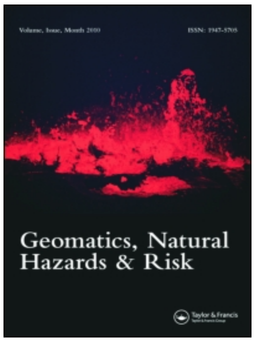

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EXPRESS LETTER

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The catastrophic 13 November 2015 rock-debris slide in Lidong, south-western Zhejiang (China): a landslide triggered by a combination of antecedent rainfall and triggering rainfall

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ABSTRACT

On 13 November 2015, a disastrous rockslide-debris avalanche occurred in the Lidong village of Liandou District, Lishui City (south-western Zhejiang, China), which overwhelmed 27 houses and killed 38 people in the village. The geological survey on the slope revealed that prior to this incident, a rupture zone existed between the highly weathered volcanic rock and the underlying weathered volcanic rock in this slope. The rupture zone has dip direction coinciding with the slope aspect and some of the existing cracks in the surface are likely extended from the surface to the rupture zone. This study summarizes the past history and main characteristics of the landslide, simulates the correlation between the safety factor of the slope and the rainfall level using a physically based triggering model, and analyses the distribution of the effective antecedent rainfall that influences landslide occurrence, showing that the landslide on 13 November 2015 was triggered by the very low intraday rainfall and the 15-day antecedent rainfall. The results demonstrate that for a potential unstable slope with increasingly wet antecedent conditions, very low daily rainfall may be able to trigger landslides on a given day, which is important for improving landslide warning systems based on the rainfall–landslide relationship.

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Landslides; triggering model; antecedent rainfall; Zhejiang, China

1. Introduction

At 22:50 on 13 November 2015, a disastrous landslide occurred in the Lidong village of Liandou District, Lishui City, Zhejiang Province, China (Figure 1). The landslide overwhelmed 27 houses and killed 38 people in the village. This catastrophic failure is the largest landslide in Zhejiang in recent years. The event originated in an unstable slope that had been identified in 2012 as highly prone to rainfall-triggered landslides (The No.7 Geological Team of Zhejiang Province 2012). This unstable slope has an altitude ranging from 197 m to about 340 masl; the entire terrain is inclined from the west toward the east and drops in a step form, and the outcropping rocks are highly crushed and weathered due to the influence of the faults.

The objectives of this study were to: (1) summarize the main characteristics of the landslide; (2) discuss its geological, tectonic and climatic setting; and (3) simulate the correlation between the

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Figure 1. (A) Oblique aerial view (to the south-west) of Lidong village landslide taken on 14 November 2015 (Photograph by Zhejiang Provincial Public Security Department Expressway Traffic Police Corps). (B) View of the head scarp of the rockslide-debris avalanche taken on 14 November 2015 (Photograph by Dr Xiaoming Tang, Zhejiang Institute of Geology and Mineral Resources).

safety factor of the slope and the rainfall level using the physically based triggering model developed by Montrasio and Valentino (2008) based on geometrical and geotechnical data of the slope where the failure occurred.

2. Climatic, geomorphologic and geologic settings of the Lidong village

The Lidong village is located at the Liandou District, Lishui City, south-western Zhejiang (Figure 2). The Zhejiang Province belongs to a subtropical monsoon zone and is highly prone to rainfall-triggered landslides because of its geologic, geomorphologic and climatic settings (Li et al. 2010, 2011, 2012; Ma et al. 2014, 2015).

Geomorphologically, the area of the Lidong village is a low mountain and hilly terrain that varies between 192 and 593 masl, which is characterized by high altitudes in the north-western and south-eastern parts and low altitudes in the central part (Figure 2). The terrain slope gradient is between 15° and 45°. A stream with a width between 5 and 15 m flows from north-east to south-west in front of the Lidong village.

The outcropping strata in the Lidong village and its neighbouring area are chiefly Upper Jurassic volcanic rocks, including a middle sequence (J_3x^2) and an upper sequence (J_3x^3) of Xishantou Group (Figure 2). The middle sequence (J_3x^2) consists mainly of rhyolitic crystal tuff and dacitic crystal-vitric ignimbrite, sandwiched with sedimentary tuff and siltstones as well as tuffaceous sandstones. The upper sequence (J_3x^3) mainly consists of rhyolitic vitric-crystal tuff, rhyolitic vitric-crystal ignimbrite, dacitic crystal-vitric ignimbrite and breccia-bearing vitric tuff. A granite stock and several different-scaled magmatic dykes or veins intruded into the volcanic rocks.

These rocks are highly weathered and are cut by faults and fractures. Several faults have been found in the area (Figure 2) of which a NE-striking fault developed along the river valley, which is at least 5 km long and 3.6 km away from the Lidong village landslide (see F_3 in Figure 2). A NW-striking fault inferred from satellite image interpretations is about 3.4 km away from the landslide (see F_5 in Figure 2). There are numerous offshoots from these faults, and because of the presence of these faults, the rocks have been highly crushed.

The Liandou area has a mean monthly precipitation ranging from 45 to about 260 mm; the distribution of rainfall over a year is not uniform and the amount of rainfall from April to September typically accounts for more than two-thirds of the annual rainfall (Figure 3). Annual mean temperature ranges from 12 to 18 °C. The average daily temperatures are highest (>35°) in July and lowest (<0°) in January.

3. Past history and characteristics of the Lidong village landslide

The rock-debris slide on 13 November 2015 originated on a 340 m high, steep and heavily bushed slope. The slope is located on the west side of the Lidong village and the village is located on the north-western bank of the stream (Figure 2). The failed slope swept down into the village and its debris reached the valley. Figure 4 shows the slope aspect before the landslide on 13 November 2015. The whole aspect of the landslide is seen in Figure 1. Figure 5 depicts the longitudinal section before and after the landslide. The crown of the landslide is located at about 332 masl, the landslide toe is located at an elevation below 200 masl, and the total volume of the landslide is over 4×10^5 m^3.

