SEISMIC EFFECTS OF WIDESPREAD CONSTRUCTIONS ON SLOPPY GROUNDS

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ABSTRACT:

Seismic failure of sloppy grounds frequently resulted in significant economic loss and increased risk of life during several past earthquakes around the world. Many buildings and other structures have been constructed gradually on sloppy grounds. They may pose a considerable weight/mass on the slope, particularly, in congested urban areas. Therefore, it is necessary to evaluate seismic slope stability where the excessive ground displacement may inflict several consequences or increase seismic risk. Traditionally, the additional mass of the structures is assumed as a surcharge on the slope. In this case, existing approaches for stability analysis of slopes and embankments can be directly applied to solve the problem with the consideration of additional mass to the soil mass above the slope failure surface. However, the complete inertial interaction of the structures supported by the slope is not considered in this approach. In this case, the amplification of the inertial forces of the buildings and other structures transmitted to the ground may be significantly underestimated resulting in a non-conservative evaluation of the seismic slope stability. This paper aims to study the significance of the effects of massive constructions of different fundamental vibrational periods on the slope stability problem with the consideration of soil-structure interaction. A two dimensional slope model was modelled in OpenSEES with pressure independent yielding constitutive model in order to perform total stress analyses for a dry cohesive soil material. The mass constructions were modelled by a distributed surcharge, a group of structures with identical fundamental periods and another time, by different groups of structures with different fundamental periods. Results demonstrated that permanent slope displacement is notably affected by the modelling assumption for the widespread construction built on the sloppy ground.

KEYWORDS: seismic slope stability, soil-structure interaction, soil nonlinear analysis, slope permanent displacement, slope instability, landslide

1. INTRODUCTION

In geotechnical earthquake engineering, slope instability is one the most important issues which has been in the center of attention due to its huge and widespread damage potential as well as monetary consequences. Generally, three procedures are available for slope stability analysis, i.e., pseudostatic analysis, Newmark's sliding block analysis and stress-deformation analysis. Pseudostatic approach was firstly presented by Terzaghi for slope stability analysis (Terzaghi 2015). This procedure provides an index of slope stability. However, it does not provide any information when the instantaneous stability is compromised. After that, stress-deformation analysis was developed (Chopra 1966). This approach may quickly become a complicated procedure depending on the complex details of the soil properties and the degree of the required accuracy in modelling (Seed 1979). The result of this approach is deemed closer to reality. Finally, a kinematic sliding block analysis was presented by Newmark (1965) to introduce a new procedure that does not contain shortcomings of the pseudostatic or complication of the stress-deformation analysis. However, since the flexibility of the sliding soil block is not considered in the Newmark's approach, its results should be considered with caution for some cases in which flexibility of the soil body is important (Makdisi and Seed 1978). Recently, several procedures have been developed to account for the flexibility of sliding blocks (Kramer, Steven L, Smith, 1997; Rathje & Bray, 1999). However, in all of these procedures, there is no way to directly consider the inertial interaction effects of the structures with the supporting soil slope system. Considering the aforementioned limitations in slope stability evaluation and large direct and indirect consequences of slope instability, it is important to study the seismic effects of growing massive constructions, particularly, in urban areas on the stability of the supporting slope.

2. MODELLNG OF SLOPE SOIL SYSTEM

In this study, a two dimensional (2D) slope as shown in Figure 1 is modelled in OpenSEES (2000) platform. The slope is meshed using rectangular and trapezoid elements in which only the elements of the slope and upslope are simulated utilizing trapezoid element and others are considered rectangular. The geometric modelling parameters shown in Figure 1 are set as follows: Q = 3, M = 21, R = 6, N = 11, P = 4. The value of a and b was set equal to three.

The "quad" element with plane strain behavior were used to discretize the soil system. While the soil thickness in the out-of-plane direction is considered unity for the slope, two boundary columns to model the free-field response of the eliminated ground were considered with a much larger thickness, i.e., one hundred times unity. These massive columns of a large aspect ratio is assembled on both right and left sides of the model as free-field columns. This is on the basis that the slope is surrounded by semi-infinite grounds on its both sides (upslope and downslope). In order to simulate the horizontal motion of the soil layers in the semi-infinite spaces, two nodes of each element are restrained to each other using "EqualDOF" command to simulate the free-field conditions. In order to model gravity forces, the soil specific weight 1.8g kN/m^3 is allocated to each element. The sloppy ground is underlain by a rigid bedrock. Building structures located on the slope are modelled by means of single-degree-of-freedom (SDOF) mass-spring-dashpot assemblies which are described in the following section. Each building was simulated by a node connected by a zero-length element to a slope element node. Input acceleration records were applied to the bedrock surface.

