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Insight into landslide kinematics from a broadband seismic network

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Abstract

The kinematic features of the 2009 Hsiaolin landslide were analyzed using a broadband seismic network in Taiwan. Both the final impact velocity and acceleration of the landslide were calculated based on the traveling distance and time of the landslide. A distance of approximately 2,500 m was observed on the surface, and the time from the initial collapse to the final impact was of 60.38 s according to broadband seismic data recorded nearby. The initial collapse time was determined using very-long-period seismic signals (20 to 50 s) created by the elastic rebound of the shallow crust as the overlying landslide initially moved downhill. The final impact time was determined by detecting the largest amplitudes of high-frequency seismic signals (1 to 10 Hz). The final impact velocity of approximately 298 km/h exhibited by this landslide had never before been recorded and thus might mark a world record; these speeds can be attributed mainly to a low friction coefficient (approximately 0.12) and a long run-out (approximately 2,500 m) along a gentle dip-slope surface (approximately 15°).

Keywords: Hsiaolin landslide; Landslide kinematics; Impact velocity; Friction coefficient

Correspondence/findings

Introduction

In 1970, a forceful high-speed debris avalanche in Peru triggered by an earthquake killed approximately 20,000 people (Schuster and Highland 2001). In general, the damage caused by catastrophic landslides depends on their size and velocity. The damage area typically depends on the landslide volume, whereas human survival is strongly influenced by the velocity; people can easily escape from the area affected by slow landslides, whereas they cannot escape from fast landslides. To classify the velocity of landslides, a 7-level scale was created by Cruden and Varnes (1996). Level 1 represents extremely slow landslides with speeds of less than 16 mm/year, whereas Level 7 represents extremely fast landslides with speeds higher than 5 m/s (18 km/h). Some landslides even exceed this speed, but to determine the exact velocity of a landslide is difficult without reliable measures.

One of the most crucial parameters for determining the velocity of a landslide is the friction coefficient calculated according to the contact area that lies between the sliding

material and the underlying layer. Less friction between the sliding material and the underlying layer engenders higher speeds. The friction coefficient typically depends on the materials, the textures of the surfaces, and given lubricants. Like the friction coefficient in the fault planes, the friction coefficient of rocks beneath landslides is a vital subject in the study of geodynamic processes (Sibson 1982; Scholz 1990; 1988). Determining whether an earthquake occurring along a fault plane exhibits high or low friction, it is interesting to know the seismogenic mechanism (Zoback et al. 1987). To determine friction coefficients along fault planes, the friction coefficients of various rock types have been measured in laboratories under simplified physical conditions (Dieterich 1978; Dieterich and Kilgore 1994; Blanpied et al. 1991). However, direct measurement of friction coefficients in the field remains difficult.

In this study, broadband seismic data were collected to analyze the Hsiaolin landslide, which occurred in Taiwan on August 8, 2009 and was one of the fastest landslides recorded worldwide. The friction coefficient of the contact area between the sliding material and underlying layer was retrospectively estimated by considering both the run-out distance and travel time.