The first record of activities of the Lidong village landslide dates back to 24 June 2012 following incessant rainfall for many days (The No.7 Geological Team of Zhejiang Province 2012). The slide caused the collapse of the walls of several houses at the base of the slope. The development of cracks in the hearths and on the ground clearly indicated that the slope was moving very slowly. A curvilinear tension crack (potential head scarp) seems to have formed near the top of the slope (Figure 4).

After this slide event, a geological prospect project for the landslide was immediately carried out at the Lidong village by the No.7 Geological Team of Zhejiang Province. The geological prospect report presented by the No.7 Geological Team of Zhejiang Province (2012) shows

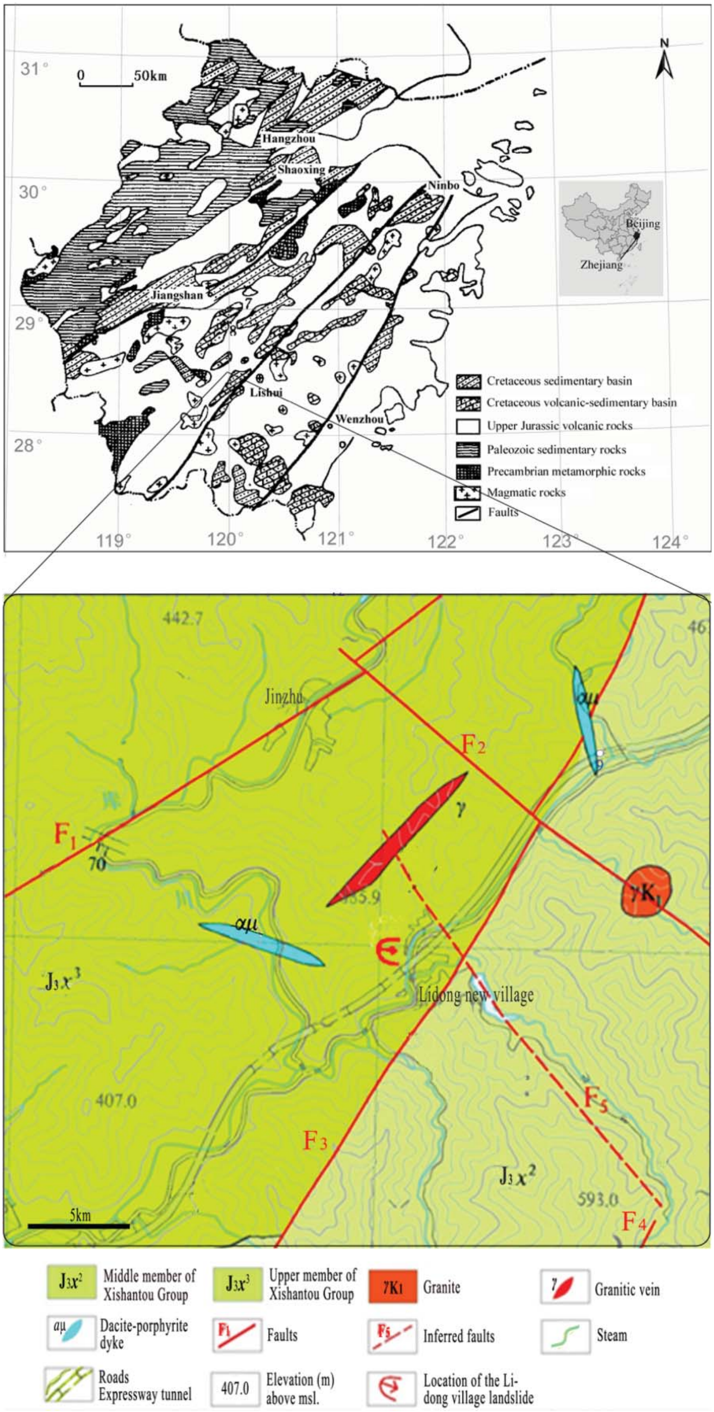

Figure 2. Schematic geological map of Lidong village and its neighbouring areas (modified after the 1:50,000-scale geological map compiled by the Institute of Zhejiang Provincial Geological Survey after the occurrence of 13 November 2015 Lidong village landslide).

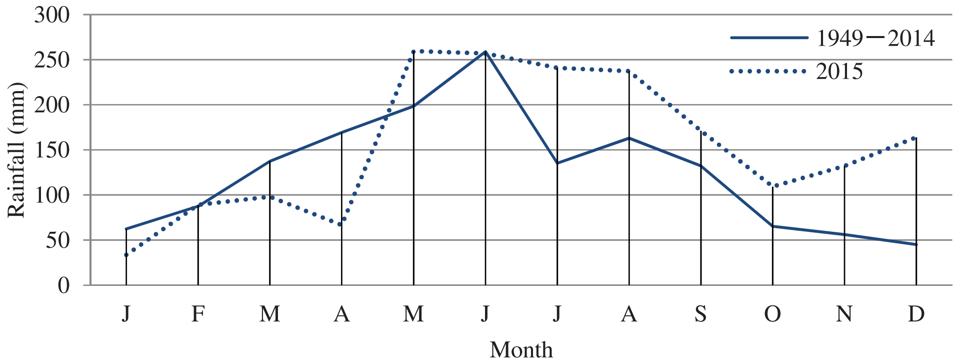

Figure 3. The mean monthly rainfall distribution in the Liandou area of Lishui City, Zhejiang Province for the 1949–2014 period (continuous line) and the monthly rainfall for the year 2015 (dotted line).

that the east-facing slope behind the village is covered by eluvial deposits with thickness ranging from 0.6 to about 10 m. The rocks around the slope are intensely weathered and jointed. Three prominent sets of joints, i.e. striking NEE dipping at an angle of 57°–80° towards SSE, striking NE dipping at an angle of 15°—20° towards SE, and striking NNE approximately vertical joint, have been observed in the exposed rocks. The rhyolitic vitric-crystal tuff underlying the eluvium has been highly weathered and fractured to a depth of approximately 8–26 m below the surface.

