State of the Art of Slope Stability Analysis Subjected to Seismic Loads

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Project Background

Landslides induced by earthquakes is an important geotechnical hazard that every year causes human and economic loses. The more than 10,000 landslides caused by the 7.5 magnitude Guatemala Earthquake in 1976 are a major example that earthquakes have a great impact in the stability of slopes (Anon 1997). The study of earthquakes-induced landslides is essential to minimize the risk associated with these events.

The first investigation of landslides triggered by earthquakes was performed in the Calabria region, Italy, in 1783, and since then, many studies have been performed (Keefer 2002). A number of methodologies have been developed to study the slope stability and failure initiation under dynamic loading. However, their accuracy is still limited and further research is required. Moreover, an important factor for risk assessment is to predict the post-failure behavior of the mobilized mass and its final run-out. Therefore, the development of methodologies capable of predicting the failure and its consequences in a unified framework is crucial to minimize the damage caused by these catastrophic events.

Project Objectives

1. To present an overview of the methodologies that have been developed over the years to consider seismic loads in slope stability analyses.
2. To emphasize the applicability of the methods to study the different stages of a landslide (i.e. failure and run-out).

Research findings

A list of research tasks and key findings is provided below:

1. A literature review was conducted to determine the different methodologies to study slope stability subjected to seismic loads. These can be classified in three groups:

   – Pseudo-static analysis: established by Terzaghi, this method introduces the seismic load as a static horizontal force equal to the weight of the potential sliding mass multiplied by a seismic coefficient (k), which can range from 0.05 to 0.25 (Duncan et al., 2014). The load is generally applied upon the center of gravity of the block. Finally, a conventional static slope stability analysis is performed using classical limit equilibrium analysis to find the factor of safety.

   – Sliding-block analysis: introduced by Newmark in 1965, this is currently one of the most common methods in engineering practice to study slope stability subjected to seismic loads. This approach considers a rigid body mass on an inclined surface and the ground motion is incorporated as an acceleration time-history. The yield acceleration (a_y) is defined proportional to the product of the gravity acceleration, and a coefficient (k_y), which is equivalent to the seismic coefficient that produces a factor of safety equal to one. When the acceleration a(t) exceeds a_y, the block begins to slide, and it stops when the velocity of the block and the velocity of the underlying mass are the same. The accelerations surpassing a_y are integrated once to find the velocity of the system and twice to find permanent displacement.

– Stress-deformation analysis: this comprises a number of numerical technics designed to approximate the solution of boundary value problems. The problem domain is discretized in small pieces and the governing equations are solved for a finite number of points. Dynamic formulations allow to incorporate seismic loads in terms of acceleration or stress time-history. Two main approaches can be distinguished: mesh-based methods and particle-based methods. On the one hand, mesh-based methods such as the Finite Element Method (FEM) or the Finite Differences are the most common technics. One limitation of mesh-based methods is that suffer from mesh tangling when large deformations are involved. On the other hand, particle-based methods, such as the Material Point Method and Smoothed Particle Hydrodynamics, are specially designed to simulate large deformation and long run-outs. In general, stress-deformation analyses allow for complex constitutive models and realistic geometries, but are computationally expensive.

2. A study has been performed to identify a) how the different methodologies evaluate the onset of failure (stability analysis), and b) the applicability these methods to predict post failure deformations and final run-outs (post failure analysis). Table 1 summarizes the findings.

Table 1. Summary of the applicability of the methods on a) stability and b) post failure analysis.

	Pseudostatic Analysis	Sliding Block Analysis	Stress Deformation Analysis
a) Stability Analysis	Factor of Safety FS >1	Allowable permanent displacements	Evaluation of the kinematic response of the slope
b) Post failure analysis (Risk analysis)	Not applicable	Constrained to very small deformations	Applicable (Large run-outs only with particle-based methods)

3. Conduct numerical analyses using particle based methods to study post failure stages of a slope subjected to seismic loads. (Not yet started)