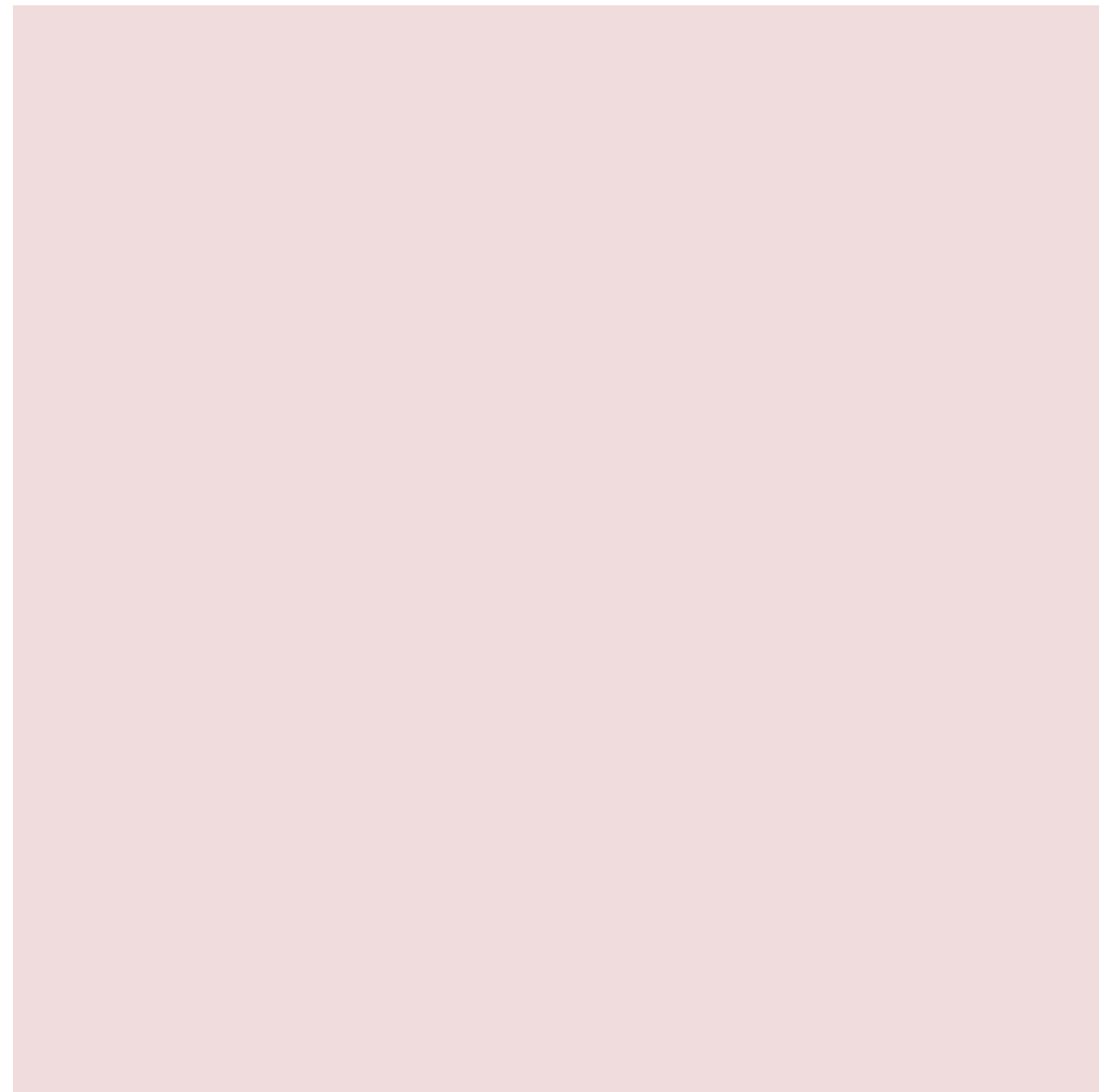


Why do earthquakes trigger catastrophic landslides?