According to the geological prospect report presented by the No.7 Geological Team of Zhejiang Province (2012), the exploration drill cores penetrating the highly weathered volcanic rock and the weathered volcanic rock revealed that a rupture zone dipping to 95° at an angle of 22°–35° exists between the highly weathered volcanic rock and the weathered volcanic rock (Figure 5). The thickness of the rupture zone varies from 0.2 to 0.9 m. The rock cores from the rupture zone are grey or

Figure 4. Slope before Lidong village landslide on 13 November 2015 (modified after the photograph by The No.7 Geological Team of Zhejiang Province on 15 August 2012).

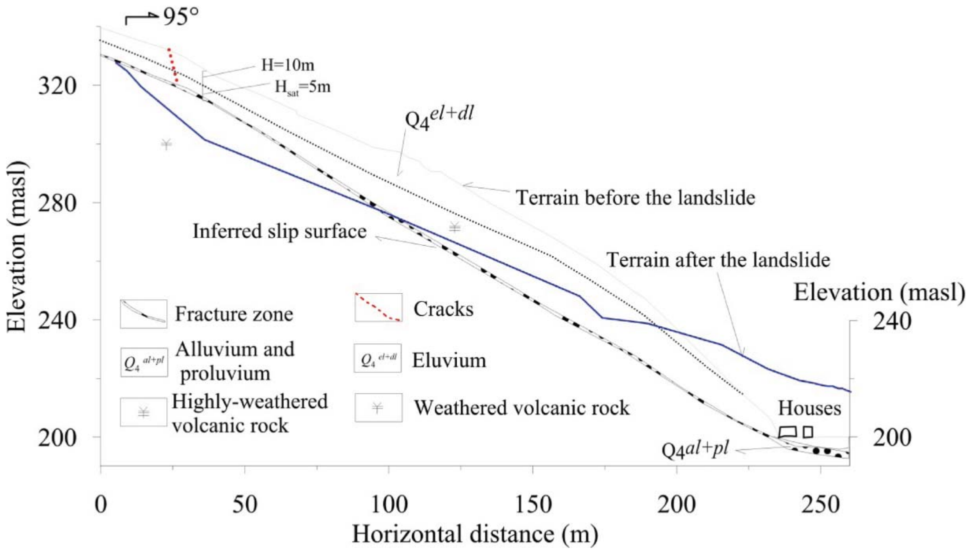

Figure 5. Schematic geological profile before and after Lidong village landslide on 13 November 2015 (modified after The No.7 Geological Team of Zhejiang Province 2012 and Tang 2015).

greyish yellow in colour, highly fractured and easy to soften under wet conditions. The surface of the fractured rock cores feels very smooth, implying the existence of some clay minerals such as smectite, kaolinite and illite on the slickenside and around the fracture surface, which can be considered as one of the factors that contributed to the landslide. As shown in Figure 5, the rupture zone can be inferred as a potential slip surface because of its dip direction coinciding with the slope aspect, and some of the existing cracks in the surface are likely extended from the surface to the rupture zone, which is conducive to rainfall infiltration into the rupture zone.

Available information indicates that, since the slide event on 24 June 2012, no landslides were triggered by rainfall in the Lidong village and its surrounding areas until the Lidong village landslide occurred on 13 November 2015.

4. Mechanism of the Lidong village landslide

The existence of the rupture zone (potential slip surface) between the highly weathered volcanic rock and the weathered volcanic rock as well as some cracks that are likely extended from the surface to the rupture zone (Figure 5) are key factors in the initiation of the Lidong village landslide. During the rainy season, rainfall can easily penetrate the cracks within the overlying soil and the highly weathered rock mass until it reaches the rupture zone. Due to the relative impermeability of the weathered rock mass, the groundwater starts building up on the rupture zone. The rise of groundwater level increases the pore-water pressure, causing the weakening of the highly weathered rock and the overlying soil until these reach failure.

4.1. Triggering and antecedent rainfall analysis

In 2015, the Zhejiang Provincial Hydrological Bureau set up a monitoring network consisting of 32 automatic rain gauges in the areas (about 1350 km^2) surrounding the Lidong village landslide. The distance between the landslide and rain gauges is ranging from a minimum of 1.5 km to a maximum of 20.9 km (Figure 6(A)). At these rain gauges, rainfall measurements are cumulated every 5, 10, 15, 30, or 60 min. The detailed rainfall records, including rainfall duration, mean rainfall intensity, as

