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Limit sliding-block seismic displacement for landslide triggering along slip surfaces consisting of saturated sand

Constantine A. Stamatopoulos [a,b,*]

[a] Stamatopoulos and Associates Co., 5 Isavron str, Athens 11471, Greece
[b] Hellenic Open University, Greece

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ABSTRACT

Slopes consisting of saturated sand have recently moved rapidly down-slope tens or hundreds of meters as a result of the action of earthquakes. In the seismic risk assessment of such slopes, typically the conventional sliding-block model is utilized. However, this model assumes constant strength along the slip surface and predicts co-seismic displacement, which typically is less than tens of centimeters. The landslide risk described above is associated with post-seismic very large displacement. It occurs when static failure occurs, as a result of loss of soil strength, under the applied earthquake loading. The paper first derives simple analytical expressions predicting when enormous displacement may occur along a planar homogeneous slip surface of saturated sand during earthquakes. For this purpose, the sliding-block model and a recently proposed simple constitutive model simulating saturated sand response along a slip surface are utilized. The paper then validates the proposed analytical expressions by extensive parametric numerical analyzes using the sliding-block model with the proposed constitutive model, and based on these analytical expressions, proposes an easy-to-apply method predicting earthquake-induced landslide triggering of any potentially two-dimensional unstable mass along slip surfaces consisting of saturated sand. Finally, the proposed equations and method are applied (a) to predict the observed triggering of four well-documented earthquake-induced landslides and (b) to establish relations giving characteristics of the seismic motion causing triggering of landslides.

1. Introduction

Slopes consisting of saturated sand have recently moved rapidly down-slope tens or hundreds of meters as a result of the action of earthquakes [1–3]. As these slides have caused much destruction and fatalities, there is a need to propose easy-to-apply but accurate methods predicting when such landslides are triggered.

Permanent seismic movement of slopes can be separated into at least two stages [4]. In the first stage, which is co-seismic, gravity in combination with transient seismic forces may bring about temporary instability and permanent displacement on a failure surface. The second stage, which is post-seismic, follows immediately after the earthquake and causes large movement when, as a result of the first stage, the strength on the slip surface is reduced to a value which is less than that required to maintain static equilibrium. The earthquake-induced landslides described above are associated with large post-seismic displacement. Indeed, ring shear devices where sandy samples can be sheared under undrained conditions, have recently been developed and applied to study the response of saturated sands along slip surfaces ([1–3,5–11]). These tests illustrate the considerable strain softening that occurs in saturated sands along slip surfaces and can explain the recently observed post-seismic large displacement of slopes consisting of saturated sand.

The sliding-block model [12] is frequently used to simulate movement of slides triggered by earthquakes [13]. In recent years, landslide seismic hazard zonation is conducted mainly by predicting the seismic displacement using the conventional sliding-block model, where the resistance along the slip surface is assumed constant [14–19]. As shown in Fig. 1, a block with constant resistance rests on an inclined plane. Critical acceleration is defined as the minimum horizontal acceleration that causes movement of the block. Every time the applied horizontal acceleration is larger than the critical acceleration, the block slides. The total displacement of the block is obtained by the addition of the partial slips. Different empirical expressions have been proposed by different researchers, predicting the seismic displacement of the block in terms of its critical acceleration and characteristics of the applied motion. These solutions, which give the distance moved by the conventional sliding-block model, are used for the

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* Corresponding author at: Stamatopoulos and Associates Co., 5 Isavron str, Athens 11471, Greece. Fax: +30 2103616919.
E-mail address: k.stam@saa-geotech.gr

