Landslides (2013) 10:219–230
DOI 10.1007/s10346-012-0362-4
Received: 11 April 2012
Accepted: 2 October 2012
Published online: 17 October 2012

Do Minh Duc

Rainfall-triggered large landslides on 15 December 2005 in Van Canh District, Binh Dinh Province, Vietnam

Abstract Landslides are one of the most dangerous hazards in Vietnam. Most landslides occur at excavated slopes, and natural slope failures are rare in the country. However, the volume of natural slope failures can be very significant and can badly affect large areas. After a long period of heavy rainfall in the fourth quarter of 2005 in Van Canh district, a series of landslides with volumes of 20,000–195,000m^3 occurred on 15 December 2005. The travel distances for the landslides reached over 300–400m, and the landslides caused some remarkable loud booming noises. The failures took place on natural slopes with unfavorable geological settings and slope angles of 28–31°. The rainfall in the fourth quarter of 2005 is estimated to have a return period of 100years and was the main triggering factor. Because of the large affected area and low population density, resettling people from the dangerous landslide-prone residential areas to safer sites was the most appropriate solution. In order to do so, a map of landslide susceptibility was produced that took into account slope angle, distance to faults, and slope aspect. The map includes four levels from low to very high susceptibility to landslides.

Keywords Large landslide · Rainfall · Fault · Landslide susceptibility · Vietnam

Introduction

Landslides globally cause major disasters every year and rank seventh as a cause of numbers of people killed by natural disasters during the period of 1992–2001 (Nadim et al. 2006). Currently, the number of disastrous landslides appears to be increasing (Schuster and Highland 2007). Landslides are among the most dangerous geohazards in Vietnam, causing annual damage of nearly 100 million dollars (US) (Tam 2001). Extensive landsliding often takes place during tropical cyclones. Most of these landslides occur on excavated slopes, especially along the national highways such as No. 2, No. 3, No. 6, and the Hochiminh route. Natural slope failures are rarely recorded, as they often occur in remote areas and do not come to the attention of the community. A change of climate in recent years has gradually brought increasing problems, as extreme climate events (typhoons, storms, and tropical depressions) happen more often, and with higher intensity. The amount of heavy rainfall in these extreme events also breaks existing records more frequently. The figure of the 10-year, 50-year, or even a century return period in some areas can appear year by year. Many large landslides have taken place on slopes that were for a long time considered as stable ones (Duc 2010).

This paper presents characteristics of a rainfall-triggered natural slope failure in Vietnam using a case study of the southwest Van Canh district (30 km from the Van Canh town), Binh Dinh province (Fig. 1). The study area is about 100 km^2. Here, after a long period of heavy rainfall, a series of landslides occurred in many places in several communes on 15 December 2005. Landslides blocked local routes for several weeks. One large landslide occurred at the mountain of Lang Chom commune; no people were injured, but it killed four farm animals and buried some rice fields. Some of the landslides were accompanied by loud booming noises, a fact that scared some nearby residents and made them very nervous.

In this study, the geological and geomorphologic settings, weathering crust, geotechnical properties of residual soils, and their relationships to landslides were investigated. Then a map of landslide susceptibility was created to provide initial information for resettling people from dangerous landslide-prone residential areas to safer locations.

Materials and Methods

The data used in the study included a topographical map at a scale of 1:10,000, a geological map at a scale of 1:50,000, and daily rainfall monitored from 1976 to 2010 at a hydrological station in Van Canh town. Additional data were mainly gathered from site investigations in Van Canh district that were carried out in August 2006 and June 2007. These investigations included the geological settings, characteristics of weathering crust, geotechnical properties of soils and rocks, and landslide properties. Detailed investigations were carried out at over 16 km^2 at Lang Chom commune and adjacent areas where the three largest landslides occurred. Electrical resistivity was measured along six sections and a geological map at the scale of 1:10,000 was made.