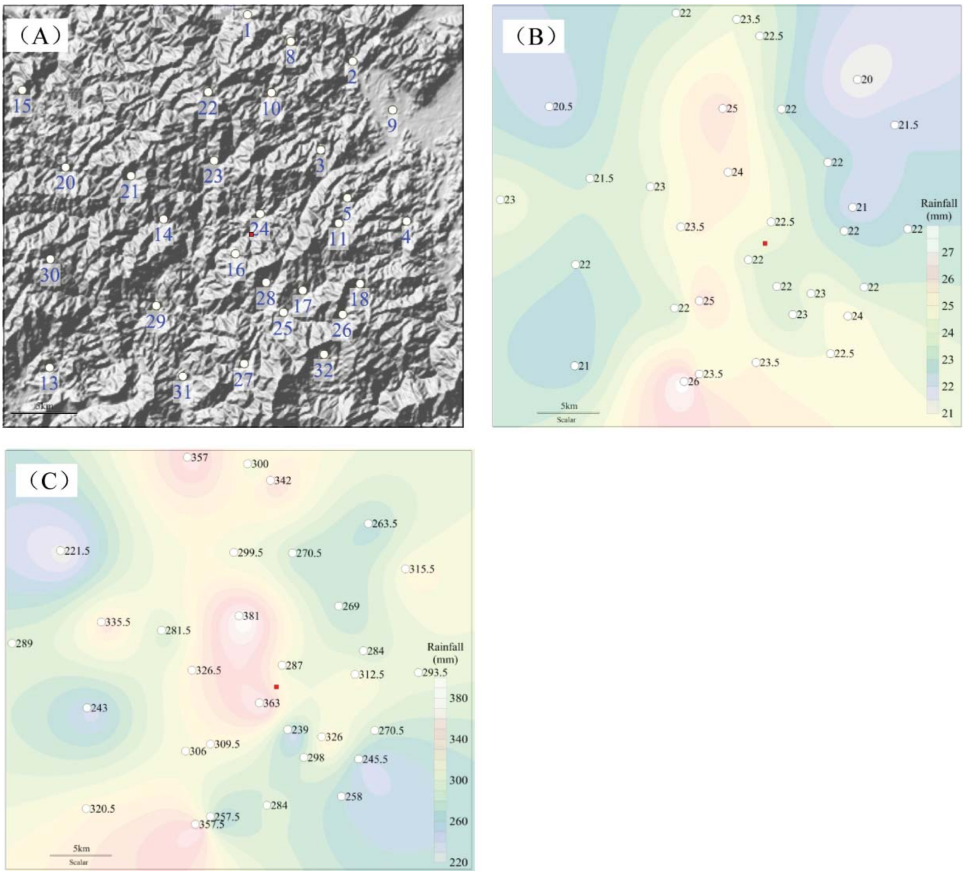

Figure 6. (A) Shaded relief map of the areas surrounding Lidong village landslide (based on 90 × 90 m DEM data shared by the Infrastructure of Earth System Science; http://www.geodata.cn/). White dots are the locations of rain gauges and the numbers represent the number of the rain gauges. (B) Spatial distribution of the cumulative rainfall registered at the rain gauges on the day of the landslide occurrence (from 12 November (23:00) to 13 November (23:00) 2015). (C) Spatial distribution of the cumulative rainfall registered at the rain gauges from 16 September to 13 November (23:00) 2015. Numbers beside the white dots in B and C denote cumulative rainfall recorded by the rain gauges. Red square shows the location of Lidong village landslide. B and C were created using a weighted average method with the second power of reciprocal of a distance to a given rain gauge.

well as maximum rainfall intensities for rolling 1, 3, 6, 12, and 24 h, can be obtained from the measurements of precipitation at the rain gauges.

As shown in Figure 3, in the Liandou area, the monthly rainfall from July to December 2015 was evidently higher than the average monthly rainfall for the same months between 1949 and 2014. During the period from October to November, the area experienced intermittent rain; the rainfall in the two months was 109 and 132 mm, respectively, which were 168% and 235% of the mean monthly rainfall (65 and 56 mm, respectively) for the area.

Figure 6(B) depicts the spatial distribution of the cumulative rainfall registered at the rain gauges on the day of the Lidong village landslide (from 12 November (23:00) to 13 November (23:00) 2015). We can see from this figure that the rainfall measured at various gauges was <26 mm. The rain gauge closest to the landslide (i.e. rain gauge 24, on the north-eastern side of the mountain ridge affected by the landslide) is located at a straight distance of about 1.5 km and its rainfall record was about 23 mm. The second closest rain gauge (i.e. rain gauge 16, to the south-west of the landslide) is located at a straight distance of about 2 km and its rainfall record was about 22 mm. The maximum 1-h rainfall amount occurring in the 24-h period prior to the landslide occurrence was <7 mm at rain gauges 24 and 16 (Figure 7). Ma et al. (2015) found that, for a 24-h duration period, the minimum hourly rainfall

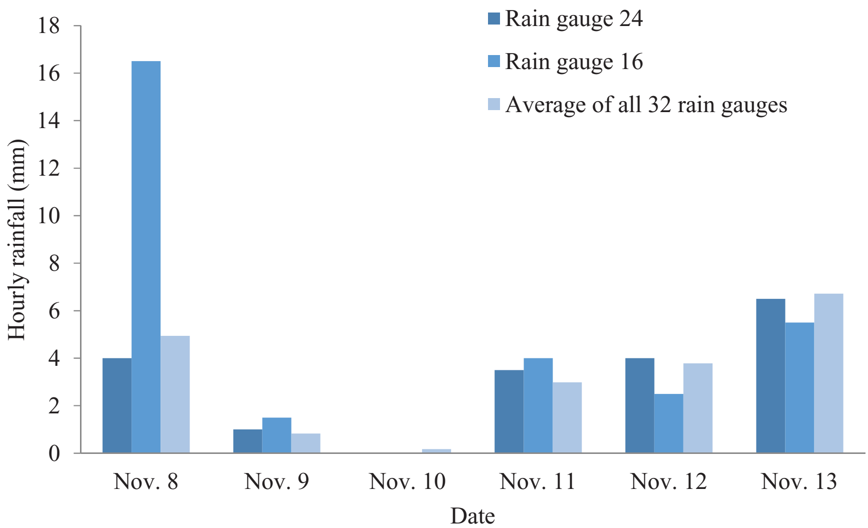

Figure 7. Maximum 1-h rainfall amount in the rolling 24-h duration period registered at rain gauges in the areas surrounding Lidong village landslide during 8–13 November (23:00) 2015.

threshold required to trigger landslides is 29 mm, while the minimum 24-h cumulative rainfall threshold is 169 mm, in the Liandou region (Lishui City, see Table 1 of Ma et al. 2015). Both the maximum hourly intensity and the cumulative rainfall within the 24-h period preceding the Lidong village landslide occurrence are far less than the thresholds observed by Ma et al. (2015). Thus, the rainfall on the day of the Lidong village landslide occurrence alone is not sufficient to cause the slope failure; the initiation of the landslide can be likely associated with a combination of antecedent rainfall and rainfall on the day of the event.

Rainfall measurements at the rain gauges in the areas surrounding the Lidong village landslide showed that the rainfall distribution prior to the landslide occurrence was intermittent. The impact of a particular rainfall event decreases in time owing to discharge and evapotranspiration processes (Canuti et al. 1985; Crozier 1986). In the following discussion, we will inspect the rainfall distribution within two months prior to the Lidong village landslide occurrence. From Figure 8 and Table 1, we can see that, prior to the landslide occurrence, there were roughly four rainfall events in the 59-day period between 16 September and 13 November (23:00). The date of the rainfall events, duration (days), and rainfall amount for each event are listed in Table 2. In the 59-day period, the spatial distribution of the cumulative rainfall recorded at the different rain gauges varies from about 221 to 363 mm (Figure 6(C)).