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Can all earthquakes trigger ground movements? Each year, earthquakes are responsible for loss of life and damage to buildings and infrastructure. Long considered as a secondary effect of earthquakes, landslides triggered by earthquakes, mainly rock falls, disrupted soil slides and rock slides, mudflows and rock avalanches, can be responsible for a significant part of the damage

associated with earthquakes [1]. During the twentieth century, nearly 80 earthquakes caused 100,000 to 1,000,000 ground movements that claimed the lives of several tens of thousands of people [2].

1. Can all earthquakes trigger ground movements?

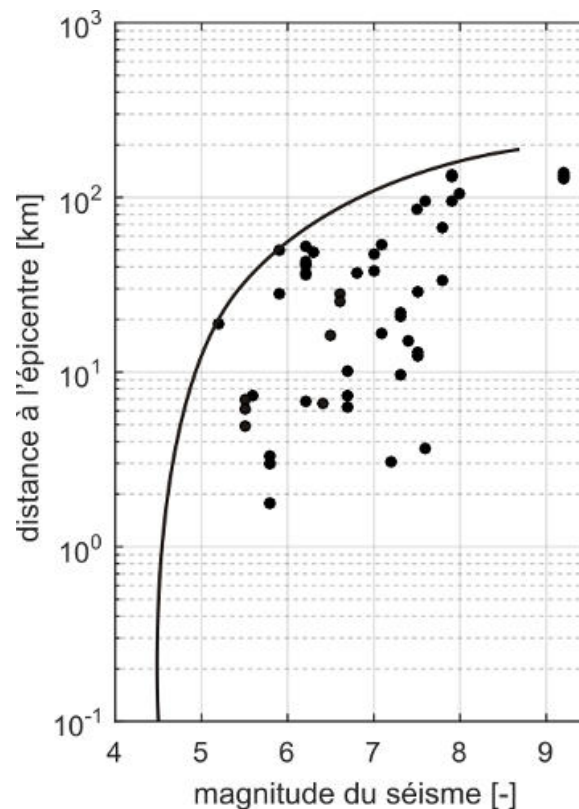


Figure 1. Correlation between the magnitude of an earthquake (horizontal axis) and the distance between the epicentre of the earthquake (projection on the surface of the earth of the focus of the earthquake) and the most distant ground movement triggered by the earthquake (vertical axis). The higher the magnitude of the earthquake, the more likely it is to trigger ground movements at a long distance from the epicentre. The black curve is the "envelope curve" that includes all ground movements triggered by earthquakes [4].

To answer this question, Keefer identified and analyzed all the ground movements triggered by earthquakes around the world between 1811 and 1980. He was thus able to define correlations between the characteristics of earthquakes that generate ground movements and those of induced ground movements:

1st observation: **Most instabilities are triggered by earthquakes of moderate to high magnitude [3], typically greater than 5** (Figure 1). However, this notion of "minimum magnitude" or magnitude threshold should be considered with caution because it does not take into account the state of stability of the slope before the earthquake. This state, often poorly known, is the result of the entire history of "loading" (earthquakes, heavy rainfall).

2nd observation: **most of these ground movements do not occur beyond a certain distance from the source of the earthquake, which depends on the magnitude of the earthquake in question.** The higher the magnitude of an earthquake, the more likely it is to trigger ground movements at a long distance from the epicentre (Figure 1) [5].