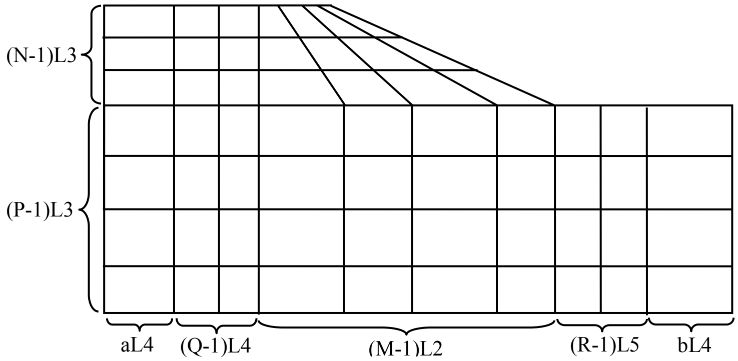

Figure 1. The schematic view of the slope and geometric modelling parameters

The soil stress-strain constitutive model is elastic-plastic in which plasticity exhibits only in the deviatoric stress-strain response. The volumetric stress-strain response is linear-elastic and is independent of the deviatoric response. This material is implemented to simulate monotonic or cyclic response of materials whose shear behavior is insensitive to the confinement change. In OpenSEES, the "PressureIndependMiltiYield" material (Yang et al. 2003) is adopted for this model which is rather appropriate under fast (undrained) loading in organic soil and clays. The shear wave velocity, soil mass density, Poissons's ratio, soil shear modulus, elastic modulus and bulk modulus are needed to define the constitutive model of this material. Other required parameters to simulate the soil include maximum shear strain which is assumed 0.05 and effective confined pressure which is considered 100 kPa in this study. The maximum shear strength can be estimated using these parameters. Also, twenty yield surfaces are utilized to simulate the nonlinear behavior of the soil. The number of yield surfaces that characterizes the soil plastic behavior to reach ultimate yielding stress is usually a value between 20 to 30. In this study, the number of yield surfaces are considered equal to 20. During the application of gravity and other static loads, material behavior is linear elastic. In the subsequent seismic excitation, the stress-strain response is elastic-plastic. Plasticity is formulated based on the multi-surface (nested surfaces) concept, with an associative flow rule (Prevost 1985). The yield surfaces are of the Von Mises type.

In order to fully define the pressure independent yielding constitutive model for cohesive soils it is necessary to determine soil density, ρ, soil cohesion, *c*, and friction angle, φ, as well as shear wave velocity of the soil, v_s. Based on the mechanical properties of soil material it is possible to compute the shear wave velocity of soil.
The ultimate bearing capacity of cohesive soil is,

$$q_u = 4c \tag{1}$$

The undrained shear strength of soil is related to the ultimate bearing capacity with the following relationship.

$$s_u = \frac{1}{2} q_u \tag{2}$$

To obtain the shear wave velocity of cohesive soils the cone tip resistance in a cone penetration test (CPT) may be obtained based on the undrained shear strength of the soil and the overburden pressure, $p_0 = \gamma z$, as follows.

$$q_c = s_u N_k + p_0 \tag{3}$$

where, N_k is the cone factor which is considered equal to a typical value of 20, and p_0 is the overburden pressure. There are several emperical relationships to estimate the shear wae velocity of soil based on the cone tip resistance in CPTs (Jaime and Romo 1988; L'Heureux and Long 2017).

$$v_s = 0.1 q_c \tag{4}$$

In this study, soil material is considered fully cohessive and dry. Therefore, the builtup of pore pressure during seismic analysis is not overly important and the total stress approach was applied. The soil cohesion is assumed 78 kPa which represents a hard clay material and the Poisson's ratio is considered 0.4 which result in a shear wave velocity about 320 m/s as per Equation 4. The shear wave velocity of the upslope free-field column was considered equal to 1500 m/s to represent the hillside. This column remains elastic during all stages of the analysis. While the soil behavior is considered linear for static analysis under gravity loads, the nonlinear (elastoplastic) soil behavior was simulated for the dynamic analyses. In this stage, the materials are updated at the end of the gravity analysis to consider the nonlinear behavior.

