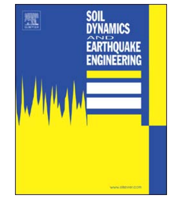

Site response analysis of vertical ground motion in consideration of soil nonlinearity

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ABSTRACT

Vertical ground motion significantly affects the seismic response of engineering structures, particularly nuclear power plants and dams. However, most ground motion predictions or site response analyses focus on horizontal ground motion. As a result, knowledge of the characteristics of vertical ground motions is inadequate. In this study, a benchmark approach for equivalent linear vertical site response analyses is developed, with focus on the modeling of soil nonlinearity. The modeled soil exhibits different nonlinear behavior in the vertical direction depending on the saturation condition (i.e., above or below the groundwater table). Moreover, the vertical nonlinearity is different from that observed in the horizontal direction. The vertical ground responses predicted by the proposed approach are generally consistent with downhole measurements associated with different geological conditions, groundwater tables, and shaking intensities.

1. Introduction

Vertical ground motions are considered in seismic designs of critical structures (e.g., nuclear power plants and dams) but disregarded when designing standard structures. However, Papazoglou and Elnashai [1] emphasized the significance of vertical ground motions and their damaging effects on ordinary structures. Field evidence from recent earthquakes shows that many buildings and bridges have experienced significant damage because of the high intensity of vertical earthquake motions [1–3]. Moreover, vertical ground motions significantly affect slope stability [4].

The evaluation of site response to earthquakes plays an important role in the seismic design of engineering structures. However, most site response analyses focus on horizontal ground motion and regard site response as a result of the vertical propagation of shear waves in a horizontally layered system. In reality, the ground is subjected to simultaneous shaking in horizontal and vertical directions during an earthquake. Vertical ground motion has received less attention compared with horizontal ground motion. As a result, knowledge of the characteristics of vertical ground motion, particularly the relationship between vertical and horizontal ground motions, is limited. Recent earthquake records [5] suggest that the commonly adopted vertical-to-horizontal (V/H) response spectral ratio (SR) of 2/3 [6] may be significantly exceeded at short periods in the near-source distance range. Moreover, the V/H ratio can exceed 2/3 because of local site effects [7].

Site response analyses are required to evaluate the local site effect on vertical ground motion. However, Elgamal and He [8] indicated that a simple 1D linear model for vertical wave propagation is inadequate for modeling the observed downhole array response. Such a simplified model requires extremely high viscous damping in the range of 15–25% even for small tremors to match the recorded downhole vertical response. Therefore, Elgamal and He [8] and Beresnev et al. [9] concluded that additional data and research are required to develop a rational procedure for the analysis of site responses to vertical ground motion. As a part of the NGA-West2 Project [10], the Pacific Earthquake Engineering Research Center recently assembled a vertical site response working group to help understand the behavior of vertical site response, particularly in the nonlinear range, for various ground motion levels and site profiles. However, the simulated results of vertical site response are inconsistent with the empirical results [11].

Elgamal and He [8] summarized observations of vertical ground motions from downhole arrays around the world and discovered that the amplification characteristic of vertical ground motion is barely affected by the level of shaking and remains similar before, during, and after strong shaking. Tsai and Lui [12] recently evaluated the differences in site effects on wave propagation in vertical and horizontal directions by analyzing three component records of five downhole arrays. They concluded that amplification of vertical ground motion is less significant than that of horizontal ground motion, the amplification behavior of vertical ground motion is less dependent on the intensity of motion (i.e., exhibiting less soil nonlinearity) than that of horizontal ground motion, and the nonlinear amplification behavior of vertical