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Hsiaolin landslide

On 8 August 2009, Typhoon Morakot landed on Taiwan and several hundreds of large, deep-seated landslides were triggered by extremely heavy rainfall (Lin et al. 2010). The most catastrophic of the landslides buried 474 residents in the village of Hsiaolin, southern Taiwan (Lin et al., 2010). Careful geological survey of the Hsiaolin landslide (Tsou et al. 2011) revealed that the major slide materials initially collapsed from an elevation of approximately 1,280 m (Hsindoshan) and were then deposited along Chishan Creek at an elevation of approximately 450 m (Figure 1). As the landslide moved downhill and reached an elevation of 590 m, it separated into two major parts that continued to move in different directions. The southern landslide affected highland regions at an elevation of 590 m and then buried all houses in the northern part of Hsiaolin Village, killing most of the residents immediately. The northern landslide moved along the gully and halted at Chishan Creek. Consequently, the landslide immediately formed a dam. After approximately 40 min later, the debris flow due to the dam breach flushed away the remaining houses, except two that were situated on the highland in the southern part of Hsiaolin Village (Chen et al. 2011).
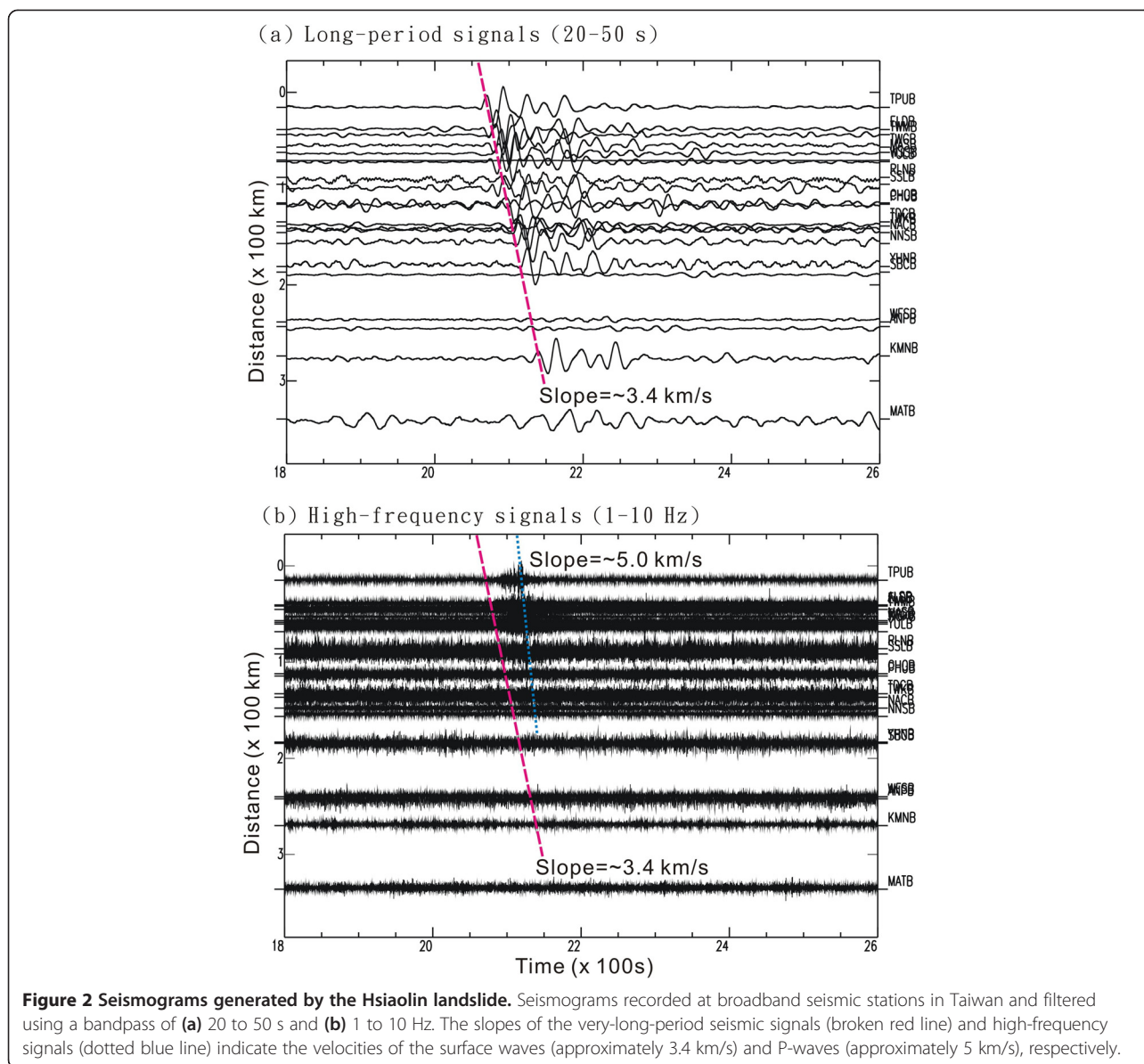
Broadband seismic data

