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# Identification of co-seismic ground motion due to fracturing and impact of the Tsaoling landslide, Taiwan

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ABSTRACT

Earthquakes can generate seismic disturbances that propagate vast distances and trigger landslides that can achieve high-speeds. It remains difficult to identify the co-seismic ground motion of these landslides and their triggering earthquakes. In this paper, we report on the analysis of co-seismic ground motions generated by the initiating fracture and deposition impact of the Tsaoling landslide. The landslide, with a source volume of $125 \times 10^6$ m$^3$, was triggered by the 1999 Chi-Chi earthquake in Taiwan. The ground motion was recorded by a strong ground motion station, CHY080, near the scar area. The polarization of the seismic waves indicates that the peak acceleration was parallel to the dip direction. Modified ensemble empirical mode decomposition (EEMD), with additional clustering analysis, was applied to decompose the seismic signals. Two instances were found in the seismic records of a series of peculiar wave packets, with the first being associated with the landslide initiation and the second the landslide impact on the deposit valley. To confirm the first landslide breakage, the decomposed signals were compared with the predictions of the analytic elastic wave model and Newmark analysis. The landslide impact was verified with a computational fluid dynamic simulation. Comparison between the EEMD decomposed signals, elastic wave theory, Newmark rigid body analysis, and numerical simulation demonstrates the claimed landslide motion.

## 1. Introduction

Landslides pose a long-lasting threat to human lives and property because of their devastating destructive capabilities. Landslides triggered by earthquakes are usually the most devastating in terms of the number of fatalities (Turner and Jayaprakash, 1996). Approximately half of the earthquake triggered landslides are classified as rock avalanches. Rock avalanches, particularly those with large volumes, are capable of traveling long distances at high speeds.

Large rock avalanches generate ground seismic motions. Several examples of seismic signatures for Mount St. Helen's landslide (Brodsky et al., 2003; Kanamori et al., 1984), Stromboli Volcano (La Rocca et al., 2004), and rock-fall avalanche events in the Alps (Deparis et al., 2008) have been reported. However, examples of landslide signatures with their co-existing earthquake ground motions are rare in the literature. This may be attributed to the scarcity of seismic records suitable for analysis which is difficult because of the complicated physical interactions between the landslide and earthquake signals. Together with topographical and geological influences, this tends to progressively disfigure the seismic signals as the waves propagate. These physical interactions, e.g. nonlinear coupling and dispersion/damping effects, ultimately make the signals indistinguishable from their original sources if the seismic monitoring stations are beyond a certain distance from the landslide site.

In this paper, we report an attempt to distinguish co-seismic landslide motion from background earthquake signals. The seismic record was from the Tsaoling landslide, which was triggered by the 1999 Chi-Chi earthquake in Taiwan. The recording station was approximately 200 m from the landslide scar area, and so, within such a short distance, the long-range physical interactions should be minor and negligible. The main focus is on the seismic signals generated by the fracturing of the landslide initiation.

Hints that this particular seismic record may contain landslide induced motion come from a simulation study of the landslide (Kuo et al., 2009), in which high frequency bursts of seismic ground motion are visually found to be coincident with the time of impact of the

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landslide reaching the deposit valley. The bursts can be deterministically decomposed using a modified empirical mode decomposition (EEMD) technique, and the decomposed localized signals were then identified phenomenologically from the point of view of seismic energy (Chang et al., 2012). The magnitude of the localized seismic motion was consistent with the energy release of the landslide impact.

These findings suggest that the landslide initiation can also be resolved accurately. We present a brief review of the characteristics of the landslide, geological settings, and ground motion record in Section 2. The agreement between the landslide course and the dominant acceleration/displacement directions of the peak ground motion indicates that this peak ground motion most likely contained the motion induced by block-breaking of the landslide mass from the bedrock. The fundamental question that arises in the present paper is: To what extent are we able to separate or identify landslide induced seismic motion from earthquake motion?

To answer the question, we applied the modified EEMD to the peak ground motion. The EEMD procedure and the ground motion were decomposed for characteristic identification, as discussed in Section 3. In the decomposed ground motion, a burst of signals, with a short time scale, was found. The burst is assumed to be associated with the fracturing of the landslide mass, and the short time scale indicates that the fracturing takes place within a short period. Therefore, we simplified the fracturing as a sudden release of the sustaining shear force of the landslide mass, and this fracture mechanism produced seismic waves propagating outwards from the scar. A two-dimensional elastic wave model was derived for the theoretical wave form of the fracture, and the wave form compared with the EEMD analysis in Section 4.

For comparison, a Newmark analysis is also presented in Section 5, and the initiation time and assumption of sudden release of the shear force verified. Finally, the impact signal and the landslide flow simulation are recapitulated in Section 6 for completion, and conclusions are drawn in Section 7.