The maximum 1-h rainfall within the six days prior to the Lidong village landslide (November 8–13) was 17 mm (recorded on November 8, at rain gauge 16, see Figure 7). During the 59-day period between 16 September and 13 November (23:00), the maximum daily rainfall occurred on 7 October, which was, respectively, 49 mm at gage 24, 66 mm at gage16, and 43 mm for an average of all 32 gauges (see Table 1 and Figure 8). If the antecedent rainfall for 7 October, or the antecedent rainfall for 8 November, was enough for the slope failure in the Lidong village, the landslide should occur on 7 October or 8 November, not on 13 November. Available information indicates that no landslides were triggered by the rainfalls in the Lidong village and its surrounding areas around 7 October or 8 November.

It has been recognized in the literature that antecedent rainfall can be a predisposing factor in the activation of rainfall-induced landslides in many regions and several antecedent rainfall models have been proposed to characterize the influence of antecedent rainfall on landslide activity (e.g. Crozier 1986; Wieczorek 1987; Glade et al. 2000; Rahardjo et al. 2001; Aleotti 2004; Gabet et al. 2004; Cardinali et al. 2006; Guzzetti et al. 2007; Li et al. 2011; Ma et al 2014). Nevertheless, for a

Table 1. Daily rainfall registered at different rain gauges in the areas surrounding the Lidong village landslide from 16 September to 13 November (23:00).

	Daily rainfall (mm)		
Date	Rain gauge 24	Rain gauge 16	Average of all 32 rain gauges
16 September 2015	0	0	0
17 September 2015	0	0	0
18 September 2015	0	0	0
19 September 2015	0	0	0
20 September 2015	24	21.5	15
21 September 2015	4.5	7	6
22 September 2015	4	3.5	1.5
23 September 2015	2	5.5	1
24 September 2015	0	0	0
25 September 2015	5	10	3.5
26 September 2015	0	0	0.5
27 September 2015	0	0	0
28 September 2015	5	9.5	6
29 September 2015	22.5	23	19
30 September 2015	13.5	12	18.5
1 October 2015	9	4	10.8
2 October 2015	0	0	0
3 October 2015	0	0	0
4 October 2015	0	0	0
5 October 2015	11	12	13
6 October 2015	11.5	0	7.1
7 October 2015	49	65.5	43.3
8 October 2015	18.5	19.5	17.3
9 October 2015	0.5	3	1
10 October 2015	0	0	0
11 October 2015	0	0	0
12 October 2015	0	0	0
13 October 2015	0	0	0
14 October 2015	0	0	0
15 October 2015	0	0	0
16 October 2015	0	0	0
17 October 2015	0	0	0
18 October 2015	0	0	0
19 October 2015	0	0	0
20 October 2015	0	0	0
21 October 2015	0	0	0
22 October 2015	0	0	0
23 October 2015	0	0	0
24 October 2015	0	0	0
25 October 2015	0	0	0
26 October 2015	0	0	0
27 October 2015	1	2	0.7
28 October 2015	0	0	0.1
29 October 2015	2	10.5	4.9
30 October 2015	12.5	18.5	13.5
31 October 2015	6	10.5	7.8
1 October 2015	16	16	15.7
2 October 2015	0.5	0	0.1
3 October 2015	0	0	0
4 October 2015	1.5	3.5	1.8
5 October 2015	0	1	0.9
6 October 2015	0	0	0.1
7 October 2015	0	0.5	0.1
8 October 2015	13	43	19.1
9 October 2015	2.5	4.5	2.4
10 October 2015	0	0	0.4
11 October 2015	11.5	14.5	12
12 October 2015	18	20.5	20.1
13 October 2015	22.5	22	22.4