2. What are the characteristics of these ground movements?

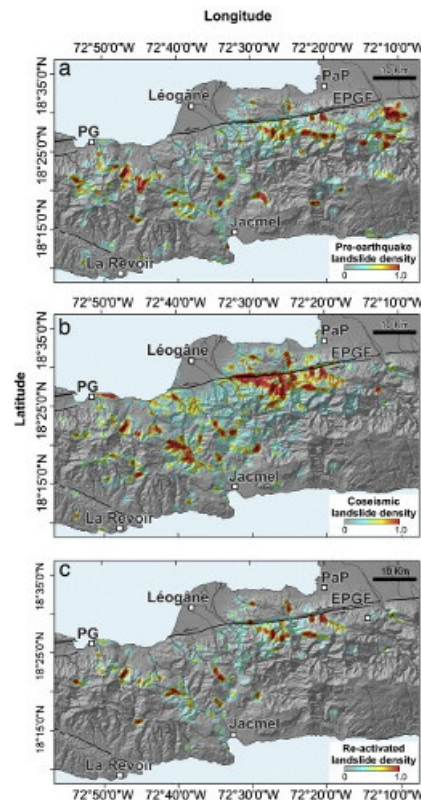


Figure 2. Distribution of the density of ground movements in Haiti. a: density of ground movements recorded before the earthquake of January 12, 2010. b: density of ground movements triggered by the earthquake of 2010. c: density of ground movements reactivated by the earthquake of 2010. These figures show that the 2010 earthquake reactivated many old ground movements. [Schematic reproduced from Gorum et al., 2013] [8]

Earthquakes generally trigger superficial ground movements. However, the volume of instability can sometimes reach several million m³, as was the case during the earthquake of 31 May 1970 in Peru: the rock avalanche of Nevado Huascarán [6], with an estimated volume of 50 million cubic metres of rock, ice and snow, covered an exceptional distance of more than 16.5 km, at an estimated speed of 210-280 km/h. This rocky avalanche killed 20,000 people in the villages of Ranrahirca and Yungay in the valley [7].

The "intensity" of earthquake-initiated ground movements can be characterized by:

- The volume of materials moved by the movement;
- the mobility of these materials during movement;
- the area covered by the materials after the movement has stopped.

Keefer's (1984) work has shown that this "intensity" depends on the magnitude of the earthquake under consideration: the **higher the magnitude of the earthquake, the greater the "intensity" of the ground movements it may trigger.**

Some earthquakes can even **reactivate old ground movements**, as was the case during the earthquake of January 12, 2010 in Haiti: this earthquake triggered about 4500 ground movements up to a distance of 46 km from the epicenter. Of the 1273 landslides recorded as active before the 2010 earthquake, 572 were reactivated by the 2010 earthquake (Figure 2) [8].

3. What is the impact of these movements on people and territories?



Figure 3. Las Colinas ground movement triggered by the earthquake of 13/01/2001 in El Salvador. This ground movement claimed the lives of more than 500 people. [© U.S. Geological Survey, Department of the Interior/USGS, Public Domain]

Earthquake-induced ground movements have long been considered a secondary effect of earthquakes as opposed to ground vibrations. However, many examples from around the world have shown that their **destructive potential** can be very high. During the earthquake of 13 January 2001 in El Salvador, for example, the Las Colinas landslide (Figure 3) claimed the lives of more than 500 people, nearly two thirds of the victims associated with the earthquake. Petley et al (2006) [\[9\]](#) estimated that during the earthquake of 08 October 2005 in Pakistan, 30% of the total number of victims, or 26,500 people, were killed by ground movements. The 12 May 2008 earthquake in China triggered more than 15,000 ground movements, which alone claimed the lives of nearly 20,000 people, or nearly a third of the victims associated with the earthquake [\[10\]](#). Earthquake-initiated ground movements can have two types of effects:

direct effects: deaths resulting from the burial of buildings or the crushing of vehicles by debris from ground movements, damage / destruction of buildings, communication networks, etc.

indirect effects: the degradation or obstruction of roads by debris from ground movements can hinder the delivery of aid to victims or their evacuation to health centres.

Sometimes debris from ground movements blocks the bed of rivers and **forms natural dams**. This leads to the formation of dam lakes upstream of ground movements. This type of phenomenon occurred in large numbers (several hundred) during the earthquake of May 12, 2008 in China. [This animation \[11\]](#) shows a slope before and after the onset of a ground movement by the 2008 earthquake.



Figure 4. Natural dam and dam lake formed by obstructing the bed of the Ote Makura River from debris from a ground movement triggered by the 14/11/2016 earthquake in New Zealand. [© GNS Science (CC BY 3.0 NZ)]

Similar phenomena also occurred during the 14 November 2016 earthquake in New Zealand as shown in Figure 4. According to the New Zealand Centre for Geological Hazards Studies [\[12\]](#), the earthquake of 14 November 2016 and its aftershocks triggered between 80,000 and 100,000 ground movements and led to the formation of about 150 natural dams. As the lifespan of these dams varies greatly (from a few minutes to several hundred years), the bodies in charge of preventing natural disasters must answer two major questions:

How can we ensure that these natural dams are properly maintained over time and thus avoid a disruption that could lead to catastrophic flooding of urban areas located near the sites

How will the lakes formed upstream of the dams evolve, especially if heavy rainfall increases the water level in the reservoirs?

