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Research Paper

A statistical study of precursor activity in earthquake-induced landslides

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ABSTRACT

In this paper, a statistical study of precursor activity in earthquake-induced landslides by means of spring block models is presented. The dynamic behavior of the rock/soil slope can be studied by using the statistics of the different distribution of slip events at the interface between the soil and the bedrock. It is shown that by introducing earthquake-induced cracks of certain length within the interface, a robust 2D spring-block model can be formulated for studying triggered landslides. A cellular automaton is built in order to examine the dynamic behavior and the stability of rock/soil slopes during and after a neighboring earthquake. The type and nature of the failure plane, as well as the triggering intensity, is studied. The different dynamic evolution modes of the slope can be mapped to different statistical evolution characteristics of specific shape parameters of the corresponding incremental displacements' distributions. Within the proposed context, spring-block models can be used in order to understand, predict and minimize the impact of catastrophic landslides triggered by earthquakes.

1. Introduction

Earthquake induced landslides are of great importance for the economy and society and considered still as an open geotechnical problem. Existing published analyses provide information about the number of landslides per square kilometer, the distance from the epicenter, and the slope steepness, which in turn are connected to the shear strength and the type of geomaterial (Keefer [10]). These studies have confirmed the dependence of the number and distribution of an earthquake-induced landslide on the earthquake magnitude. The areas where these landslides occur present an irregular and asymmetric shape with respect to epicenters and fault ruptures, and also show a strong correlation with the magnitude of the earthquake (Keefer, [10,11]). The number of landslides caused by an earthquake generally increases with earthquake's magnitude. In this manner, Keefer [10] presented a magnitude scale to quantify the number of landslides triggered by an earthquake. Consequently, Malamud et al. [12] have proposed an independent landslide-event magnitude scale on the earthquakes based on the logarithm of the maximum number of landslides associated with the event. These studies relate the landslide magnitude scale with visible results of the triggering mechanisms. For earthquake-induced landslides, the main effect is the reduction of slope stability which is caused by the shaking intensity (Keefer, [10,11]; Piegari [17]). The main failure mechanism during a landslide is that shearing occurs along either a discrete sliding surface or within a zone below the ground surface. If the shear force (i.e. driving force) is greater than the shear strength of the interface (i.e. resisting force), then, the slope becomes unstable. Instability will take the form of a displacement, which leads to the failure of the slope either suddenly or gradually [18]. Over this basic framework, Zaiser and Aifantis [20,21] and Zaiser and co-workers [22,23], considered the evolution of deformation/slip avalanches when both material softening and stochasticity, are stabilized by higher-order gradients of the constitutive variables. The introduction of higher-order gradients is necessary for the convergence of the numerical solutions of either continuous or discrete models, as was first indicated in the pioneering work of Aifantis [1,2], and in a more recent account in Aifantis [3]. In addition, the well-known fractal structure of the landslide phenomena and their corresponding frequencies can be analyzed as functions of the critical affected area through power laws. The investigation of the relation between self-organized criticality (SOC) and natural hazards (earthquakes, landslides, forest fires, etc.) remains an active field of scientific research in the last thirty years. In this context the concept of SOC applies in avalanche dynamics modeling the

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tendency of certain natural systems to approach a critical state described by power law through the exponent b, the value of which remains constant for a wide range of system parameters.

To investigate the inherent mechanisms that lead to the appearance of various catastrophic phenomena, several statistical models have been proposed using SOC features. One of them is the Olami-Feder-Christensen (OFC) model (1992), which has been presented as a simplification of the classical Burridge-Knopoff (BK) spring model Burridge and Knopoff [7]. The OFC model corresponds to the classic non-conservative model revealing SOC. Spring-block models, were introduced several years ago to describe the seismic dynamics in the context of SOC. In the case of landslides, Piegari et al. [15,16] presented a cellular automaton (CA) model based on the dynamic evolution of a space- and time-dependent factor of safety (FS). They assumed a continuously driven anisotropic CA based on the OFC model, by describing landslide size distributions. They concluded that different distributions for the landslide sizes were attained by different driving rates. Furthermore, Piegari et al. [17] proposed a relation between the landslide magnitude scale and the strength of the trigger, by introducing the intensity scale in terms of the rapidity of the system to reach instability. In this analysis there is an estimation of the time needed to build up the critical stress in the slope. In situ observations show that the random distribution of the factor of safety values, which capture the heterogeneity of the rock/soil, fluctuate around a mean value due to the interaction with climate and/or external perturbations. Piegari et al. [17], claim that only in the case of the trigger action is there a monotonic change (a decrease) of FS, and the entire system moves towards the instability in the estimated time. It was demonstrated that the frequency-size distribution exhibits inverse power-law behavior with exponents similar to those of the probability density function from real data. Moreover Juanico et al. [9] have demonstrated experimentally the theoretical results by Piegari et al. [15], where they observed the existence of a crossover from power law to non-power law statistics of the driving rate. Next, Zhang et al. [24] introduced a modified version of the OFC model, to study avalanche size differences, by using a concept of weighted edge in order to improve the original redistribution rule and to obtain an inhomogeneous network with different local frictions and elastic behavior. Recently, Avlonitis and Papadopoulos [4] and Avlonitis et al. [5] proposed, within the aforementioned gradient approach for softening materials, a generalized OFC model which incorporates softening behavior within the interface of two moving plates. It was shown that as the interface enters into the softening regime, a significant change of the exponent b occurs, as by the governing gradient-dependent evolution equation. In the same study, cellular automata simulations have been used in order to verify the analytical findings for the evolution of b in macroscopic records. It is noted that for the two aforementioned dynamical systems, i.e. the evolution of earthquake triggered landslides in the present system and the evolution of earthquake sources in Avlonitis and Papadopoulos [4], it is assumed that similar precursor activity may be emerging, manifesting itself as a sudden change in the power-law exponent b. It is even more interesting, the corresponding precursor mechanisms are completely different in nature: for the evolution of earthquake source, the precursor activity is attributed to the spatial evolution of shear strength the interface of the tectonic plates, while in the present study it is attributed to the sudden formation of a crack of a certain length at the slope's interface with the bedrock, due to a nearby earthquake.

