



Mechanisms of Earthquake-Induced Landslides: Insights in Field and Laboratory Investigations

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Abstract. In this lecture, the author will share his experience in investigating several earthquake-induced landslides that occurred in Japan, Indonesia, and China, and discuss the mechanisms of slope failures and contributing factors. This work will present data from reconnaissance field surveys conducted at landslide sites and analysis of geological conditions related to slope instability. It will also discuss the results from a series of laboratory tests performed on soil specimens subjected to various loading modes and issues that may occur during investigations. This lecture will be of interest to researchers in the field of soil dynamics as well as engineers and decision-makers who are interested in the causes and mechanisms of earthquake-triggered landslides.

Keywords: Earthquake-triggered landslides · Landslide mechanism · Investigation

1 Introduction

Earthquake-triggered landslides are one of the most dangerous natural disasters that claim many casualties and cause significant damage to infrastructure. Accounts of destruction caused by the 2004 Mid Niigata Prefecture Earthquake, Japan [1], 2009 Sumatra Earthquake, Indonesia [2], and 2008 Wenchuan earthquake, China [3] have been documented in the literature. The understanding of this natural phenomenon shall assist engineers and decision-makers in building more resilient infrastructure for safer communities.

This lecture will present the major factors that cause landslides and discuss different methods of landslide investigations. A few earthquake-triggered landslides whose mechanisms the author has investigated through field and laboratory work are used as examples. The author will also share his knowledge and experience, and discuss some issues that can arise during similar studies. Finally, using the data from field and lab investigations, common mechanisms of earthquake-triggered landslides will be discussed in relation to site geology, geomorphology and soil properties. For more detailed studies, the interested reader is referred to the wealth of the literature on landslides that is easily accessible via national or university libraries. It is noted that some observations and insights presented by the author in this paper may not be applicable to all landslide sites, as the mechanism of this natural phenomenon is rather complex. Yet, it is believed that

this lecture will be of interest to students, researchers in the field of soil dynamics as well as to engineers and decision-makers who are interested in the causes and behavior of earthquake-triggered landslides.

2 Reconnaissance Surveys and Laboratory Work

The complex mechanism of earthquake-induced landslides involves several factors, which can be identified and studied using different methods of site investigation as well as a series of laboratory tests. This section will discuss the major aspects of such investigations.

2.1 Reconnaissance Surveys

Reconnaissance surveys are essential in collecting vital information on landslide characteristics and soil mass conditions which can shed light on the mechanism of landslides. The field work may include a series of boreholes (which is desirable but not always feasible) and field tests such as SPT and CPT. However, due to time and budget constraints and technical issues such as access to the landslide site, reconnaissance surveys are rather limited to detailed examinations of landslide area and collection of soil/rock samples for laboratory testing. In addition, portable field tests such as dynamic cone penetrometer [2] or portable cone penetrometer tests [4] are often performed to obtain estimations of landslide mass strength. Unfortunately, most field tests are commonly performed on disturbed soil masses after the landslide event (or a site next to the landslide), and for this reason, they don't provide an accurate estimation of soil mass conditions prior to earthquake. Thus, engineering judgement must be exercised when using the obtained results.



Fig. 1. Landslide sites and debris material that buried a settlement during the 2009 Sumatra Earthquake, Indonesia.

A challenging task during a reconnaissance survey is to obtain reliable data on groundwater conditions before the earthquake. In such cases, the groundwater characteristics and degree of soil mass saturation can be roughly estimated based on the historical precipitation data from the nearest Bureau of Meteorology station. Witness accounts can also provide important information which will help to better understand

the landslide mechanism. For example, witness accounts of significant amount of water coming out of the landslide site at a rural area in Sumatra (Fig. 1) helped the investigation team [2] to justify the assumption that the landslide mass was saturated (or close to saturation) prior to the 2008 Sumatra earthquake.

It is noted that water not only weakens the soil strength, but it also deteriorates rock properties, a process of chemical weathering that can also lead to slope instability. For example, highly acidic groundwater was believed to be responsible for the formation of heavily weathered volcanic rock at the Aratozawa landslide site, making the dominant rock (pumice) extremely loose and weakened [4]. For this reason, it is recommended to obtain data on surface and ground water pH when possible.