Few scientific studies to date have anticipated what could happen in such circumstances.

4. How do we explain these instabilities?

To decide on the state of stability or not of a slope, one must compare:

the **driving forces that tend to destabilize the slope**. These forces are caused by an earthquake, heavy rainfall.

the **resistant forces that oppose the movement**. These forces are provided by the intrinsic characteristics of the materials, in particular their cohesion and internal friction angle, two parameters that reflect the failure criterion of soils according to Mohr Coulomb's law [\[13\]](#).

During an earthquake, several phenomena can occur and contribute to the onset of instability.

4.1. Site effects

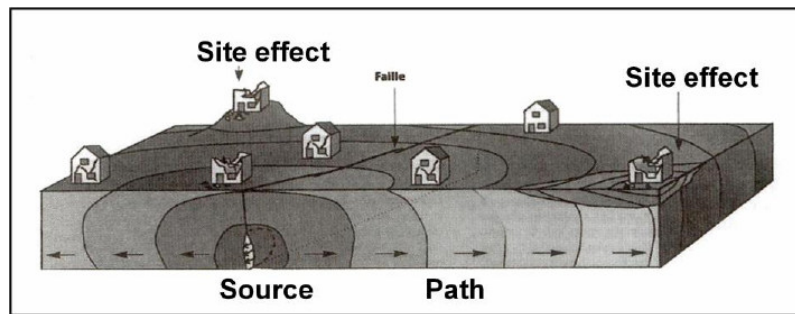


Figure 5. Schematic illustration of the phenomena affecting the propagation of seismic waves from the source to the site. The seismic motion recorded at the surface depends on the type of Source, the wave path from the source (Path) and the local response of the site or "site effect". [© MaxWyss (CC BY-SA 3.0), via Wikimedia Commons]

Figure 5 below shows that at a given point on the Earth's surface, the movements recorded during an earthquake depend on three parameters:

A parameter related to the **source of the earthquake**. This parameter reflects the nature of the earthquake: failure mechanism at the focus of the earthquake, length of the fault, etc.

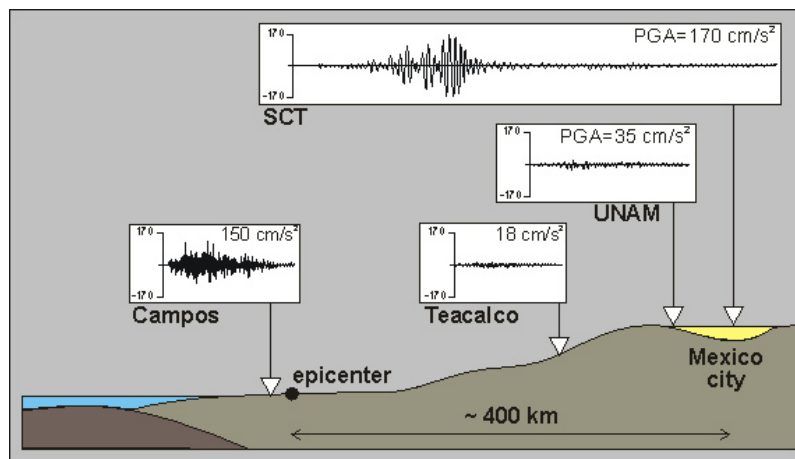


Figure 6. Seismic movements recorded during the 1985 Michoacan earthquake in Mexico. Site effects cause variability in seismic movements recorded at different points on the surface. Thus, during the 1985 Mexico City earthquake, the movements recorded in Mexico City (SCT sensor) had a greater amplitude and duration than those recorded near the source of the earthquake (Campos sensor), despite the large distance travelled by the waves between the source and the sensor. [© Jean-François Semblat (CC BY-SA 3.0), via Wikimedia Commons]

A parameter related to the **propagation of seismic waves between the source of the earthquake at depth and the sensors where surface movements are recorded**: during this journey, the volume waves emitted at the source will undergo multiple transformations that depend on the properties of the environments crossed.