3. MODELİNG OF MASSIVE CONSTRUCTIONS ON THE SLOPE

The purpose of this research is investigating the seismic response of slope under massive loads of flexible structures and comparing the results with the situation that the slope does not bear any loads and the case in which construction loads are solely considered as a distributed surcharge. A fraction of the mass of the triangular area under the slope enclosed between the slope line and a vertical line drawn from the slope top node as well as a horizontal line passing through the slope bottom node was allocated to the structures built on the slope to estimate the mass and weight of them. This mass was divided equally between a number of structures considered as single-degree-of-freedom (SDOF) oscillators being connected with zero length elements to the soil nodes in the model. In this study, a 10 percent of the mass of the mentioned triangular part was considered as the total mass of all structures. Structures were considered at the locations of all eleven slope nodes. In one case, stiffness of SDOF systems was computed to result in identical oscillators with a 1.0-sec period. In another case, the stiffnesses were calculated to generate four groups of SDOF systems with identical mass but different periods of 0.1, 0.5, 1.0 and 1.5 sec. This is to account for a variety of structures on a sloppy ground that may cause unsynchronized inertial forces .

In fact, the structures were considered as mass-spring systems to vibrate in their fundamental modal characteristics on the slope. As mentioned, structures were modeled by using zero-length elements. In order to model a zero-length element, two nodes are required. One node is the one used to define a quadrilateral element of the soil system and another one is located at the same node to which the structural mass and weight is allocated. The vertical motions of the structures were constrained to vertical motions of their corresponding surficial soil nodes. It should be noted that as the overturning moments of the structures do not generate any driving force to the slope, the height of the structure is not overly an important parameter for this study and was not considered in modeling.

According to the abovementioned assumptions, four different models were assembled for analyses as follows.

- bare slope soil system with no structure and no surcharge.
- slope soil system with construction surcharge applied to the soil nodes on the slope.
- slope soil system with structures modeled by a vertical surcharge and SDOF oscillators with a 1.0-sec period.
- slope soil system with structures modeled by a vertical surcharge and SDOF oscillators with 0.1, 0.5, 1.0 and 1.5-sec periods.

First, the models were analyzed elastically under static gravity loads. The model was then updated and analyzed dynamically by imposing selected ground motion acceleration records to the rigid bedrock.

4. RESULTS AND DISCUSSIONS OF SEISMIC SLIP UNDER DIFFERENT SCENARIOS

Seismic slope displacements were computed and plotted in Figures 2−4 for different scenarios to model widespread constructions on the sloppy ground subjected to three earthquake ground motions listed in Table 1. All ground motions were applied by a 0.5 scale factor to approximate the free-surface effects of recorded ground motions.

Table 1. Selected earthquake ground motions for numerical analyses

event	**station**	**magnitude, M_w**	**shear wave velocity, (m/s)**
Montenegro, 1979	Ulcinj-Hotel Olimpic	7.1	318
Loma Prieta, 1989	Gilroy-Historic Bldg	6.9	309
Kobe, 1995	Takatori	6.9	256

Results were plotted for three locations on the slope surface, i.e., top, middle and bottom. In all cases, middle horizontal displacements of the slope are larger than those of top and bottom locations. Moreover, for all earthquakes, the permanent slope displacements are larger when only a single group of structures with an identical period ($T = 1$ sec) is modelled on the slope. When four groups of structures with different vibrational periods ($T =$ 0.1, 0.5, 1 and 1.5 sec) are considered the permanent slope displacements are reduced but remain larger than the cases in which the soil-structure interaction is not modeled. Seismic slope displacement is larger when surcharge of the widespread constructions is considered but it is always smaller than the cases in which soil-structure interaction is modelled. Therefore, it is very important to consider the soil-structure interaction when massive constructions have been built on a sloppy ground. It is demonstrated that a single group of structures with identical period may results in conservative results. However, further investigations are required to generalize this conclusion to all vibrational periods.