2.2 Soil Examination and Laboratory Testing

Forensic investigations in the mechanism of earthquake-related landslides also include a careful examination of soil (or rock) material from the landslide mass and soil testing in the laboratory by means of conventional triaxial, shear box, and/or ring-shear apparatuses. The experimental programs shall include a series of tests with both cyclic and monotonic stress applications to soil samples so that the soil strength before, during and after an earthquake event can be obtained. There are several issues discussed in the following sections which need to be considered and addressed to obtain reliable laboratory data.

3 Factors Related to Earthquake-Triggered Landslides

The major factors contributing to the occurrence of landslides can be divided into two categories: ‘triggering’ factors such as earthquake magnitude and its epicenter; and ‘causing’ factors which are related to geomorphological and geological settings of the area, and soil/rock properties of the landslide mass.

3.1 Earthquake Characteristics

Earthquake magnitude and the epicenter location have a strong effect on the occurrence of landslides. It is logical to assume that the closer the studied area to the epicenter, the greater the damage caused by the earthquake can be expected. Keefer (1984) [5] conducted a first systematic investigation on relations between landslide distribution and seismic parameters such as magnitudes and distance from epicenter and reported that the landslide concentration tends to increase towards the epicenter. Although this relationship seems to work for most past earthquakes, recent studies also suggest that there are other factors that can affect the landslide distribution. For example, Gorum et al. (2011) [3] did not obtain any obvious relation between the distance from the epicenter and concentration of landslides triggered by the 2008 Sichuan earthquake, China. The investigators reported that the landslide distribution was primarily controlled by the geological fault rupture when most of events occurred within a 10 km range from the fault. This would lead to the next important factor, site geology, which is described in the following section.

3.2 Geological and Geomorphological Factors

It is already well-known that sound knowledge and understanding of the local geology can assist with landslide hazard assessment. Site geology and geological structures will be a key factor in determining the type of landslides. For example, a geological structure known as caldera was associated with earthquake-induced landslides triggered by the 2008 Iwate-Miyagi Nairiku earthquake, Japan [4] and 2009 Sumatra Earthquake, Indonesia [2]. The caldera-like structures are commonly made of combination of relatively weak and weathered sedimentary debris deposits overlain by volcanic rocks. Such geological setup tends to 1) amplify the ground motion of the rock during earthquake, and 2) provide a longer period of vibrations, which are two factors that can contribute to the relatively larger number of earthquake-triggered landslides within this caldera structure [6].

It is common that geological and geomorphological conditions are related. For example, steeper terrains/slopes are typically made of relatively harder geological material such as rock (note that rock can be of different levels of weathering) (Fig. 2), while relatively gentle slopes (about 30–35°) can be mostly made of coarse-grained material [7].



Fig. 2. Omigawa landslide triggered by the 2007 Chuetsu Oki earthquake, Japan. The landslide mass was formed in weathered sandstone on a steep slope of 55–60°.

The gradient of valleys adjoining to steep slopes as well as the presence of water can be crucial to the formation of debris flow. Jiufengchun landslide (Fig. 3), which was triggered by the 2008 Sichuan earthquake, buried more than 60 local people in Jiufengchun village. According to eyewitness accounts and the site survey conducted by [8], it was initiated as rockslide in weathered, relatively dry granite; however, as the landslide mass plunged in a valley that contained water springs, it immediately turned in a rapid debris flow that buried a village within 1 min [8]. The width of the landslide at the toe part was estimated as 300 m with about 1,500 m distance from the landslide source area to the toe.



Fig. 3. Jiufengchun landslide triggered by the 2008 Sichuan earthquake, China. It started as rock fall in weathered granite (see exposed slopes in the background) and turned in catastrophic debris flow.

The thickness of the landslide mass can vary depending on geology and material properties. Experience shows that most of earthquake-triggered landslides are relatively shallow, with the average thickness of 2–3 m. Thicker landslide masses are typically attributed to coarse-grained deposits, which can be a product of sandstone/siltstone weathering as observed during the 2004 Niigata earthquake [1, 9, 10]. It is noted that such large landslides may be part of ancient landslide mass that was re-activated by a strong earthquake shaking [1].