A parameter related to the effect of local geological and topographical conditions (i.e. type of material under and near the sensor, terrain morphology) on seismic wave propagation and recorded surface movements. This parameter is called the **site effect**. Due to site effects, **seismic movements vary from one point to another on the surface of a slope**. When compared to the reference seismic movement measured near the slope of a rocky site (Campos station in Figure 6), it can be seen that movements in sedimentary basins (SCT station in Figure 6) or at the top of the slope generally have **higher amplitudes and a longer duration**. Field observations [14] and numerical modelling results [15] show that site effects most certainly contribute to the initiation of ground movements.

4.2. The decrease in the mechanical characteristics of materials

Repeated earthquakes on a slope lead to a deformation of the materials that make up the slope. This can lead to a decrease in the intrinsic characteristics of materials that tend to oppose movement and thus facilitate the development of an overall break in the slope.

4.3. The increase in pore pressures

When the [compression waves](#) emitted by earthquakes propagate in loosely compacted soils, they tend to compress the soils. When these soils are saturated with water, water occupies all the pores (or interstices) between the soil grains. In response to soil compression, the pressure of water in soil pores increases and water seeks to escape from the soil generally to the surface. However, when the earthquake is rapid, large enough or repeated over time in front of the time needed to drain the soil, water cannot escape from the soil. The higher the water pressure in the soil, the lower the mechanical strength of the soil and the more likely it is that the slope will break.

5. What methods can be used to assess slope stability in earthquakes?

When considering slope stability in earthquakes, two questions in particular should be addressed:

can the slope be ruptured during an earthquake of given characteristics?

if so, what are the characteristics of this failure, in particular how far can the slipped mass propagate and at what speed?

Few scientific studies to date have focused on the characterization of instability in terms of propagation speed and distance, given the complexity of the phenomena involved.

5.1. Slope characterization

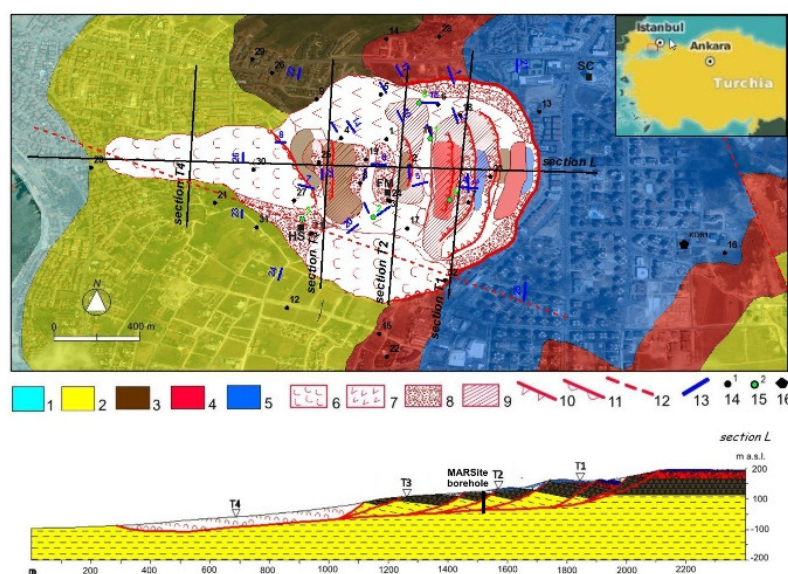


Figure 7. Example of reconstruction of the geological structure of the Büyüçekmece slope (Turkey) with identification of the materials and the different phases of reactivation of the ground movement. The top figure shows an image of the site with the plan outlines of the moving area. Several two-dimensional sections (black lines) have been defined in this image to reconstruct the geological structure of the slope. As an illustration, the bottom figure represents the longitudinal section constructed in the direction of movement to analyze the causes behind the reactivation of this ground movement. On this section, the different materials are represented by colours: brown clay deposits, red sands and gravels, blue limestone arenites and yellow silty clays. The red lines represent the sliding surfaces identified on this site and reflect the different phases of reactivation of the ground movement: throughout its history, instability, which began to develop at the foot of the slope, has spread towards the crest of the slope. [© Salvatore Martino, with permission; see reference 16]