Herein, the following sequence is studied: nearby earthquake, crack of a certain length forming at the slope's interface with the bedrock, sudden change of b value, slope destabilization. More specifically, it is shown that a sudden change in the power-law exponent b of an unstable slope after a neighboring earthquake may be used as an indication for possible earthquake-induced landslides. At the instance of an earthquake there is an extra external force which is the main cause for producing one or more cracks with different length sizes. It is observed that the bigger the magnitude of the trigger mechanism (i.e. earthquake), the larger the length of the formed critical crack. At the interface the crack with the maximum length is considered to be the main characteristic for the trigger mechanism. The aforementioned crack length is used in the simulation code and what has been obtained is the dependence on b-values of the distribution of slip events at the interface. Long cracks correspond to small b-values. From the estimated b-values a relation between the aforementioned critical crack length and the average slope can be formulated.

2. Numerical model: 2D spring block model

The methodology followed is in line with the similar landslide study by Avlonitis et al. [5], i.e., two constitutive variables, stress and strain, are used instead of the one dynamic variable e.g. force or displacement as it was introduced in Olami et al. [14] and the corresponding dynamics was studied by means of the evolution of the exponent b of the power-law distribution of sizes of slip events within the interface. A system of two distinct plates moving relatively to each other is assumed, with their interface being represented with a number of blocks (nodes) interconnected with springs of a certain spring constant (Fig. 1). A dynamic variable f_{ij} is assigned to each node of a two-dimensional grid (i,j denoting the number of rows and columns of the grid, respectively) representing the interface of the plates. Assuming isotropy at the horizontal plane, $f_{ij} = K\ell^2\nabla^2 u_{ij} + K_L\delta u_{ij}$, where u_{ij} is the node's displacement at x_{ij}; K, K_L are the spring (elastic) constants, and $\delta u_{ij} = \upsilon t - u_{ij}$, where υ is the constant velocity of the upper moving plate and υt is the imposed driving displacement. The second-order gradient term in the right hand-side models (as usual in the continuum limit) the expression $2u_{ij} - u_{i-1j} - u_{i+1j} + 2u_{ij} - u_{ij-1} - u_{ij+1}$, and ℓ (is assumed unity) is a characteristic scale associated with space discretization. The dynamic variable f_{ij} is the total force (or stress dividing by unit area). When the force on an arbitrary node is larger than a threshold value F_{th}, which is the maximal static friction, the node slips. This implies that for the node n_{ij} of the sliding plane to become unstable the following inequality must be fulfilled,

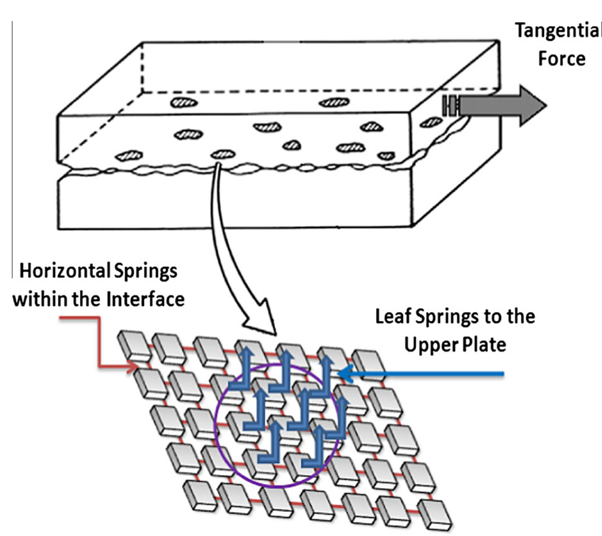

Fig. 1. Graphical illustration of the generalized OFC model. Two distinct plates are moving relatively to each other where the interface between them is represented with a number of blocks interconnected with springs of a certain spring constant.