All maps (topography and geology) were then digitized so that a map of landslide susceptibility could be digitally produced by overlaying factors affecting landslide susceptibility, including slope angle, distance to faults, and slope aspect using ILWIS—a GIS-based software. Thematic maps of slope angle and aspect were created from topographical maps (details are available in ILWIS 3.0 Academic User's Guide 2001). The distance from faults was determined from geological maps. Slope angles were categorized through stability analysis using the infinite-slope-analysis method (Duncan 1996).

Field investigations

Field investigations were carried out in August 2006 and in June 2007. The following data were recorded for each investigation point.

a. Geographical location was determined using a Garmin GPS (GPS 72) with an accuracy of about 5–10 m.
b. Angles and heights of slopes were measured, and the description of a landslide included further information such as slope angles of adjacent areas, upper and lower length of landslide, thickness of the sliding mass, and characteristics of the slip surface. These data were then used to calculate areas of cross-sections at various parts of the landslide. The landslide volume was estimated as the product of average area of cross-sections and length of the landslide. The date the landslide occurred was determined by the author after conversations with local authorities and residents.
c. Geological descriptions included lithological composition, color and initial classification of rocks, bedding surfaces, dip angles, fault, and joint systems.

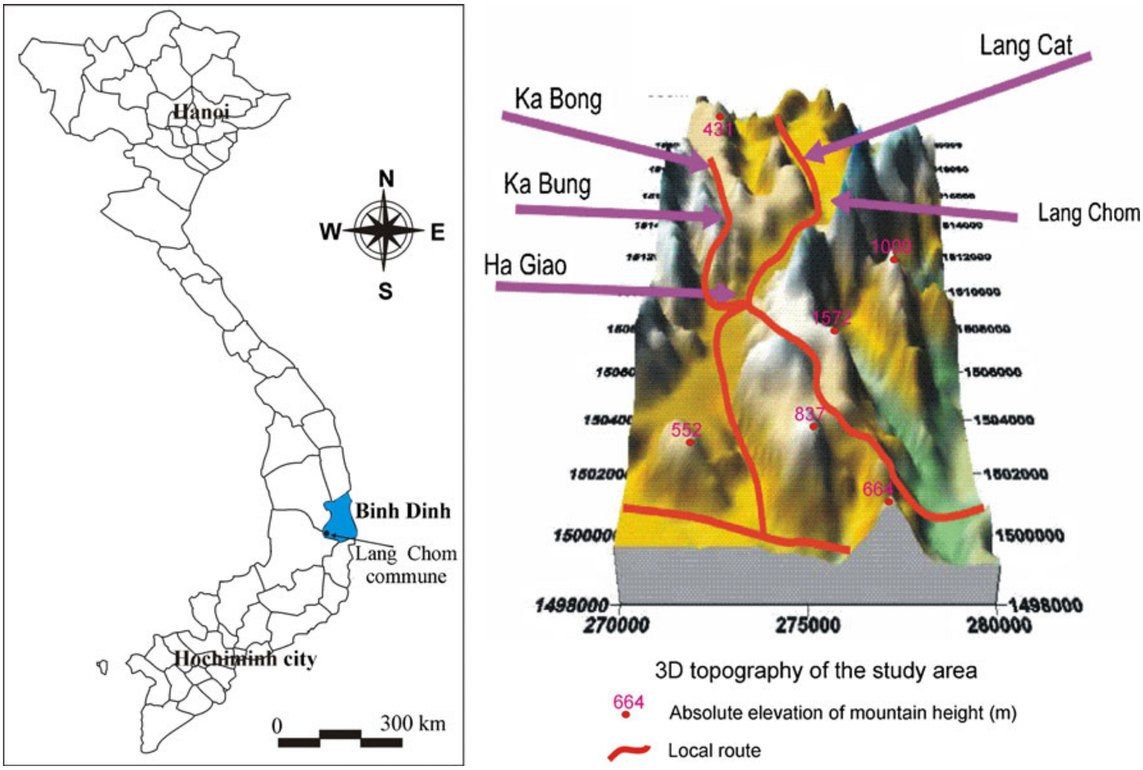

Fig. 1 Study area

d. Residual soil descriptions included the thickness and distribution of the residual soil layers. Each layer was described in terms of soil composition, color, moisture, and consistency.
e. Surface and groundwater observations included gullies, streams on the slope, and existence and discharge of groundwater at the slope (if any). Groundwater level was measured in adjacent wells of local residents, including information based on conversations with the owners about seasonal discharge and water-level changes.
f. Vegetation coverage information included types of trees and brush, density of coverage, and comparison with adjacent areas.