It should be noted that the results of this study are solely predicated on a single case study 2D slope with a specific geometry that made of a single layer of dry clayey soil with mentioned physical and mechanical properties in the previous sections. The confining pressure was averaged and applied to all soil elements. Additionally, only three earthquake ground motions were used in this study to draw the abovementioned conclusions. All ground motions were recorded on the ground or near the ground surface but they were applied to the rigid bedrock underlying the soil deposit of the model. Free-field columns at both right and left hand sides of the model may model the real free-field response with important limitations. Moreover, the implemented computational model is unable to perform a kinematic runout analysis if a landslide is triggered by the imposed ground motion.

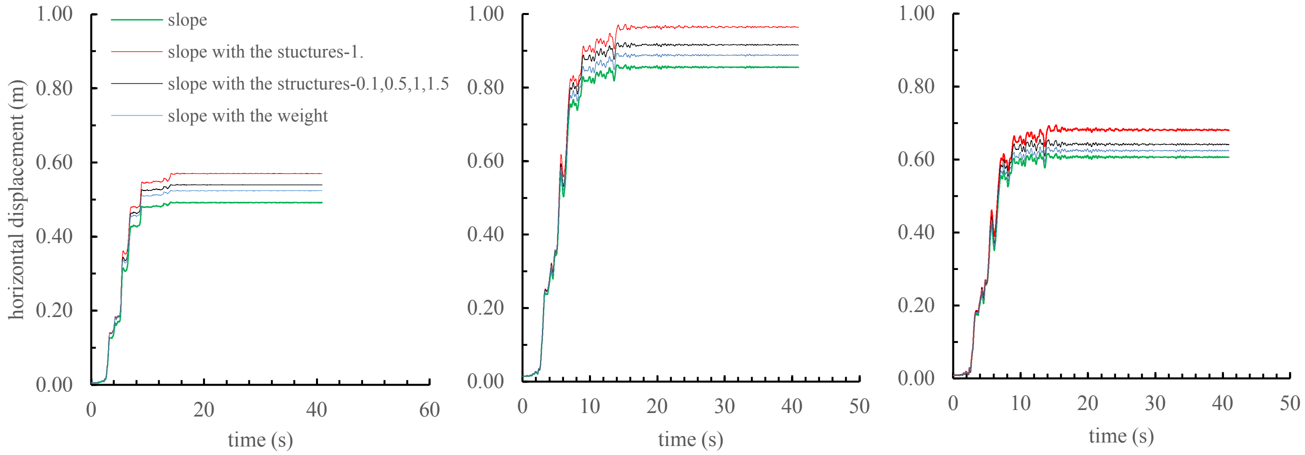

Figure 2. (a) Bottom, (b) middle and, (c) top displacements of a 20° slope subjected to Takatori, 1995 Kobe ground motion with/without consideration of construction surcharge and soil-structure interaction

