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Seismic analysis of nailed soil slope considering interface effects

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ABSTRACT

Natural soil slopes are often reinforced with nails to stabilize them against earthquake loading. Although pseudo-static method is widely used in designing such slopes; it fails to provide important information such as deformation of slope, effect of soil-nail interface etc. A 2-D finite element model of typical nailed slope has been prepared during this study using OpenSees to perform seismic analysis with due consideration to soil nonlinearity, pressure dependency of soil and separation-sliding at soil-nail interface. It is found that the soil-nail interface modelling can significantly influence the permanent deformation of slope after seismic event. The overburden pressure on the nail varies significantly during the earthquake loading and the variation is more when sliding and separation is allowed at the soil-nail interface. It is also found that the model with fixed interface leads to a perception of reinforced soil acting as a relatively rigid block, which results into an unconservative design from overall deformation perspective.

1. Introduction

The seismic stability of in-situ slopes and embankments is often increased by reinforcing them with nails. During 1989 Loma Prieta earthquake, nailed excavations, even in the vicinity of the earthquake epicenter, in the San Francisco Bay area performed exceptionally well although such performance was mainly attributed to the conservative design and stability analysis [1].

Finite element (FE) analysis of slopes is becoming a standard practice as compared to alternative conventional equilibrium methods [2]. Zhang et al. [3] developed a 3-dimensional FE model for static stability analysis of excavated steep slopes and found that there was good agreement between predicted and observed movements. Wang and Richwien [4] studied the soil-nail interface friction and found that the mobilized friction between soil and nail depends upon the dilatancy angle and the elastic parameters of soil. Ann et al. [5] performed 2-D finite element analysis to back analyse the instrumented soil nailed slopes under gravity loading. They felt need of higher order soil and interface models to capture the behavior of nailed soil slopes. Fan and Luo [6] carried out nonlinear finite element analysis, for static loading to determine the optimum layout of nails in slope and found that nails in the lower one-third part of slopes play important role in the stability of slopes. Sahoo et al. [7] carried out 3-D finite element analysis of small and steep nailed soil slopes subjected to earthquake loading using software MIDAS GTS. Interface elements were provided at the soil-nail interface. They studied effect of parameters such as nail inclination, nail length, frequency amplification and slope angle on the seismic resistance and failure mechanism. It was found that the inclined nails offer more resistance to deformation than the horizontal nails. Effect of nail length and amplification factor on the seismic resistance was found to be negligible.

The effect of modelling interface between the nail and soil on the seismic response of the soil-nail system has been explored in the present study. This aspect has remained relatively unexplored in the previous investigations, although it is expected to have significant impact on the overall deformation response of nailed soil slopes. In addition to this, in the conventional Pseudo-static design of nailed soil slopes, the overburden pressure on the nail is assumed to be constant. However, in reality, during the seismic shaking this overburden pressure will vary. Therefore, it becomes essential to study the variation of overburden pressure on the nail and to see how far the assumption is reliable.

In this study, nonlinear finite element analysis of a typical nailed soil slope subjected to earthquake loading has been carried using an open source code OpenSees [8] to investigate the abovementioned issues. Two cases of soil-nail interface modelling have been considered; first with perfect bonding between soil and nail, and second with the sliding and separation allowed at the soil-nail interface. Radiation damping at the boundaries of the model has been incorporated by providing Lysmer boundary [9]. Soil is assumed to be dry and cohesionless, and analyzed under plane strain conditions. The effect of

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Nomenclature

A_n	cross sectional area of nail
A_p	cross sectional area of plate with width equal to spacing S_h of nails
E_n	modulus of elasticity of nail
E_p	modulus of elasticity of plate
G	shear modulus
K_N	normal penalty
K_T	tangential penalty
S_h	horizontal spacing between nails
ρ	density of soil

interface modelling on the overall deformation of slope has been discussed in detail.

2. Design of nailed soil slope considered in the study

Fig. 1 shows schematic of the 12 m high soil-slope considered in this study. Soil profile of 62 m depth is rested on bed rock and it consists of three layers; top 12 m of the profile consists of medium sand followed by 20 m thick layer of medium-dense sand overlying 30 m thick layer of dense sand. The inclination of slope from horizontal is 60°. The number and length of the nail to be used in finite element model was obtained after designing the slope using Michalowski's method [10,11] by considering 1940 Imperial valley earthquake loading recorded at CSMIP station number 117 at El Centro site [11]. This method is based on the kinematic limit analysis of geosynthetic reinforced slopes subjected to earthquake loading. In the first step, the minimum strength of reinforcement required to keep slope just stable is worked out by performing upper bound limit analysis, and assuming tensile failure of reinforcement layers. While doing so a log-spiral failure surface which is kinematically admissible is used in the analysis. In the next step, the length of the reinforcement, for a given number of reinforcement layers, is worked out by considering pull-out of some layers and rupture in others. To calculate reinforcement length two types of failure surfaces have been considered; one is rotational and the other sliding. The maximum of two calculated lengths are used in design. Details of the nails provided in the designed slope are given in Table 1.