Laboratory testing

Undisturbed soil samples were taken at the landslides; the depths of sampling were 0.2–0.5 m. Thirteen samples were retrieved at three large landslides, with samples taken at the landslide main scarp, body, and foot. At each smaller landslide, one or two samples were also taken. Soil samples subsequently were analyzed in the laboratory to define geotechnical properties. The tests were performed according to the specifications of ASTM (American Society for Testing and Materials). A modification was made for analysis of grain-size distribution, in which all steps followed ASTM D-422 (2001a), but the diameters of sieves were 20, 10, 4.75, 2, 1.0, 0.5, 0.25, and 0.074 mm. Soils are classified by the Unified Soil Classification System (USCS—ASTM D 2487 (2001b)).

Rainfall data

The rainy season in Binh Dinh province is from September to December, with the highest monthly rainfall normally in October and November (Table 1). The rainfall is often concentrated during the period of extreme climate events such as tropical cyclones. About 45 % of these events can lead to rainfall of 200–300 mm; 20 % of the events induce rainfall of over 300 mm. The time of heavy rain is commonly 2–3 days. However, when a storm or tropical depression occurs during the period of cold northeast wind, the time of heavy rain can extend to 3–5 days and the total rainfall can reach to 300–700 mm. To investigate rainfall-triggered large landslides on 15 December 2005, records of daily rainfall for the year 2005 in Van Canh town monitoring station were used. The station is 30 km away from the area of the landslides and is the closest station to the landslide area. The whole area of Van Canh district is considered to be uniform area in term of climate (Huong 2004). Therefore, the data is assumed to be acceptable for assessing rainfall-triggered landslides.

Table 1 Average monthly rainfall in Van Canh district (Huong 2004)

Month	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Total
Rainfall (mm)	33	18	31	43	138	97	83	78	210	560	571	251	2,113

Geophysical investigation

The main purpose of geophysical investigation is to provide more information for assessing landslide susceptibility around current residential areas and tentative sites for resettlement. It was designed to include information on layering of the weathering crust, and especially to define potential slip surfaces, which are tentatively assumed to be fault and/or joint planes, and interfaces between residual soils and/or high fractured rocks with intact bedrock.

Electrical resistivity measurements were carried out from 30 January to 28 February 2007. The maximum distance of electrodes (ABmax) is 140 m, which allowed us to investigate materials up to a depth of about 50 m. Six sections were measured, which are abbreviated as T.1, T.2, T.3, T.4, T.5, and T.6, respectively (Fig. 2). Each section is 450 m long. A total of 60 measuring points were included. Sections T1, T2, and T3 are designed to cut through the Ba mountain fault. Section T2, together with T3 and T4, are also for assessing landslide hazard at the hillside close to the main residential area of Lang Chom commune. T5 and T6 are for landslide hazard assessment in the tentative resettlement areas.