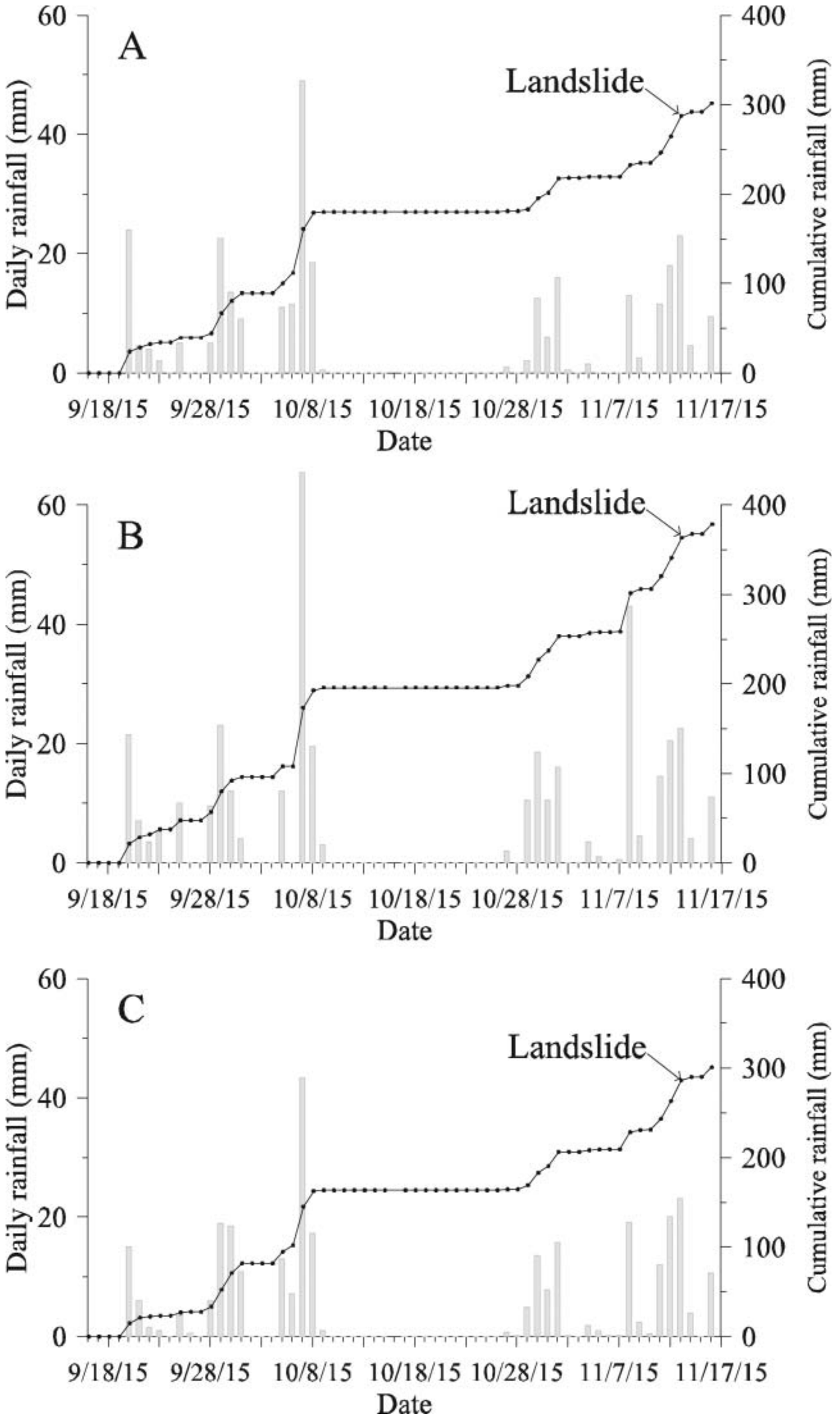

Figure 8. Daily and cumulative rainfall registered at rain gauges in the areas surrounding Lidong village landslide from 16 September to 13 November (23:00) 2015. Histogram indicates the daily rainfall. Curve shows the cumulative rainfall (Right side scale) (A) at rain gauge 24; (B) at rain gauge 16; and (C) an average of all 32 rain gauges.

Table 2. Rainfall events registered at different rain gauges in the areas surrounding the Lidong village landslide from 16 September to 13 November (23:00).

Rainfall event dates	Number of days for rainfall event	Rainfall (mm) at gauge 24	Rainfall (mm) at gauge 16	Average rainfall (mm) at all 32 gauges
20 September–1 October	11	90	96	82
5 October–9 October	6	91	100	82
27 October–4 November	9	40	61	45
8 –13 November (23:00)	6	68	105	76

specified amount of rainfall on the day of a given slope failure, it is often difficult to determine the duration of antecedent rainfall that has the strongest influence on the landslide occurrence. The total amount of rainfall (i.e. antecedent rainfall and event rainfall) required to trigger a slope failure depends on the geometric and geotechnical parameters of the geological materials involved (e.g. strength and permeability properties, the inclination of the topographic surface (slope angle), and the thickness of the saturated zone). It is also not possible to use only rainfall data to make a decision on the length of the time period over which to accumulate the antecedent rainfall needed to trigger the Lidong village landslide.

4.2. Physically based modelling of the slope stability

In the following discussion, the stability of the Lidong village slope is modelled by using the physically based triggering model developed by Montrasio and Valentino (2008). This model is based on the limit equilibrium method and on the infinite slope model.

The applied model defines a direct correlation between the safety factor (F_s) of the slope and the rainfall depth (in terms of the daily or hourly rainfall amount) through the introduction of quantity m, a parameter between 0 and 1, which expresses the relationship between the thickness of the saturated zone (H_{sat}) and the total, potentially unstable thickness (H) ($m = H_{sat}/H$). The parameter m as a function variable over time is correlated with the amount of rainfall within a given time interval (e.g. hourly or daily) and the variation of m at each time interval depends on previous rainfalls (i.e. antecedent rainfall). This model provides the safety factor of a given slope as a function of the time-variable rainfall intensity. The slope is stable if $F_s > 1$, while the failure of the slope occurs when $F_s \leq 1$. The detailed description of the model can be found in Montrasio and Valentino (2008) and Montrasio et al. (2012).

In our modelling, the safety factor of the Lidong village slope was evaluated for the period from 1 January to 14 November 2015. The daily rainfall recorded at rain gage 24, the nearest to the landslide and the average daily rainfall of the five rain gauges closest to the landslide site (i.e. rain gauges 24, 16, 28, 11 and 14, see Figure 6(A) for the location of the gauges) in that period were, respectively, taken as rainfall input data. The geometrical and geotechnical input data, including the slip surface (rupture zone) inclination β, the thickness H of the soil–highly weathered rock on the rupture zone, the thickness H_{sat} of the saturated stratum (which is directly linked to the rainfall depth), the porosity n, the specific weight G_s, the effective friction angle ϕ and the effective cohesion C of the highly weathered rock, and the coefficient K_T of global hydraulic conductivity, are shown in Table 3. The

Table 3. Geometric and geotechnical parameters relative to the computed safety factor[a].

								S_r			
β (°)	H (m)	H_{sat} (m)	n	G_s	Φ(°)	C (kPa)	K_T (s^{-1})	Winter (Nov-Feb)	Spring (Mar-May)	Summer (Jun-Aug)	Autumn (Sep-Oct)
25.5	10	5	0.45	2.7	18.0	27.0	5×10^{-6}	0.9	0.75	0.6	0.75

[a]See Figure 5 for the location of the site of geometric parameters measurements. Source of geotechnical parameters: The No.7 Geological Team of Zhejiang Province (2012).

parameters were obtained from the report done by The No. 7 Geological Team of Zhejiang Province (2012), who carried out a detailed field geological survey in the Lidong village slope and its surrounding areas and did exploration drilling at the slope during the period from August to September 2012.

Moreover, for the application of the model, Montrasio et al. (2012) considered that the degree of saturation (S_r) of the soil varies seasonally. Here, referring to the climatic and geomorphologic settings of the Liandou area, the S_r value of the soil–highly weathered rock mass was considered equal to 0.9 during the winter months (November–February), 0.6 during the summer months (June–August) and 0.75 during the remaining periods (see Table 3).