Whatever the cause of the instability, the study of the stability of a slope involves several steps:

an in-depth **geological study** whose objective is to define the geometry, stratigraphy, geological history of the site (Figure 7 [\[16\]](#)).

a **hydrogeological study** to characterize water flows in soils, for example by means of piezometers that measure changes in

groundwater levels in boreholes, since water is very often the driving force behind these movements.

the **characterisation of the mechanical behaviour of the materials** making up the slopes by means of mechanical tests, most often carried out in the laboratory, the objective being in particular to define their shear strength, characterised by cohesion and the internal friction angle.

From the above parameters, calculation software can be used to determine whether a slope is stable or unstable, by comparing the driving forces that tend to destabilize the slope with the resistant forces that oppose movement. This defines the **static safety coefficient of the slope**. When this coefficient is greater than 1 (in the case of a slope in which the resistant forces are greater than the driving forces), the slope is stable. When it is less than 1, the slope is unstable. The closer this coefficient is to 1 (e.g. in the case of a slope that has suffered many earthquakes in the past), the more an earthquake, even of moderate magnitude, can trigger a rupture in the slope.

To analyze the stability of a slope during an earthquake, it is also necessary to characterize the potential earthquake(s): it is on this characterization that the different methods used to evaluate the stability of a slope during an earthquake are based.

5.2. Methods for analyzing slope stability in earthquakes

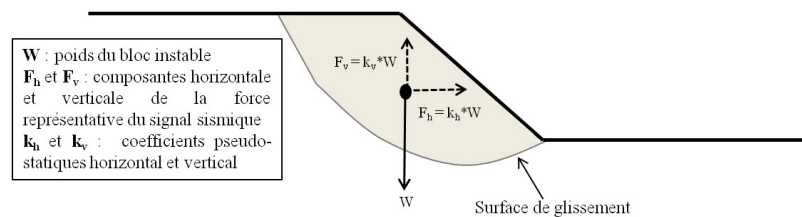


Figure 8. Illustration of Terzaghi's pseudostatic method (1950). [© Céline Bourdeau]

There are three types of methods.

The simplest of these, **Terzaghi's pseudo-static method** [17], consists in calculating the pseudo-static safety coefficient of the slope. In this method, the earthquake is represented by a constant and unique volume force, of modulus proportional to the weight of the unstable block. This force noted F is divided into a horizontal component F_h and a vertical component F_v (Figure 8). In practice, F_v is often neglected because the most damaging forces for slope stability are horizontal or shear forces. This method makes it possible to determine whether the slope is stable (pseudo-static safety coefficient greater than 1) or unstable (pseudo-static safety coefficient less than 1) during the earthquake.

Disadvantage of the method: This method does not provide information on the probability of slope failure or on the "intensity" of movements induced by the earthquake. It is therefore advisable to limit its use to a preliminary analysis of the stability of a slope during an earthquake, in an area where there are few human or material challenges.