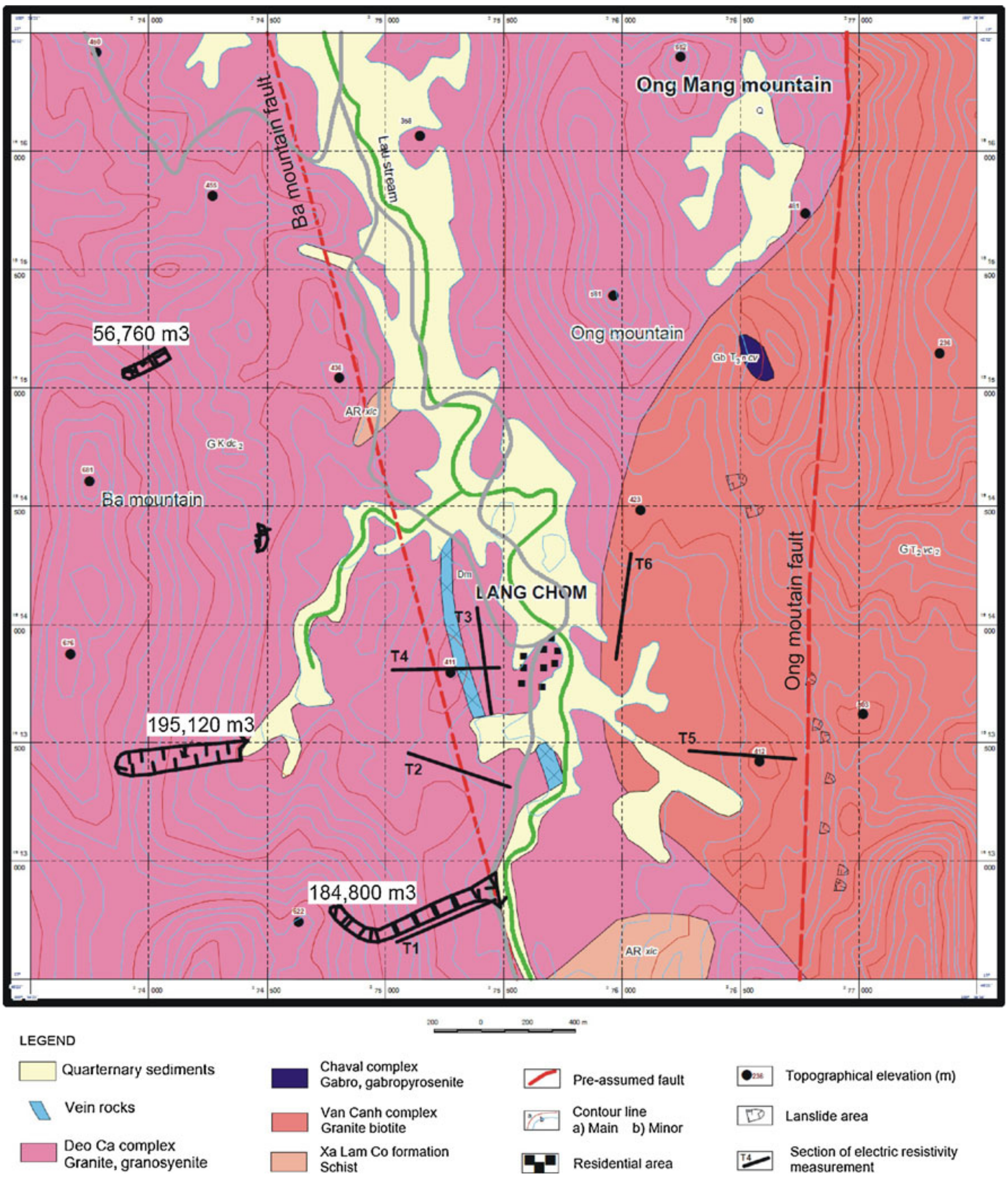

Fig. 2 Geological map of Lang Chom commune (detail investigation)