Figure 9 depicts the trend in time of the safety factor as a function of daily rainfall for the Lidong village slope. We can see from the figure how the model accurately estimates the drastic reduction of the safety factor down to the condition $F_s < 1$ for the landslide site. Figure 9(A) is different from Figure 9(B) in that the former took the daily rainfall recorded at rain gage 24, the nearest to the landslide (see Figure 6(A) for the location of the gauge), as rainfall input data, while the latter used the average daily rainfall of the five rain gauges closest to the landslide site as rainfall input data, which leads to slight difference in the fluctuation of the F_s values between the two figures. In Figure 9(A),

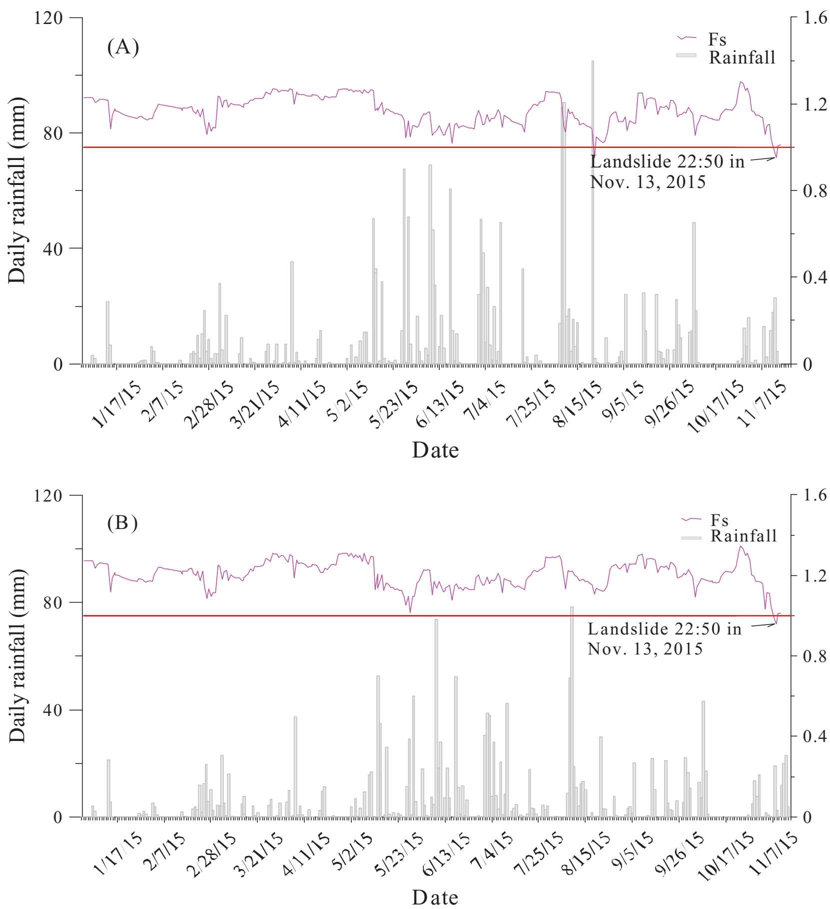

Figure 9. Distribution of the daily rainfall registered at rain gauges in the areas surrounding Lidong village landslide and the safety factor as functions of time for the landslide locality (right side scale) from 1 January to 14 November 2015: (A) daily rainfall registered at rain gauge 24 and (B) average daily rainfall of the five rain gauges nearest rain gauge 24.

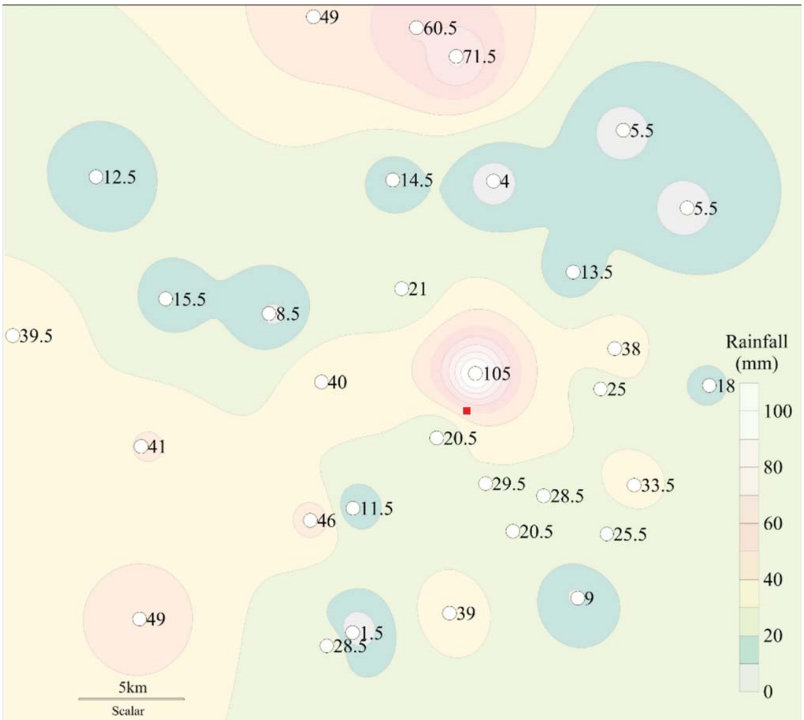

Figure 10. Spatial distribution of the rainfall registered at the rain gauges in the areas surrounding Lidong village landslide on 22 August 2015. White dots are the locations of rain gauges. Numbers beside the white dots denote daily rainfall amount recorded by the rain gauges. The map was created using a weighted average method with the second power of reciprocal of a distance to a given rain gauge.

the safety factor falls below 1 on 22 August and 13 November 2015, and the latter is consistent with the date of the landslide occurrence. While in Figure 9(B), the safety factor falls below 1 only on 13 November, in agreement with the date of the landslide occurrence.