Like most of the large landslides that occurred on 8 August 2009, the Hsiaolin landslide (Lin et al. 2010) generated valuable seismic data, namely very-long-period seismic signals (20 to 50 s; Figure 2a), which were well recorded by the broadband array in Taiwan for seismology (BATS) (Kao et al. 1998). The propagating velocity of the very-long-period signals measured approximately 3.4 km/s, which is characteristic of typical surface waves on the earth. These very-long-period signals could propagate along distances of more than 2,000 km (Lin et al. 2010). By contrast, some of the high-frequency seismic signals (1 to 10 Hz) with a propagating velocity of approximately 5 km/s were detected only at nearby stations, at distances of less than 100 km (Figure 2b). These high-frequency seismic signals were probably the P-waves propagated in the crust; thus, they decayed substantially as the distance increased.

Of the many broadband seismic stations in Taiwan, Station TPUB, which is located approximately 12.5 km north of the location of the Hsiaolin landslide (Figure 3a), recorded valuable seismic signals, including the first clear arrivals of the very-long-period signals (20 to 50 s). These signals were measured at 22 h 16 min 13.1 s on 8 August (Greenwich Mean Time), or 6:00 AM, 9 August (local
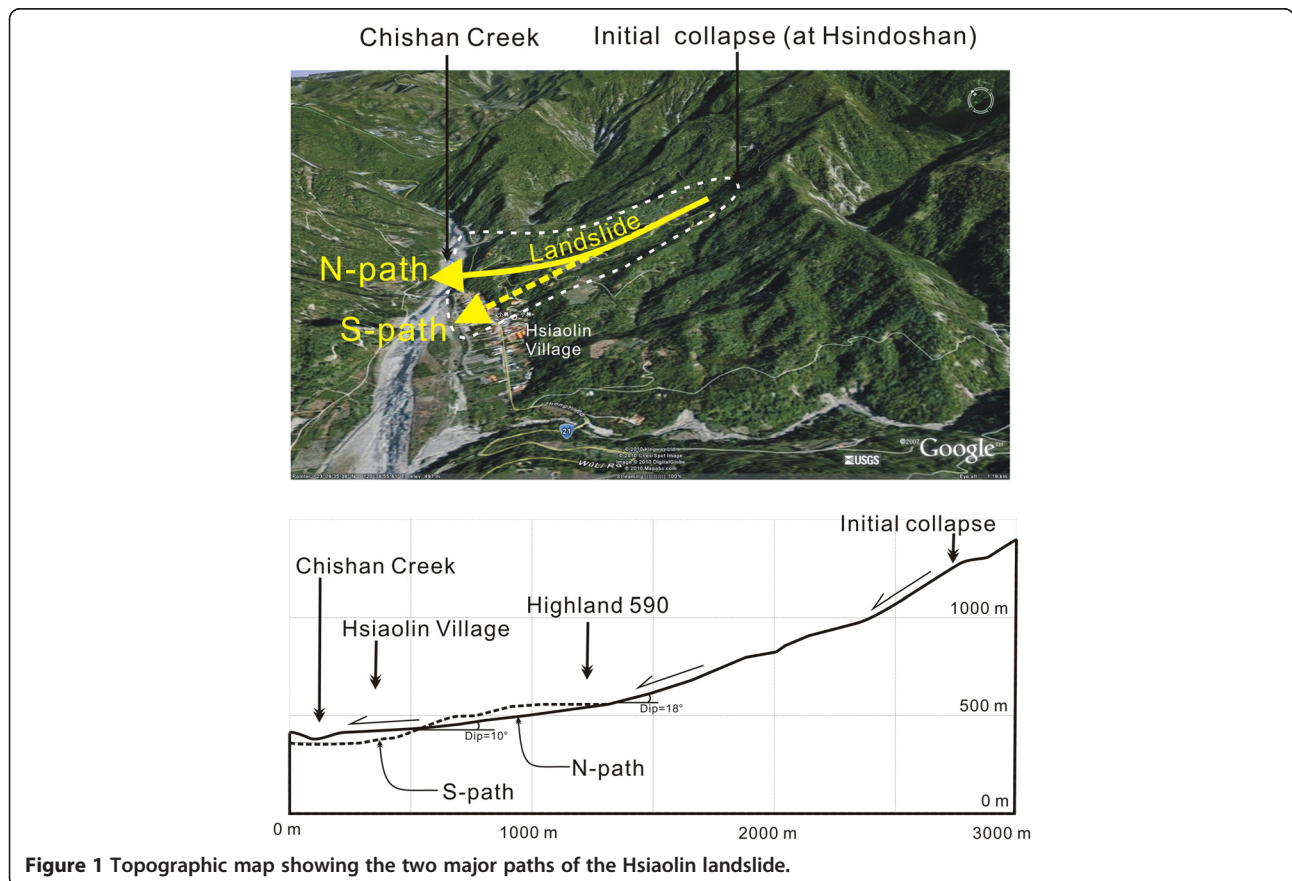

