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Stability analysis of a slope subject to real accelerograms by finite elements. Application to San Pedro cliff at the Alhambra in Granada

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ABSTRACT

The dynamic stability analysis of slopes is often conducted by the traditional method of slices, using pseudo-static calculations. However, the response of a geotechnical structure subjected to seismic loads can be studied through a dynamic finite element analysis, which can be considered one of the most complete available tools, as information about the stress distribution and the deformations can be obtained. The dynamic analysis of the stability of San Pedro cliff at the Alhambra in Granada is studied in this paper. The results have been compared with pseudo-static calculations worked out with the method of slices. Real accelerograms have been selected for the dynamic tests. Thorough in situ and laboratory tests have been conducted in order to properly characterize the cliff. The soil constitutive model is also explained in this paper. Finally, the influence of the sources of energy dissipation has been studied through the material damping, the integration scheme and the boundary conditions.

1. Introduction

Hanging towns, built at the edge of a cliff and subjected to instability of slopes, are one of the main problems for the conservation of historic sites. An example of this problem is San Pedro cliff, a dihedral 65.5 m high, which has progressed to place itself at a distance of 23.8 m from the Alhambra palace-wall, a World Heritage site (Fig. 1. View of San Pedro Cliff cutting the Alhambra hill; at the foot of the hill runs Darro River; to the right the scar of the 1985 slab fall).

Active normal faults (Fig. 2. Outline of the site showing the river meander, the main cracks at La Alhambra palace and faults at the hill slope) surround the cliff and have created an extensional tectonic regime that loosens the ground and actives the fall of slabs. A main fault matches the western face of the faces of the dihedral. Pseudo-static stability analysis suggest that the Factor of Safety (hereinafter, FOS) of this slope under 1000-year return period earthquake loading may drop below 1.0 and the critical slip surface could penetrate the Alhambra walls [17]. A restoration project based on a high-yield-stress wire mesh, post-tensioned by anchors and coloured to blend with the cliff is proposed. The mesh applies a pressure on the slope. This might be the only acceptable solution and its visual impact is moderate.

A dynamic analysis of the stability of San Pedro cliff has been carried out with Plaxis [27]. Accelerograms have been selected with the method proposed by Morales-Esteban et al. [22]. The calculations have been repeated for every accelerogram. The information about the geotechnical properties has been obtained from the site investigation conducted by Justo et al. [17].

2. The safety of slopes during earthquakes

This paper refers to ground which does not lose an appreciable part of its strength due to the build-up of pore pressures induced by the vibrations.

Many stability analyses still use pseudo-static calculations, where horizontal forces are used instead of accelerograms. The dynamic calculation by means of the finite element method (hereinafter FEM) is accurate, versatile and requires fewer assumptions, especially the failure mechanism [11]. Moreover, it can be considered one of the most complete tools to estimate the seismic response of a geotechnical system, as the information about the stress distribution and the deformations/displacements can be obtained. Slope failure occurs naturally through the zones in

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which the shear strength is insufficient to resist the shear stresses. However, it requires an appropriate constitutive model of the soil, a complete description of the soil characteristics and a proper definition of the seismic data.

From the paper written by Ambraseys [2] the dynamic earthquake calculations were based upon the assumption that the nonlinear hysteretic stress–strain response of soils could be determined by an equivalent linear–elastic method of analysis, based upon a damped linear–elastic model if the properties of that model were satisfactorily chosen. This model will be called the equivalent linear model.

It has been recognized by earthquake engineers long ago that the usual concept of a FOS on shear strength does not properly asses the behaviour of a slope during strong earthquakes. The FOS is the factor by which the strength should be reduced so as to bring the slope to a state of limiting equilibrium with the stresses along a failure surface. If the FOS is less than one, a section of the slope will slide along the failure surface. This state cannot be permitted under static conditions, as the stresses will exist until large displacements change the geometry of the structure. But under dynamic conditions it may be possible to allow the FOS to drop momentarily below one, as this state will exist only for a short time, and the slope might come to rest again at a time when the new stresses do not exceed the available strength. The performance should rather be measured in terms of the relative displacement that the sliding mass may undergo during the earthquake.

Fig. 1. View of San Pedro Cliff.

Since the final analysis with strain-compatible soil properties in the equivalent linear model is purely elastic, the permanent deformation caused by earthquake shaking cannot be computed by this type of analysis. However, the stresses derived from these strains are assumed representative of stresses in the ground and the accelerations are also assumed to be reasonably representative of field values [10]. Seismic slope deformation models are used to make predictions of earthquake-induced permanent displacements in natural slopes and constructed earth systems.

The first model was the rigid-block model established by Newmark [25]. This model was extended to sliding along an inclined plane by Sarma [31], which first examined the stability of a rigid block resting on a plane surface. In this paper the calculations will be limited to horizontal accelerations and zero pore pressures. The angle of the acceleration has little influence on the final result [31]. In Fig. 3 (Model of a rigid block on a sloping surface), K is the seismic coefficient.

The driving shear force along the sloping plane is as follows:

$$D = W(\sin\beta + K\cos\beta) \tag{1}$$

If the contact is cohesionless, the resisting force is as follows:

$$R = W(\cos\beta - K\sin\beta)\tan\Phi' \tag{2}$$

The critical acceleration is defined as the acceleration that applied on the block will produce a state of limiting equilibrium. Equating expressions (1) and (2) and operating:

$$K_c = \frac{\tan\varnothing'\cos\beta - \sin\beta}{\tan\varnothing'\sin\beta + \cos\beta} = \tan(\varnothing' - \beta) \tag{3}$$

When the driving force exceeds the resisting force, the acceleration of the block relative to the plane surface is as follows:

$$\frac{W}{g}\frac{d^2x}{dt^2} = D - R \tag{4}$$

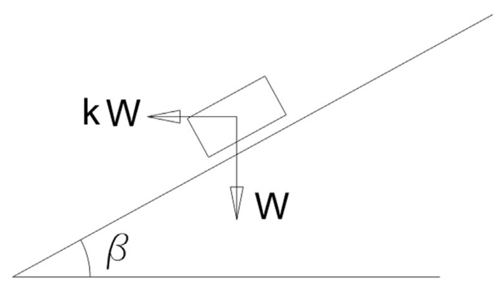

Fig. 3. Model of a rigid block on a sloping.

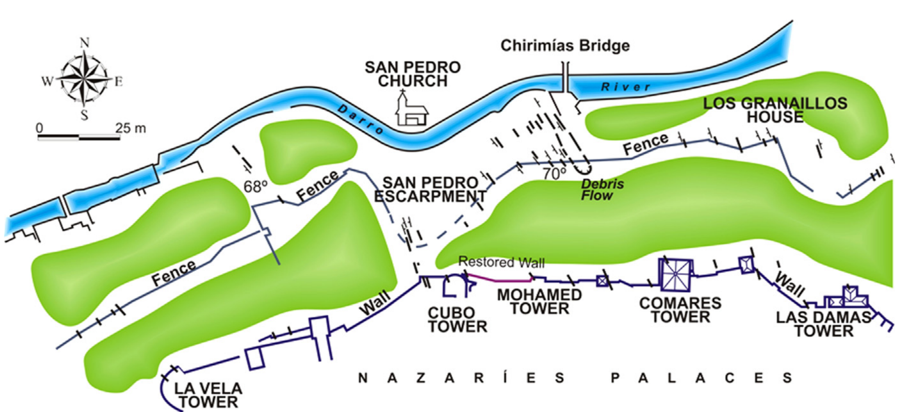

Fig. 2. Outline of the site.