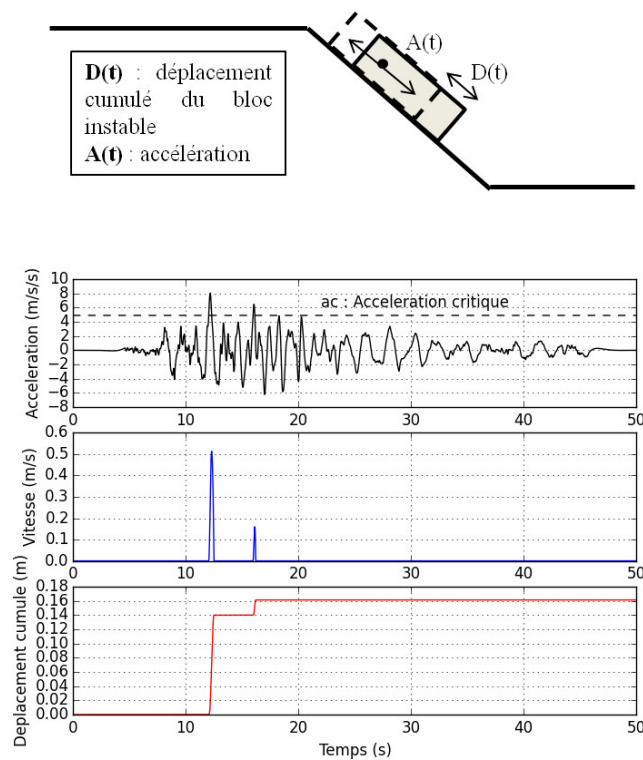


Figure 9. Illustration of Newmark's (1965) method for assessing earthquake-induced displacement in a ground movement represented by a rigid block sliding on a slope (see top figure). The three signals in the lower figure represent respectively: the acceleration $A(t)$ to which the slope is subjected (black solid line curve), the relative speed of the unstable block with respect to the supporting ground (blue curve) and the cumulative displacement of the unstable block with respect to the slope (red curve). The unstable block starts moving as soon as the acceleration $A(t)$ of the supporting ground exceeds the critical acceleration value (black dotted line) defined as the acceleration leading to a pseudo-static safety coefficient equal to 1. [© Céline Bourdeau]

The second type of method is the "**method for calculating permanent displacements**" introduced by Newmark in 1965 [18] (Figure 9). It consists in evaluating the displacements likely to occur in a ground movement represented by a rigid block sliding on a supporting ground under the effect of an earthquake represented by an accelerogram [19]. The displacement of the unstable block is obtained by a mathematical operation: all acceleration peaks that exceed a "critical acceleration" value defined as the acceleration leading to a pseudo-static safety coefficient equal to 1 are integrated twice in time (Figure 9). Once this displacement has been calculated, an expert judgment can be made to determine whether or not the slope material can withstand such a displacement without a total failure of the slope.

Disadvantages of the method:

This method does not take into account the internal deformations of the unstable mass during the earthquake (paragraph 4.2.). Its use is therefore reserved for the study of relatively superficial ground movements in rigid materials unlikely to deform during the earthquake.

This method does not take into account the pore pressures that can develop in soils as a result of earthquakes (section 4.3.).

This method does not take into account site effects (paragraph 4.1.).