3. Finite element modelling of soil-nail system

The finite element model of the soil-nail system is described here including material models, finite elements, meshing scheme, boundary conditions, application of earthquake motion, nail-soil interface modelling, verification of model, etc.

3.1. Soil and nail

The overall FE model of the nailed slope is shown in Fig. 2. The soil domain is discretized using four-node quadrilateral elements with four gauss points as shown in Fig. 2a. Each node of the element has two translational degrees of freedom. The constitutive behavior of soil was modeled using a pressure dependent multi-yield (nested yield surface) material model proposed by Iwan [12], Mroz [13], and Prevost [14], and modified later by Parra-Colmenares [15] and Yang [16]. It is a nonlinear elastic-plastic material model that captures the essential characteristics such as dilation (i.e., volume contraction or expansion during shearing), cyclic mobility (i.e., non-flow liquefaction) of sand or silt typically observed during monotonic or cyclic loading. The model has been already calibrated and validated for cyclic loading by Elgamal et al. [17] and Yang et al. [18]. Thus; it is expected to simulate the seismic response of the soil well enough. The detailed description of yield function, hardening rule, and flow rule of the constitutive model can be found elsewhere [15,16]. Table 2 presents the relevant parameters and their values needed for the constitutive model of soil, which were taken from typical values given in the OpenSees Manual [8,19]. The present study considers dry cohesionless soil. The maximum size of element in the direction of propagation of wave was restricted to one eighth to one tenth of the shortest wavelength expected to be traveling through the soil medium [20]. The soil domain was analyzed assuming plane-strain condition.

Nails are the discretely placed elements in three-dimensional (3D) space. In the present study, two-dimensional (2D) plane strain modelling of nailed soil slope was carried out. Therefore, 3D nails were converted to equivalent 2D nails using the equivalent plate approach proposed by Al-Hussaini and Johnson [21]. In this approach, the nails are replaced by a plate of equivalent axial stiffness. The equivalent axial stiffness of plate is obtained using the following equation [22]:

$$E_p = E_n \frac{A_n}{A_p} \tag{1}$$

Where, A_n is cross sectional area of nail, A_p denotes the cross sectional area of plate with width equal to the horizontal spacing (S_h) of nails, E_n and E_p are the Young's modulus of the nails and plates, respectively. The nails were considered to be linear-elastic under earthquake shaking. Therefore, these were modeled as two-node elastic beam-

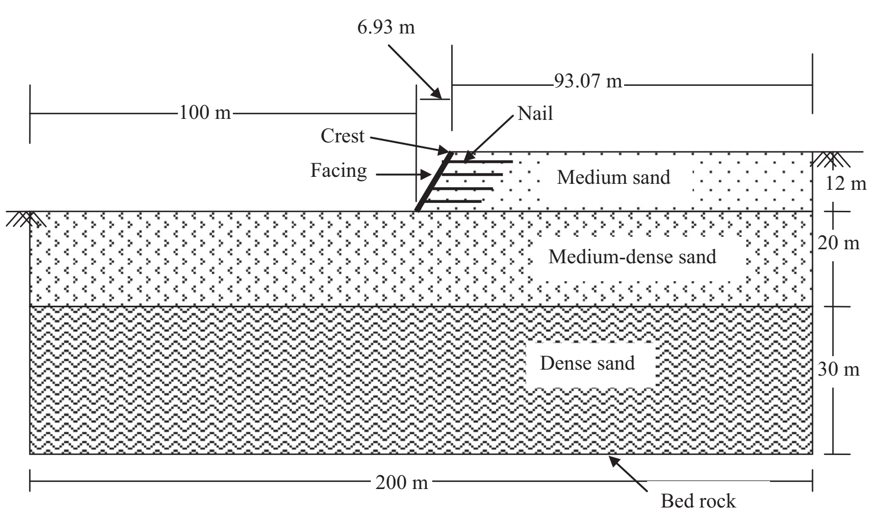

Fig. 1. Schematic of the model used in the present study.