Figure 1 Topographic map showing the two major paths of the Hsiaolin landslide.

Figure 2 Seismograms generated by the Hsiaolin landslide. Seismograms recorded at broadband seismic stations in Taiwan and filtered using a bandpass of **(a)** 20 to 50 s and **(b)** 1 to 10 Hz. The slopes of the very-long-period seismic signals (broken red line) and high-frequency signals (dotted blue line) indicate the velocities of the surface waves (approximately 3.4 km/s) and P-waves (approximately 5 km/s), respectively.

time) (Figure 3b). However, the exact occurrence time of the landslide was starting at 22 h 16 min 9.42 s if one considered the traveled time of 3.68 s from the landslide to the seismic station at a distance of 12.5 km by given a propagated seismic velocity of 3.4 km/s. A possible mechanism underlying the very-long-period signals is elastic rebound from the shallow crust after the landslide started (Kanamori and Given 1982; Kawakatsu 1989). The rebound theory is also consistent with the observations obtained from various large-scale landslide experiments (Moriwaki et al. 2004) that clearly showed that overlying materials are bent downward by the gravitational force of the sliding material before the material moves downhill (Figure 4). Thus, elastic rebound of the shallow crust might have been caused immediately after the landslide

occurred. The very-long-period signal clearly arrived considerably earlier than any other high-frequency seismic waves (1 to 10 Hz) generated by the landslide (Figure 3b).
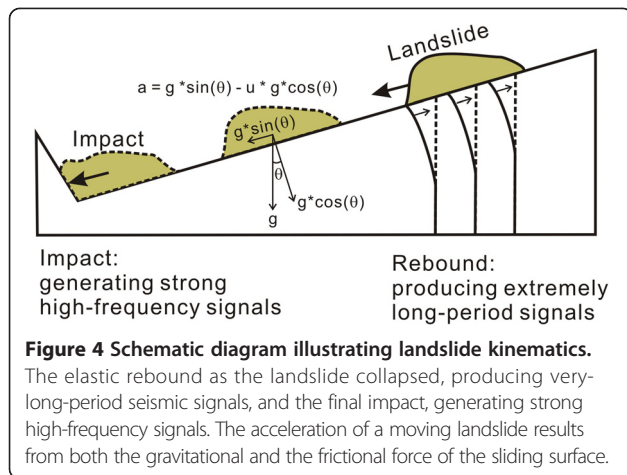
The seismic amplitudes of the high-frequency signals (1 to 10 Hz) recorded at Station TPUB increased in the first minute after the initial collapse and then decreased subsequently (Figure 3b). This pattern might represent the entire process of landslide movement. It is assumed that high-frequency seismic energy was largely released from the