3.3 Soil and Rock Properties

The data on soil mass properties shall include information on soil type, the level of saturation, and in-situ soil characteristics such as void ratio and strength. Numerous studies have indicated that the resistance of soil to earthquake depends on soil capacity to generate excess pore water pressures during cyclic loading. Experience indicates that a soil structure that forms significant amount of pore space and the presence of water in these pores may contribute to this. As water plays a key role in the occurrence of landslides, the generation of excess pore water pressures during earthquake can significantly decrease the shear strength of soil to a value that is no longer sufficient to withstand the shear stresses acting on soil mass. For coarse-grained soil mass (where sand fraction is dominant), the term ‘liquefaction’ is commonly used as a reason for strength reduction and consequent slope instability. It should be mentioned that although there is lots of evidence showing that relatively loose saturated sand can liquefy in the lab (effective stress drops to 0), that may not be the case in the field. However, significant decrease

in the effective stress can still lead to substantial reduction in shear strength of soil and slope instability.

It has been reported by [9] and [11] that the presence of fines may increase soil resistance to liquefaction, and soil with a relatively large plasticity index [12] have much smaller potential for generation of excess pore water pressures, and thus it may not liquefy. In addition, the fine-grained matrix in such soils may provide some additional strength against liquefaction. As a result, the cyclic shear strength of plastic fine-grained soils may not significantly decrease during an earthquake. Yet, there are still some landslides (as shown in Fig. 2) reported in the literature that occurred in plastic fine-grained soils. Gratchev and Towhata (2008) [13] noted that the factor leading to earthquake-triggered landslides in plastic fine-grained soils can include: 1) large initial shear stresses originated from the high slope inclination and 2) permanent displacements of large magnitudes developed in soil mass during the earthquake loading.

4 Mechanism of Earthquake-Triggered Landslides

The mechanism of earthquake-triggered landslides can be explained to a certain level using the principles of soil mechanics. It is noted that this explanation involves a few assumptions and simplifications which would make it possible to apply the laboratory data from a small-scaled test to a large-sized landslide site.

4.1 Assumptions and Simplifications used to Study the Mechanism

Some of the main assumptions, which are related to data collection, soil mass inhomogeneity, and laboratory specimen testing techniques, are discussed below:

- Landslide sites can be quite large, and it is challenging to collect a good number of samples which will be sufficient to accurately reproduce the soil conditions prior to earthquake. Even within an area of a few meters, the soil conditions may vary significantly with the depth and width. Also, it is rather difficult to collect undisturbed samples that would have an intact soil structure that existed before the earthquake event. For this reason, it is not uncommon that disturbed samples are used during a forensic investigation because disturbed samples can still provide some idea about the soil conditions. Nevertheless, caution is needed when such results are analyzed as the strength properties of undisturbed and disturbed samples of the same soil material can be significantly different as shown by [4].
- It can be difficult to accurately represent earthquake loading in laboratory tests due to technical issues. To deal with this, a procedure developed by Seed et al. (1975) [14] may be used to estimate the number of load cycles based on the earthquake record.
- While performing lab tests, it is required by the relevant testing standard to saturate soil specimens to the highest level of saturation possible, which is commonly defined as $B > 0.95$, where B is the saturation parameter. However, it is still debatable that the landslide mass would be saturated, which is another common assumption that requires scientific judgment. Unfortunately, there is still limited amount of research in this field that can clearly show relationships between the degree of saturation and cyclic behavior of various types of soil.

- It should be mentioned that the pore water chemistry can affect the shear strength of fine-grained soil as shown by [15]. Although the pore water chemistry is generally ignored during forensic investigations, it can have some effect on both cyclic and monotonic strength, especially for those types of soil that contain expansive clay minerals such as smectite or montmorillonite.

4.2 Mechanism of Earthquake-Triggered Landslides through Soil Mechanics Principles

To better understand the mechanism of earthquake-triggered landslides, the data from ring-shear box tests (adapted from [10]) will be analyzed. Figure 4 presents a time series data from ring-shear box tests on coarse-grained material. The initial normal and shear stresses applied to the specimen before and after the cyclic loading represent the static field stress conditions prior to and after earthquake. The cyclic shear stress is then applied to the specimen (cyclic loading), reproducing the changes in shear stresses caused by the earthquake.