## 2. Tsaoling landslide and seismic ground motion

The Tsaoling landslide was the largest landslide triggered in Taiwan by the Chi-Chi earthquake, $M_L = 7.3$ (Kao and Chen, 2000; Lallemand, 2000; Angelier et al., 2003; Ma et al., 2006). The slide volume of the landslide was approximately $125 \times 10^6$ m$^3$, with an average thickness of 160 m. The landslide moved approximately 1990 m and deposited some $150 \times 10^6$ m$^3$ debris. The deposit formed a dam blocking the Chinshui River valley (Hung et al., 2002; Chen et al., 2006).

The geological setting, landslide scar, and debris deposit in the Tsaoling area are shown in Fig. 1. The landslide was initiated on the northern slope of the Chinshui River and flowed toward the southwest (SW). In the following discussion, we define a profile in the NE–SW direction, shown in the inset to Fig. 1, referred to as the main profile. The slope has an inclination of 15.8° and a dip angle of approximately 14°, and is oriented NNE–SSE. The slope is much steeper on the southern side of the river than the northern. The sliding surface, composed of fine layered shale and silty mudstone, is parallel with the stratigraphic bedding plane. After the landslide, thin layers of pseudotachylytes were found scattered on the sliding surface, indicating frictional heating and melting of the sliding plane during the sliding process (Lin et al., 2001).

Approximately four fifths of the slide mass was transported across the river and deposited around the Taochiashan hill on the southern bank of the river, which was approximately 140 m higher than the riverbed before the earthquake. The existing topology implies that the slide material reached a substantially high speed, moving with such kinetic energy that the mass was able to move across the river valley and overflow the Taochiashan hill. The characteristics of the flow morphology, e.g. the up-hill movement and reflected debris flow surges, were observed in the field.

Because of the high seismicity and high population density of the island of Taiwan (Tsai and Lee, 2005), they have one of the densest earthquake monitoring networks in the world, serving a variety of purposes, e.g. early warning and earthquake identification. A strong motion seismological station, code-named CHY080 (120.67770 E, 23.59720 N, El. 840 m, TWD97 standard) was installed on top of the Tsaoling slope in the 1990s. The station is located less than 1 km north-west of the depleted mass center, approximately 200 m from the landslide boundary, as indicated in Fig. 1, thus was safe from the violent seismic shaking, the landslide flow, and remained fully functional throughout the earthquake event.

The total duration of the earthquake signals recorded by CHY080 is 159 s at a standard sampling rate of 200 Hz. The recorded peak ground acceleration (PGA) values are 792.4, 841.5, and 715.9 gal for the E–W, N–S, and vertical components, respectively (Lee et al., 2001). The P-wave arrived at 20.0 s, and the S-wave arrived at 25.2 s. The horizontal trajectories of the acceleration and displacement are shown in Fig. 2(a) and (b). The signals and trajectories show a sharp instance of activity at approximately 38.1 s. The signals around this time, highlighted by the red/green line segments for clarity, show ground motion with well-defined principal orientations. Both the acceleration and displacement are in the NE–SW direction, with principal directions 47° and 37° to the east, respectively, from the principal component analysis. Despite minor discrepancies, these directions are nearly parallel to the direction of the slide and the strata dip. The acceleration signals, rotated into the principal direction, are shown in Fig. 2(c).

## 3. Empirical mode decomposition with cluster analysis

The modified EEMD is applied to inspect the sharp peak ground motion. Chen et al. (2014) used a widely applied short-time Fourier transform method to inspect the CHY080 ground acceleration and suggested that the landslide fracturing generated high frequency signals. The

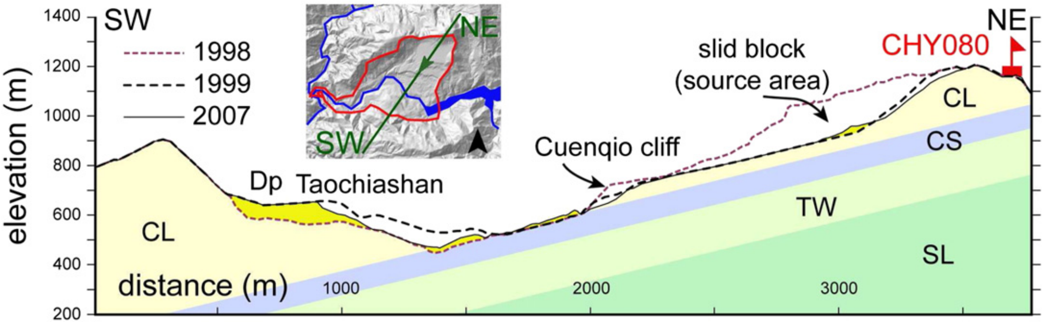

**Fig. 1.** Geological profile of the Tsaoling area. The inset figure depicts the area surrounding the landslide site and the landslide slide direction (the dark green arrow). The NE–SW profile is defined through the gravity center of the slide mass and is parallel to the slide direction. This profile is referred to as the main profile. Geological formation: SL = Shihliufeng shale; TW = Tawo sandstone; CS = Chinshui shale; CL = Cholan formation; Dp = debris deposit.