Results and Discussion

Geological and geomorphologic settings

The geological settings of the study area are rather complicated and are characterized by three formations: the Xa Lam Co (AR*xlc*), Mang Yang (T_2my), and Quaternary (Q), and four complexes, including Van Canh (T_2vc), Chaval (T_3ncv), Deo Ca (K*dc*), and Cu Mong (E*cm*). A small portion of the area of detailed investigation in Lang Chom commune also has two formations (AR*xlc* and Q) and three complexes (T_2vc, T_3ncv, and K*dc*; Fig. 2). Geological activity has led to a significant topographical differentiation. The mountain heights can reach to the elevations of over 1,500 m (Fig. 1), meanwhile the elevations at some places are lower than 200 m, such as northeast part of Lang Chom (Fig. 2). The topography is also characterized by many slopes with steep angles (Fig. 3). The topography includes three types, including erosional, abrasive-erosional, and accretion relief. The area with erosional relief is small and is underlain by volcano-clastic rocks of the Mang Yang formation (T_2my). It occurs at elevations of 700–1,000 m; the slope angle is 45–75°. The area with abrasive-erosional relief is dominant and is underlain by granite of the Van Canh (T_2vc), diorite of Dinh Quan (J_3dq), and granite of Deo Ca (K*dc*) complexes; metamorphic rocks of the Xa Lam Co formation (AR*xlc*); and extrusive sedimentary rocks of the Mang Yang (T_2my) in some small areas. This relief types occurs at elevations of 250–700 m; the slope angle is 10–45°. Accretion relief occurs as small stripes along streams in the study area. Along the local routes, excavated slopes are very steep, with slope angles of 60–75°.

Faults of north–south and northeast–southwest oriented are dominant. The northeast–southwest oriented Ong mountain fault is a normal fault. A new fault was discovered during the detail investigation of geological settings, named the Ba mountain fault. It is a normal fault with strike of 165–345° and dip angle of 45° (Fig. 2). The fault system, especially the 165–345° fault leads to many cracked blocks of bedrock which accelerates the weathering process that can make conditions suitable for the sliding of large rock and soil masses. Fault planes even form the slip surfaces of some large landslides (details in "Landslide properties").

Weathering crust

Tropical climate conditions lead to intensive weathering of bedrock in the study area. The landslides mainly take place in the weathering crust of the granite and granosyenite of the