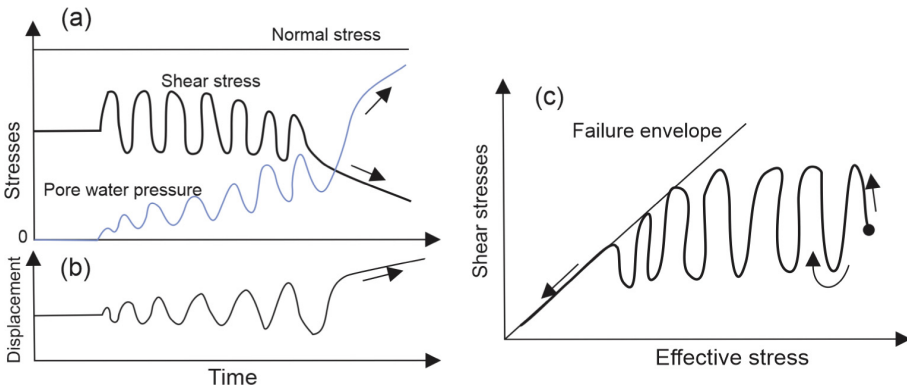


Fig. 4. Time series data of normal stress, shear stress, pore water pressure (a) and displacements (b) before, during and after earthquake loading. (c) Stress path of the test.

As the cyclic loading stage continues, the excess pore water pressure generates with every loading cycle and the specimen develops shear displacements (Fig. 4b). In Fig. 4c, a decrease in the effective stress due to the excess pore water pressure can be seen through the stress path moving to the left towards the failure envelope. If the excess pore water pressure generated by the cyclic loads is high enough to make the stress path touch the failure envelope line, then failure occurs. As a result, the shear strength of soil decreases, and at some point, it becomes insufficient to withstand the shear stresses acting on the soil mass after the earthquake. It can be seen in Fig. 4a when the shear stress plot goes down after the end of cyclic loading. This drop in soil strength is followed by increased values of shear displacement (Fig. 4b). Such rapid increases in shear displacement would represent the landslide movement in the field.

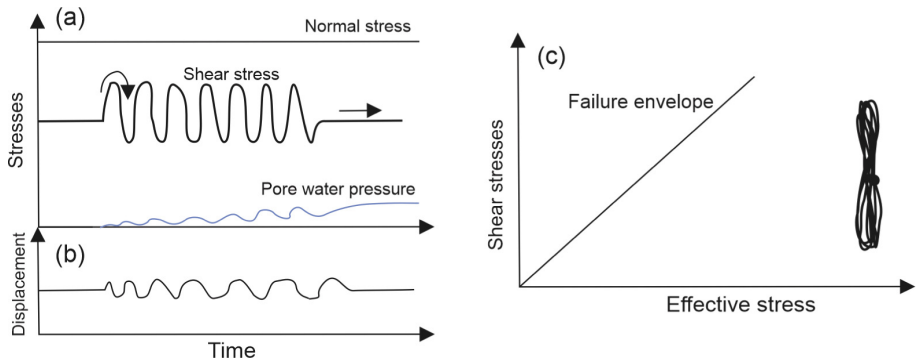


Fig. 5. Time series data of normal stress, shear stress, pore water pressure (a) and displacements (b) before, during and after earthquake loading. (c) Stress path of the test. Compared to Fig. 4, no failure has occurred in this test.

Figure 5 presents similar test results with the exception that the excess pore water pressure generated during the cyclic loading phase of the experiment was not high enough to decrease the effective stress acting on the soil specimen (Fig. 5c). Although the shear displacements were generated during the cyclic loading (Fig. 5b), they ceased after this phase of experiment was over. No failure occurred. Such soil mass behavior during an earthquake event would be expected from stable slopes.

5 Concluding remarks

This lecture summarizes the author's experience in regards to earthquake-induced landslides and discusses issues that may arise during site and laboratory investigations. The main features of earthquake-related landslides are discussed in relation to site geology and soil mass conditions. The following main observations can be drawn:

- The complex mechanism of earthquake-induced landslides involves a combination of triggering and causing factors. The triggering factors are related to the earthquake characteristics while the causing factors are related to geology, geomorphology of the site, and the in-situ properties of landslide mass. The combination of these factors will determine the size of landslides, slope inclination, and type of movement.
- Earthquake-triggered landslides may occur in different soil types (coarse-grained or fine-grained soils) and weathered rock mass. The capacity of soil mass to generate excess pore water pressures is essential in the process of landslide initiation and movement. The soil types that generate sufficient amount of excess pore water pressures can be associated with earthquake-triggered landslides more often than the soil mass with smaller potential to do so.

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