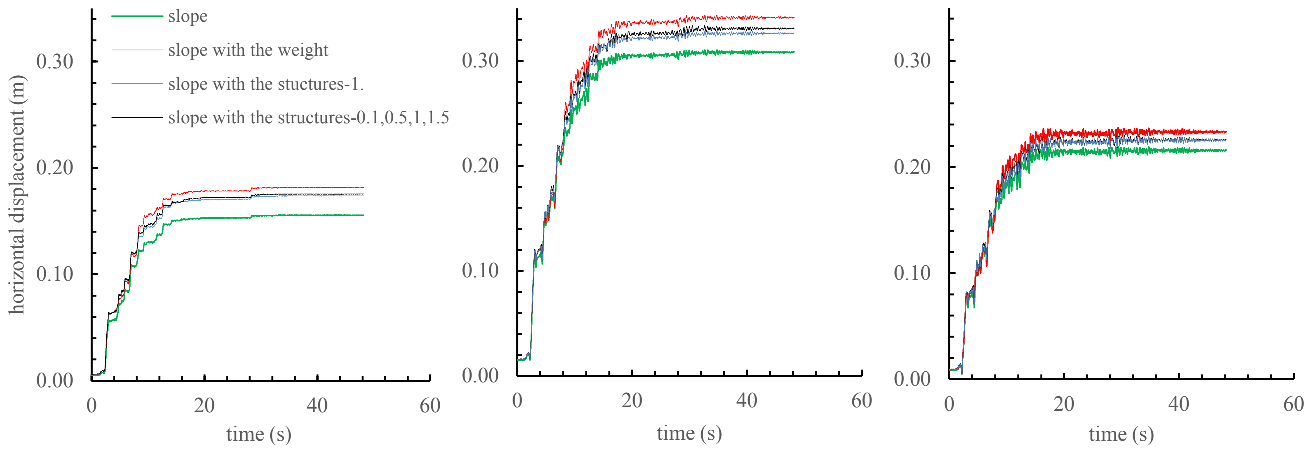

Figure 3. (a) Bottom, (b) middle and, (c) top displacements of a 20° slope subjected to Ulcinj, 1979 Montenegro ground motion with/without consideration of construction surcharge and soil-structure interaction

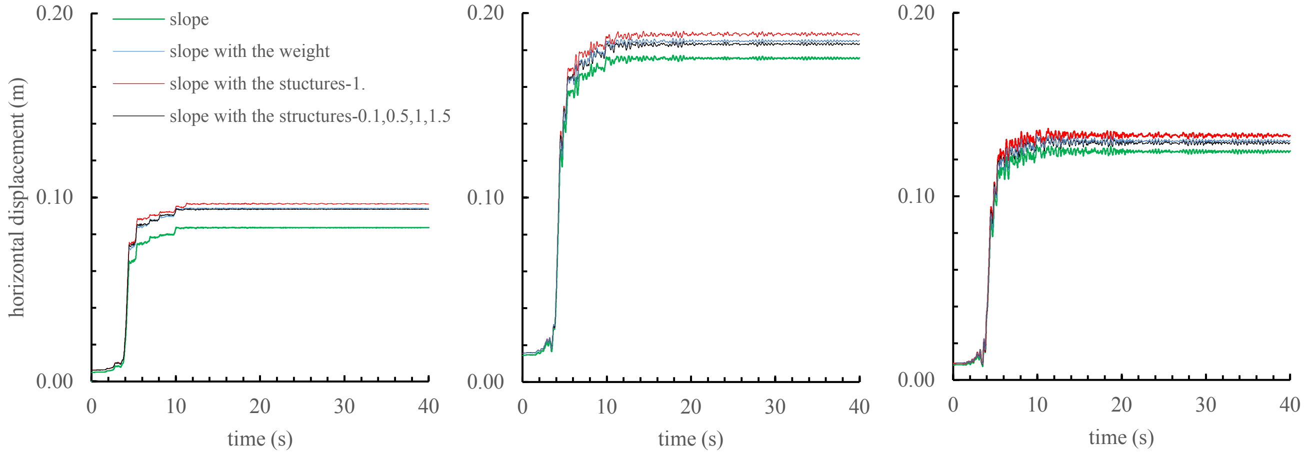

Figure 4. (a) Bottom, (b) middle and, (c) top displacements of a 20° slope subjected to Gilroy, 1989 Loma Prieta ground motion with/without consideration of construction surcharge and soil-structure interaction

5. CONCLUSIONS

There are many regions around the world that heavy civil engineering constructions such as buildings and bridges have been built on sloppy grounds in active seismic areas. Slope instability which is mostly characterized by the level of seismic induced slope displacement may results in huge economic consequences even if the life threatening effects of landslides are mitigated in some ways. In this study, the effects of soil-structure interaction of built constructions on sloppy grounds were taken into account by means of 2D modeling of the soil system in OpenSEES with and without presence of the structures. The total stress analysis approach was implemented on a single layer of dry and hard clayey material modeled with pore pressure independent multi-surface yielding material. The results of analyses were computed and compared for the cases in which structures are (a) not modeled, (b) considered as concentrated gravitational surcharges at each node on the slope, (c) modeled with spring-mass assemblies with a 1.0-sec period, and (d) modeled with four groups of oscillators. Three recorded earthquake ground motions were applied to a rigid bedrock supporting the soil system. Results of the study demonstrate that it is important to consider the soil-structure interaction explicitly to evaluate the seismic slope displacements. For all ground motions soil-structure interaction effects of a single group of structures with an identical period exacerbated the seismic induced slope displacements more than other cases. Even when structures are divided into four groups with different periods the soil-structure interaction effects increased the permanent displacement of the slope when structures are modeled solely with a surcharge.

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