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Notation

a_1, a_2, R_m , r, u_1, u_2	Parameters of the constitutive model (Eq. (1a) and (1b))
$a(t)$	Acceleration time history applied at the sliding block model
a_c	Critical acceleration for relative motion
$a_{c\text{-}m}$	Critical horizontal acceleration for only frictional resistance along the slip surface equal to atan (R_m)
$a_{c\text{-}r}$	Critical acceleration for only frictional resistance equal to atan (r*R_m)
a_{max}	The maximum value of the applied acceleration $a(t)$
A_i	Cross-sectional area above soil type “j” along the slip surface
Ave	Average value
d	Increment
D_r	Relative density
D_{50}	The median particle diameter
E_M, E_r	Areas defined in Fig. 3
F	Factor given by Eq. (12a) and (12b)
F_{st}	Factor F when $u^*_f = u_{st}$
FS	Factor of safety of the potentially sliding mass
FSo	Factor of safety prior to the application of the seismic motion for only frictional resistance along the slip surface equal to atan (R_m)
FSe	Factor of safety against earthquake-induced triggering given by Eq. (15).
$f(a_{max})$	Function giving the M value causing the triggering of a landslide in terms of a_{max}
g	The acceleration of gravity
M	Earthquake magnitude
	Max, Min
	Maximum, minimum value
Meas	Measured value
mp	Model parameter of the constitutive model (Eq. (1a) and (1b))
N	Number of (τ, u) points defining the shear stress–displacement response of a shear test
Pred	Predicted value
R	τ/σ'_o
R_{res}	The final (residual) R value ($=r^*R_m$)
R_e	The shear resistance normalized by σ'_o of the equivalent conventional sliding-block model giving the same displacement as the improved sliding-block model with the constitutive Eq. (1a) and (1b)
Rst	Stress ratio corresponding to static failure
R^2	Coefficient of correlation
Stev	Standard deviation
	SL1, SL2, SL3, SL4 Landslides described in section 8.1
t	Time
u	The displacement along the slip surface
u'	The displacement given by Eq. (1b)
u_f	The final value of u
u_o	The initial value of u given by Eq. (7).
u^*_f	Displacement u_f between u_1 and u_2
uM_f	Final seismic displacement predicted by the conventional sliding-block model
$uM(R_m{}^*F_{st})$	Seismic displacement predicted by the conventional sliding-block model when the soil resistance equals ($\mathrm{R_m}^*\mathrm{F_{st}}$)
$uM_f(R_m{}^*F_{st})$	Final value of $uM(R_m{}^*F_{st})$
β	The inclination of the sliding-block model (Fig. 1)
β_{eq}	The inclination of the conventional sliding-block model predicting the same seismic displacement as a general sliding mass
σ'	Effective stress normal to the slip surface
σ'_o	Effective stress normal to the slip surface prior to the initiation of shearing
τ	Shear stress
τ_o	Shear stress prior to the initiation of shearing
φ_{sb}	The frictional component of resistance along the slip surface of the sliding-block model

prediction of permanent seismic movement along any slip surface with constant shear strength by applying a block with similar critical and applied acceleration with those of the potential sliding mass under consideration [12,20–22]. For landslide seismic hazard zonation, the critical acceleration is often obtained from the average slope inclination of each unit of the region [14].

The conventional sliding-block model with constant shear resistance actually predicts co-seismic displacement that is typically not excessive, less than tens of centimeters. However, as described above, the movement of rapid landslides is associated with large post-seismic displacement, which occurs when static failure occurs as a result of a permanent decrease in soil strength. The magnitude of post-seismic displacement depends on the rotation of the sliding mass during motion and has been modeled recently by two-block and multi-block models assuming that soil strength along the slip surface is at the residual [4,23,24]. Furthermore, in order to predict when triggering of post-seismic movement will actually occur, constitutive equations modeling soil response along slip surfaces must be coupled with the sliding-block model.

Constitutive equations modeling soil response along slip surfaces have recently been developed [13,25,26]. These equations relate the shear stress with the shear displacement along the slip surface. For dry soils, this is in agreement with the proposition made by Aubry et al. [27] that the constitutive model of displacement and stress of an interface should be of the same form and derived from the constitutive model of strain and stress of continuum soils. For saturated soils, this is consistent with the fact that, along slip surfaces their response is different from their response inside a continuum, due to grain crushing in saturated sand and collapse of the soil structure of saturated clay, at large shear displacement [13,25,26].

In the general case, constitutive models must be formulated in terms of effective stress in order to predict, not only the shear stress, but also the generation of excess pore pressure along the slip surface. Such models have recently been proposed [13,25]. Yet, in sliding-block models only the shear resistance versus shear displacement soil response along the slip surface affects the solution. This response depends on the drainage conditions and may alter as a result of dissipation of excess pore pressure in saturated sand. Yet, under earthquake-induced slides, triggering and slide movement are so rapid that dissipation of excess pore pressure does not occur and saturated sands behave in an undrained manner [1–3,13,24]. A simple constitutive model predicting only the shear resistance versus shear displacement response of saturated sand was developed recently by Stamatopoulos and Di [24]. The model predicted with good accuracy the shear stress–displacement response measured in ring shear tests. Advantages of the proposed model are because of its simplicity, its