impact of the sliding momentum on a barrier or a particularly rough surface. A stronger impact generates seismic energy with a larger amplitude. At the early stage, small seismic amplitudes were generated by the slowly moving landslide, exhibiting low momentum; as the landslide accelerated, it generated larger seismic amplitudes.
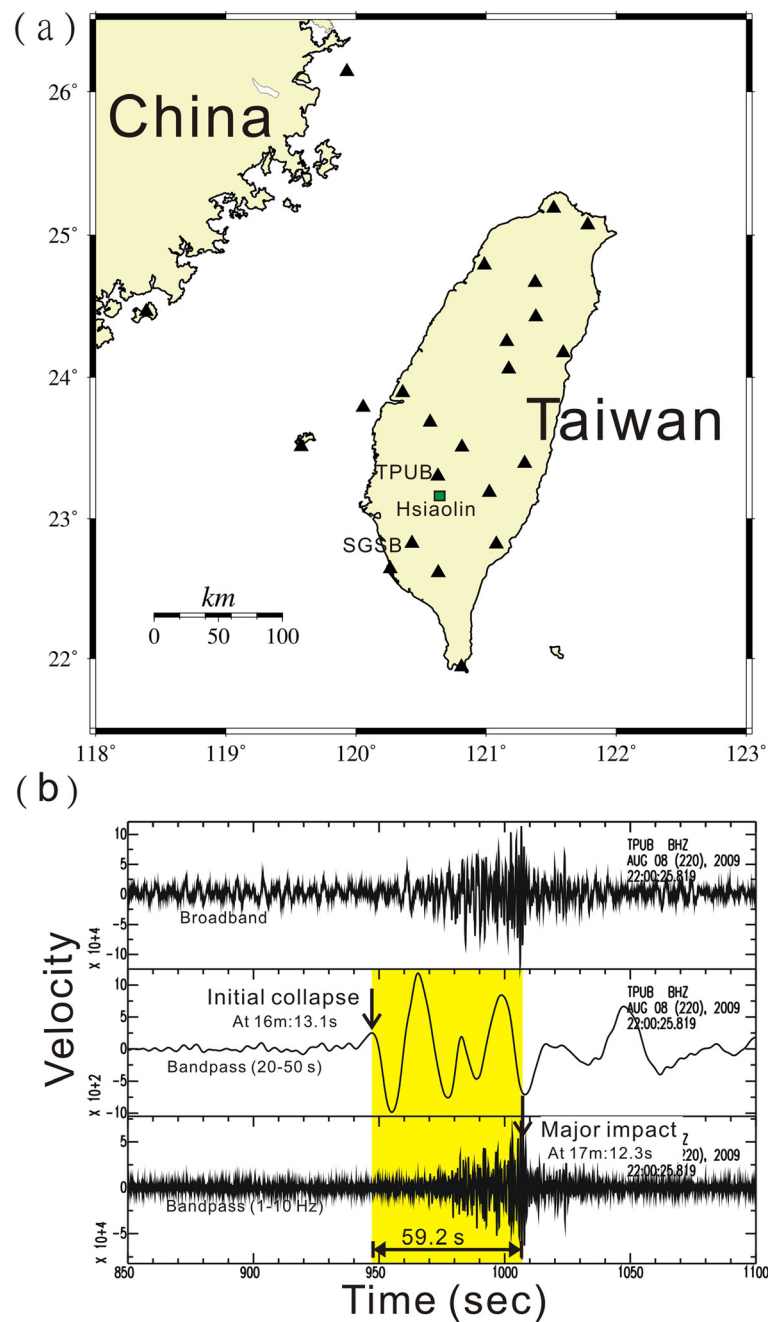
Figure 3 Seismic station distribution and seismograms recorded at Station TPUB. (a) Locations of broadband seismic stations in Taiwan (triangles) and the Hsiaolin landslide (square). **(b)** Broadband seismograms (top) and band pass filtered by 20 to 50 s (middle) and 1–10 Hz (bottom) and recorded at Station TPUB, which lies approximately 12.5 km north of the location of the Hsiaolin landslide.

The high-frequency seismic signals exhibited the largest amplitude at 17 min 12.3 s at station TPUB, likely marking the time when the major part of the landslide hit and then stopped at Chishan Creek (Figure 4). However, the exact impact time of the landslide was reduced to 22 h 17 min 9.8 s if one considered the traveled time of 2.5 s from the landslide to the seismic station at a distance of 12.5 km by given a propagated seismic velocity of 5.0 km/s. Thus, the final impact of the landslide occurred approximately 60.38 s after the very-long-period seismic signals were first detected, indicating the initiation of the Hsiaolin landslide. Although some high-frequency signals were detected after

Figure 4 Schematic diagram illustrating landslide kinematics.
The elastic rebound as the landslide collapsed, producing very-long-period seismic signals, and the final impact, generating strong high-frequency signals. The acceleration of a moving landslide results from both the gravitational and the frictional force of the sliding surface.

the landslide produced its major impact, they might have been generated by subsequent landslides.