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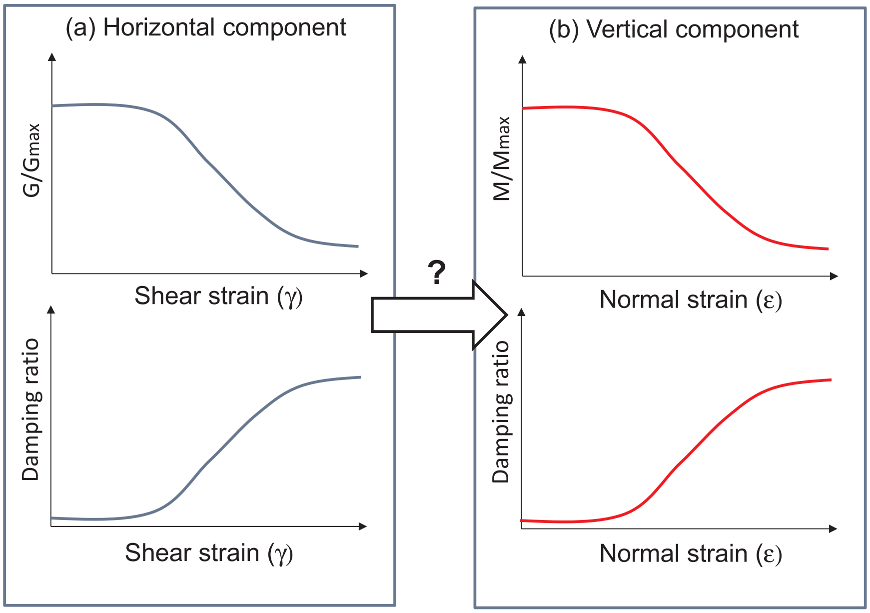

Fig. 1. Soil modulus reduction and damping curves for site response analysis: (a) horizontal component and (b) vertical component.

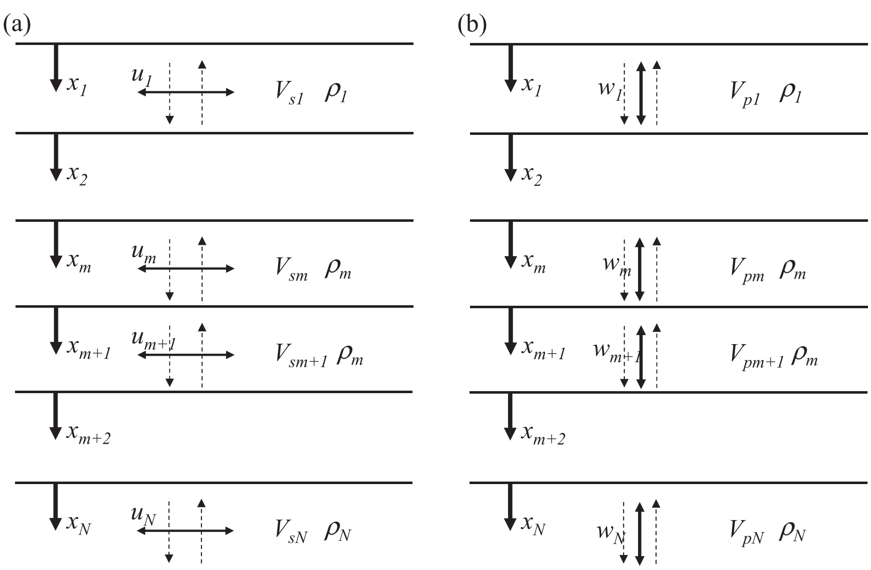

Fig. 2. (a) Vertically propagated shear wave and (b) compression wave in a horizontally layered system.

Table 1
Arrays and records used for analysis.

Array	Ground motion record depth	Groundwater depth	Geological condition	Reference
Lotung	0 m, 17 m	1.5 m	Interlayered silty sand and sandy silt over clayey silt	[32]
La Cienega	0 m, 18 m	9 m	Silty clay over gravel	[38]
Wildlife array	0 m, 7.7 m	2 m	Interlayered silty clay and silty sand	[39]
Corona array	0 m, 8 m	13 m	Medium- to fine-grained sand and lesser silt	[41]
Turkey Flat array	0 m, 23 m	> 25 m	Clayey sand and sandy clays	[33]

ground motion is dependent on the location of the groundwater table. These observations indicate that amplification behavior in the vertical direction differs from that in the horizontal direction, as indicated in previous studies [7,13,14]. These differences should be considered in dynamic site response analyses and ground motion predictions.

The importance of earthquake vertical ground motion to structures and the differences in site effects on wave propagation in vertical and horizontal directions motivated the present study to develop a simple but accurate procedure for predicting vertical site responses. The developed procedure was verified with vertical ground motions recorded by five selected downhole arrays.

2. Current state of vertical site response analysis procedures in practice

Soil nonlinearity is usually accounted for by shear modulus reduction and damping curves (Fig. 1a) using equivalent linear (EQL) approach [15] or nonlinear (NL) scheme [16] for horizontal motion propagation. Review of previous studies shows that two approaches are commonly adopted to consider soil nonlinearity and damping in the