Figure 10 depicts the distribution of the rainfall registered at the 32 rain gauges on 22 August 2015. We see from this figure that, except for rain gauge 24, the daily rainfall recorded at the remaining 31 rain gauges varies from about 2 to72 mm, with an average of 29 mm. At rain gauge 24, the recorded rainfall was 105 mm; this amount is also the maximum daily rainfall for the period between 1 January and 13 November 2015 (see Figure 9). The differences in rainfall amount between rain gauge 24 and its closest rain gauges are between 163% (for rain gauge 14, 40 mm) and 400% (for rain gauge 16, 21 mm), and the average rainfall level of the Lidong village landslide location is about 50 mm (see Figure 10). This implies that the intense rainfall only registered at rain gauge 24 should belong to a local convective event influenced by small-scale topography (Minder et al. 2008), which cannot represent the rainfall conditions at the landslide location on 22 August. Therefore, taking the average daily rainfall of the five rain gauges closest to the landslide as representative of the rainfall condition at the landslide location may be more reasonable in the modelling. Available information indicates that no landslides were observed in the place next to rain gauge 24 around mid-August. This case can be explained as the rainfall level (antecedent rainfall and event rainfall) is less than that needed to trigger the slope failure. The factors affecting landslide susceptibility in an area, for instance, rock types, soil properties, topography etc. vary spatially and rainfall thresholds for landslide occurrence also vary from place to place, depending on variations of these factors in the area (Li et al. 2010).

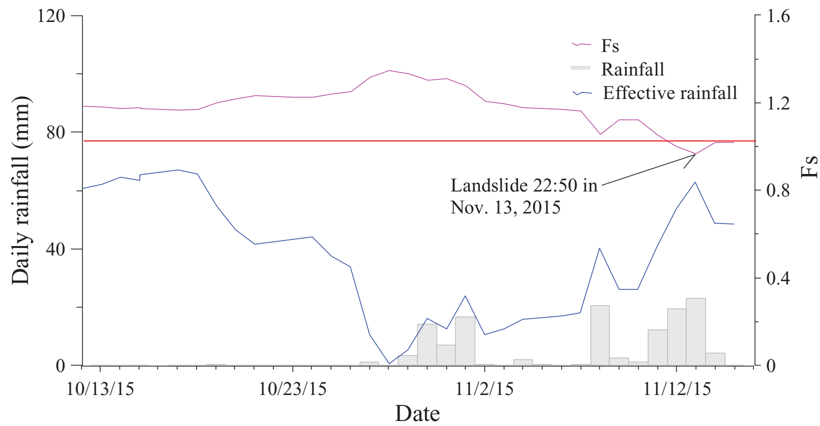

Figure 11. Distribution of the effective antecedent rainfall (blue curve) within the 30 days prior to the Lidong village landslide occurrence (Left side scale). The effective antecedent rainfall is derived from the average daily rainfall of the five rain gauges closest to the landslide site using PLR model with scaling exponent $\alpha = 0.20$ (see Equation (9) of Ma et al. 2014). Red curve shows the safety factor. Histogram shows the daily rainfall.

Because of discharge and evapotranspiration processes, the impact of a particular rainfall event decreases in time (Canuti et al. 1985; Crozier 1986). Only the amount of water infiltrating into hill slopes during a rainfall preceding landslide event rainfall can be associated with the landslide activity; the rainwater infiltrating into hill slopes preceding a landslide occurrence is defined as the effective antecedent rainfall that has an impact on the initiation of the landslide (Ma et al. 2014). A model (PLR, power-law relation of landslide occurrence and rainfall level) accounting for the effective antecedent rainfall was developed by Ma et al. (2014) based on the power–law relationship between the frequency of landslide occurrence and the landslide-triggering rainfall level in the Zhejiang region. The detailed description of the model can be found in Ma et al. (2014). Figure 11 shows within the 30 days prior to the Lidong village landslide occurrence the distribution of the effective antecedent rainfall derived from the average daily rainfall of the five rain gauges closest to the landslide site using the PLR model. From the figure we can see that, after a rainless period of 19 days (10–28 October refer to Table 1), the effective rainfall prior to 28 October had been attenuated to near zero by that day. While from 28 October onwards, the effective rainfall increased fluctuantly and reached its maximum on 13 November, corresponding to the fall ($F_s < 1$) in the safety factor. Consequently, the initiation of the Lidong village landslide can be considered to be related with a combination of the 15-day antecedent rainfall and the rainfall on the day of the failure after a long period of intermittent rainfall progressively weakened the slope. This also suggests that for a potential unstable slope with increasingly wet antecedent conditions, very low daily rainfall may be able to trigger landslides on a given day.

5. Conclusions

A landslide in the Lidong village of Liandou District, Zhejiang Province occurred on 13 November 2015 on the slope that had been identified as unstable in 2012. In this slope, the rupture zone that has the dip direction coinciding with the slope aspect formed between the highly weathered volcanic rock and the underlying weathered volcanic rock. Some of the existing cracks in the surface are likely extended from the surface to the rupture zone, suggesting that the slope was predisposed to failure before the landslide on 13 November 2015.

In the Liandou area, the monthly rainfall from July to December 2015 was evidently higher than the mean monthly rainfall for the same period of a normal year. Especially, the cumulative rainfall in October and November was, respectively, 168% and 235% of the mean monthly rainfall for the area. However, it is worth mentioning that because the maximum hourly rainfall occurring in the 24-h period prior to the Lidong village landslide occurrence was low (<7 mm) and the daily rainfall was low (<26 mm), the antecedent rainfall must play an important role in landslide occurrence. A simulation of the correlation between the safety factor of the slope and the rainfall level using the physically based triggering model that was employed by Montrasi and Valentino (2008), combining analysis of the effective antecedent rainfall, showed that the initiation of the landslide can be associated with a combination of the accumulated antecedent rainfall of 15 days and the rainfall on the day of the event. This indicates that under wet antecedent conditions, very low daily rainfall may be able to trigger landslides on a given day. This result is important for improving landslide warning system based on the rainfall–landslide relationship.

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