Landslide kinematics
Various crucial kinematic parameters of the Hsiaolin landslide can be derived by combining the obtained seismic data with detailed field survey data. First, the acceleration of the sliding materials can be estimated using the measurements of the run-out distance and the traveling time obtained from the broadband seismic data. Although the total distance of the landslide, from the crown of the collapsed area at an elevation of 1,380 m to the deposition area near Chishan Creek, was approximately 3,200 m (Tsou et al. 2011), the average run-out distance of most of the landslide material, from the center of the collapsed area to Chishan Creek, might be only approximately 2,500 m (Kou et al. 2011). The time required to cover the average run-out distance (60.38 s) can be estimated using measurements of both the very-long-period seismic signals (20 to 50 s) and high-frequency (1 to 10 Hz) signals. Thus, when the distance and time are known, the average acceleration of the Hsiaolin landslide can be calculated using the following kinematic equations.

$$D = 0.5 \times a \times t^2 \text{ and } V = a \times t,$$

where a, V, D, and t are the acceleration, velocity, run-out distance, and traveling time of the moving block, respectively. The average acceleration of the landslide was approximately 1.37 m/s², and the final impact velocity was 82.81 m/s (or approximately 298 km/h).

In addition to the velocity and acceleration of the Hsiaolin landslide, the coefficient of friction between the sliding material and the overlying ground surface can be calculated using a simple kinetic equation commonly used in physics (Figure 4).

$$a = \text{g} \times \sin(\theta) - u \times g \times \cos(\theta),$$

where a is the acceleration of the moving block, g is the gravitational acceleration (980 cm/s²), u is the friction coefficient, and θ is the inclination of the slope. Thus, the coefficient of friction beneath the moving material is only approximately 0.12, given an average inclination of 15° in the major landslide profile, although the inclination exhibits gradual variations in the range of 10° to 20° (Figure 1).

Discussion
A velocity as high as that of the Hsiaolin landslide (approximately 298 km/h) had not been reported anywhere in the world prior to 2009. A high-velocity landslide of that scale is difficult to observe unless it can be predicted. The factors contributing to such a landslide includes a low friction coefficient, long run-out distance, and gentle dip-slope ground surface. The friction coefficient of the Hsiaolin landslide (approximately 0.12) is lower than that of most comparable landslides and debris flows (Scheidegger 1973; Brodsky et al. 2003). This low friction coefficient was can be attributed mainly to extremely heavy rainfall, which infiltrated the space between the sliding material and the overlying ground. In addition, the long run-out distance of approximately 2,500 m resulted from a gentle dip-slope surface extending from Hsindoshan to Chishan Creek. The dip slope has an average incline of approximately 15°, and the inclination varies from 10° to 20°. Consequently, the major portion of the collapsed landslide moved downhill smoothly until it reached the Chishan creek.

It is difficult to fathom the devastation caused by the Hsiaolin landslide when it reached Chishan Creek and Hsiaolin Village. Approximately, 25×10^6 m³ of debris (Tsou et al. 2011) slid down the slope at a maximal speed of approximately 298 km/h and destroyed all structures and buildings.

Conclusion
This detailed study of the 2009 Hsiaolin landslide in Taiwan demonstrated that the kinematic parameters of a landslide, such as the velocity (298 km/h) and acceleration (1.37 m/s²), can be derived directly from broadband seismic data. The starting time of the landslide was obtained from the very-long-period seismic signals (20 to 50 s) generated by the elastic rebound of the shallow crust beneath the landslide, whereas the end of the landslide was estimated using the largest amplitude of the short-period seismic signals produced by the impact on Chishan Creek. The results revealed that the velocity at the time of the final impact reached approximately 298 km/h, equaling

the speed of the fastest high-speed trains and constituting a landslide velocity that had previously not been reported. In addition, the friction coefficient of the landslide was 0.12. Such low friction can be attributed mainly to extremely heavy rainfall, which infiltrated the space between the sliding materials and the overlying ground.

Competing interests
The author declares that he has no competing interests.

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