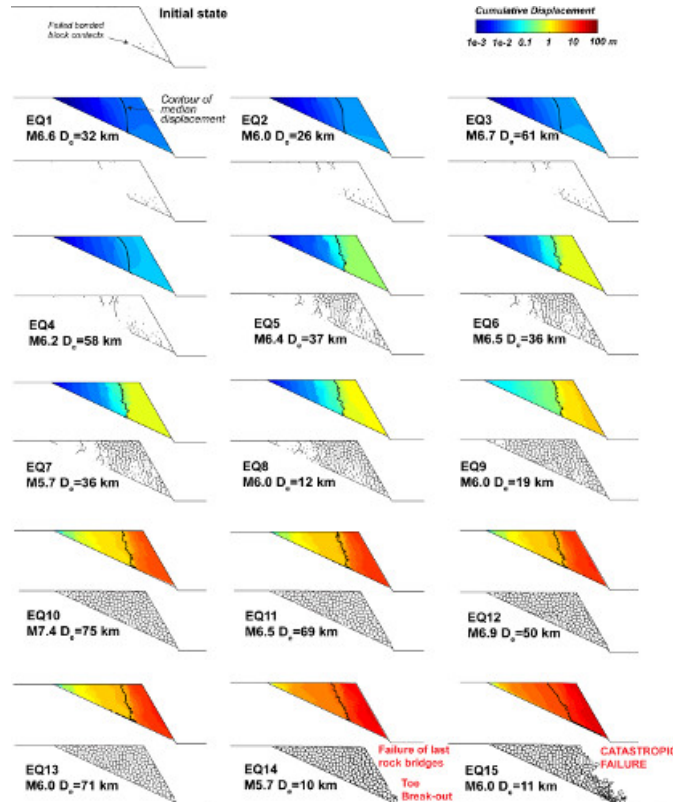


Figure 10. Simulation of the displacements induced by a series of earthquakes (EQ1, EQ2, EQ3, ... EQ15, of given characteristics: M = magnitude and D_0 = distance to the site) in a slope using the UDEC[20],[21] discrete element software (for a definition of discrete elements, refer to <http://www.encyclopedie-environnement.org/physique/comment-matiere-deforme-fluides-solides/>: How matter deforms: fluids and solids). The displacements are represented by a scale of colors that goes from blue (small displacements) to red (displacements reaching 100m). The black lines within the potentially unstable block bounded by a flat sliding surface represent fractures created on the slope by repeated earthquakes. The catastrophic failure of the slope occurs after the application of the last earthquake EQ15. [Source : Schematic reproduced from Gishig et al, 2016, see footnote 4, with permission]

The third type of method includes **stress-strain methods** whose use is strongly recommended for studies of specific sites where human and/or material stakes are high and where data quality is sufficient. These methods consist in evaluating the displacements induced by a given earthquake in a slope using two- or three-dimensional calculation software that integrates all the complexity of the sites (presence of different materials, morphology of the terrain, etc.) and earthquakes. Figure 10 below shows an example of a numerical simulation of the progressive failure of a slope due to repeated loading by several earthquakes over time.

6. What are the current challenges in research on earthquake-induced ground movements?

The study of earthquake-initiated ground movements is now the subject of much research aimed at improving relative knowledge:

to **the effects of water**. According to current knowledge, the role of water in triggering ground movements during earthquakes is relatively unknown.

to **three-dimensional effects** (or 3D effects). Due to the complexity of the phenomena, the stability of the slopes is often analysed in an approximate way by means of two-dimensional (2D) sections often oriented in the direction of propagation of instability. This approximation, justified in the case of anthropic slopes, is often unrealistic for natural slopes. Representing the slope in all its dimensions (3D) in a numerical calculation code makes it possible to take into account the direction of propagation of seismic waves and to study its impact on the stability of the slope.

to **the prediction of earthquake-initiated ground movements**. To organize disaster prevention, it is necessary to be able to predict where and when the next earthquake-induced ground movements will occur. This requires knowing at some point the state of stability of the slopes, a state that is often poorly known and has resulted from the entire history of "loading" on the slopes in the past. It also requires the ability to predict what type of earthquake is likely to affect a given site and when it may occur. Finally, this requires being able to quantify the "intensity" of the expected phenomena, i.e. to characterize both the volume of instabilities or the surface that could be covered by the deposits of this instability, the propagation speed of the

unstable mass and its propagation distance. These are difficult parameters to assess because earthquake-initiated ground movements are complex and variable from one earthquake to another.

Field observations have also shown that **earthquakes can also have long-term effects on slope stability**: in the years following the 21 September 1999 earthquake in Taiwan, for example, there was an increase in the number of ground movements triggered by monsoon episodes [22]. The latter is explained by the fact that the earthquake weakened the slopes, making them more susceptible to instability during the subsequent episodes of heavy rainfall.

7. Messages to remember

Earthquakes with a magnitude greater than 5 are likely to trigger ground movements that can be responsible for a significant proportion of the victims and the damage associated with earthquakes.

There is a wide variety of ground movements triggered by earthquakes and these phenomena are generally very complex.

Reducing the risk posed by this type of hazard requires a better understanding of the mechanisms that trigger ground movements on the one hand and the mechanisms that control the speed and distance of material propagation on the other.

References and notes

Cover image. A ground movement that occurred in the city of Minamiaso, Japan, following the April 2016 earthquakes. [Photo © Kyodo/Reuters via Flickr, Public domain.]

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[11] Contains modified Copernicus Sentinel data {{{year}}}} [CC BY 3.0 (<https://creativecommons.org/licenses/by/3.0>) or Attribution], via Wikimedia Commons

[12] GeoNet, Geological hazard information for New Zealand

[13] Mohr Coulomb's law: this mathematical law is used in geotechnics to describe in an approximate way the behaviour of most long-term soils subjected to shear stresses (known as shear failure). This law is characterized by two parameters: cohesion, which defines the shear strength of the soil under zero normal stress, and the internal friction angle, which corresponds to the angle naturally formed by a soil placed in a pile, with respect to the horizontal.

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