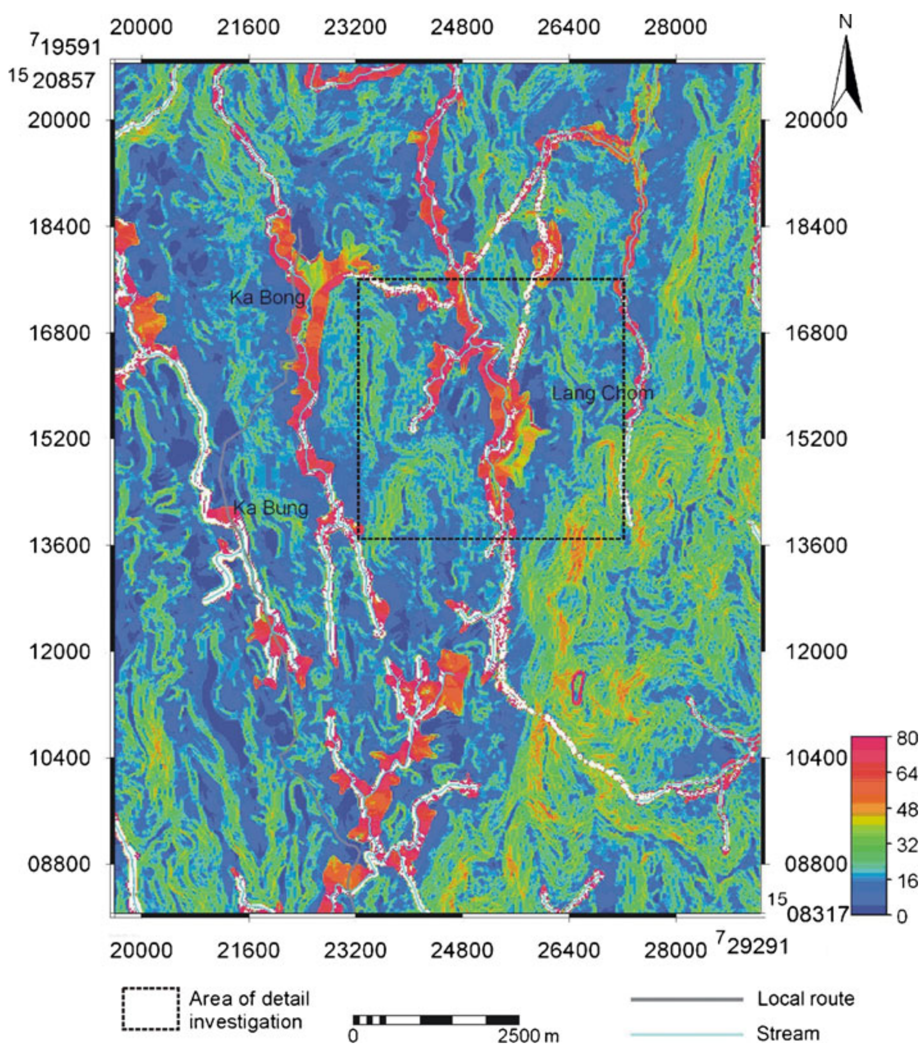

Fig. 3 Slope angles (in degree) of Van Canh district

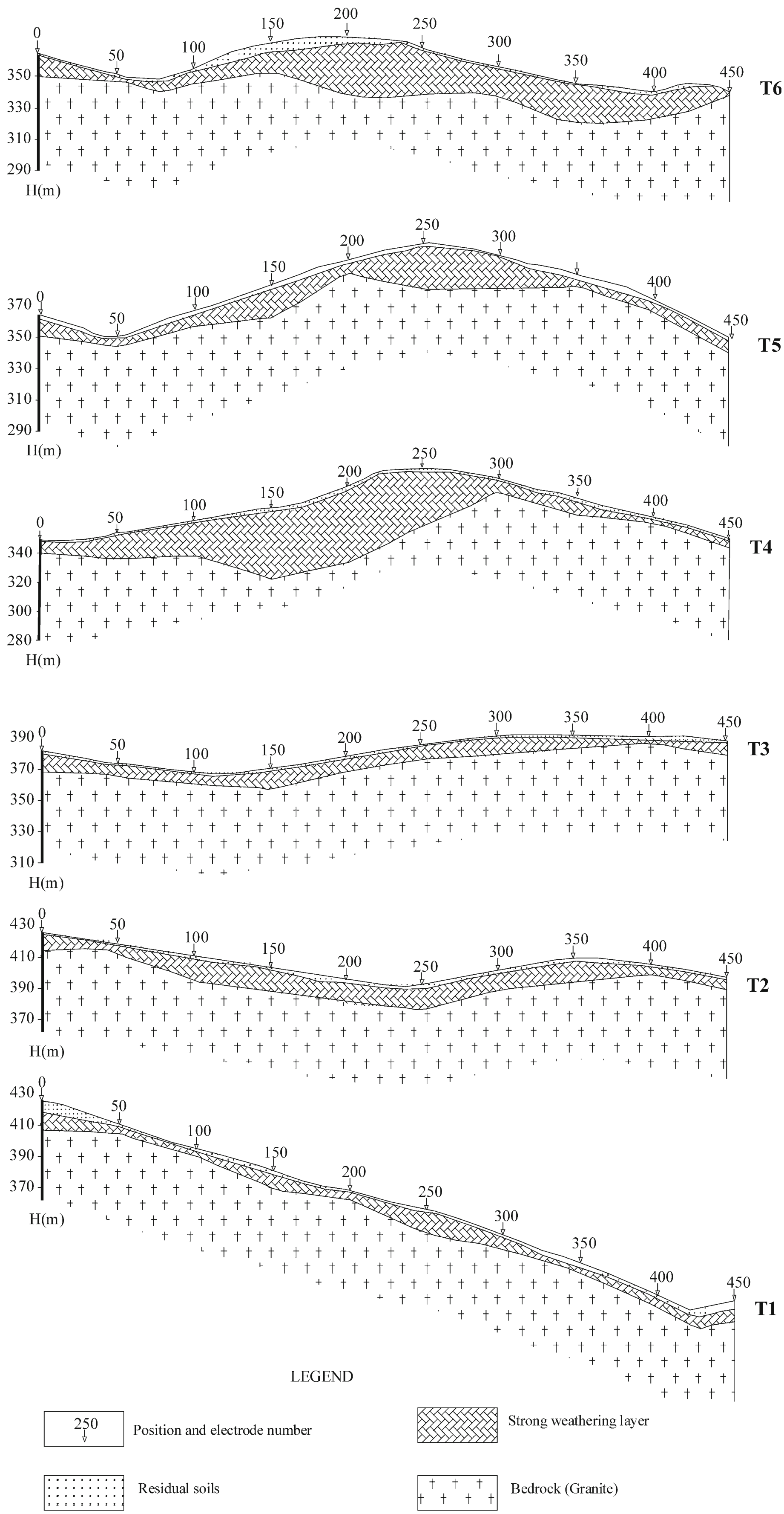

Fig. 4 Weathering crust (defined by electric resistivity measurement)

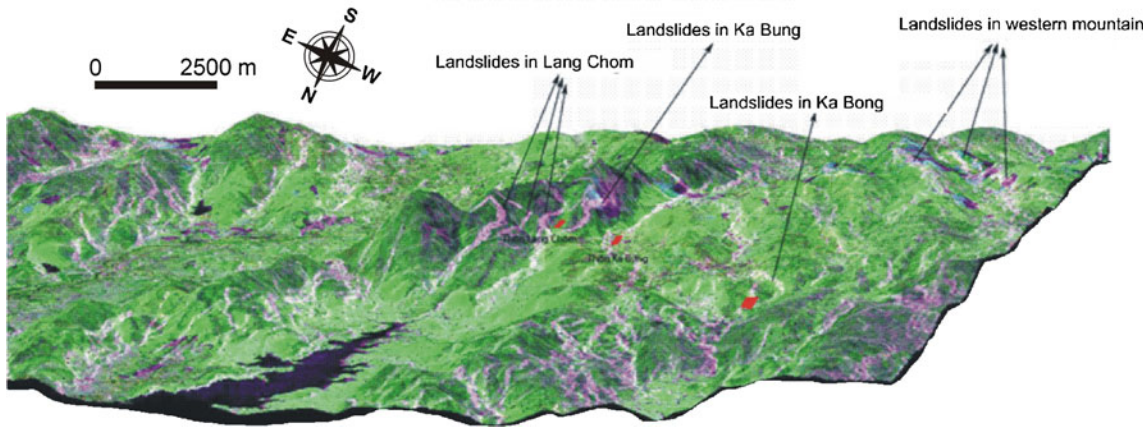

Fig. 5 Landslides in Van Canh district in December 2005 (interpretation of PALSAR satellite image on the third of November 2009) (revised from Ha 2011)

Deo Ca complex. The crust has three layers of soils and rocks (Fig. 4).

- The upper layer is residual soils which are classified as silt (ML), clayey sand (SC), and well-graded sand (SW). The thickness varies from 0.5 to 6.2 m. The layer has resistivity ranging from 174 to 4,136 Ωm. This layer is covered by trees, *Acacia mangium*, at a medium density. The trees are cut and replanted every 3 years for the paper industry.
- The second layer is fractured and strongly weathered bedrock with a resistivity of 62–6,318 Ωm. The thickness varies over a large range: from 1.2 to 50.6 m (Fig. 4), greater thicknesses occur at fault zones and above vein rocks.
- The lower layer is intact bedrock with a resistivity of 1,168–50,175 Ωm.

Landslide properties

The three largest landslides took place in Lang Chom commune and had volumes of 56,760, 184,800, and 195,120 m^3, respectively (Figs. 5 and 6). The landslides were accompanied by remarkable loud noises. The landslide slip surface has two parts. The upper surface is in residual soils and has an arc shape. The height of this part is 3–6 m. The main part of slip surface is the fault plane of the Ba mountain fault (Fig. 6). The figure shows that fault plane is the interface between intact rocks and weathering soils, sheared rocks in the landslide body. Residual soils are weathered from rocks of the Deo Ca complex and have a thickness of 4–6 m. The slope angles are 27–32°. Numerous granite boulders of about 10 m^3 were transported downslope along a distance of hundreds of meters (Fig. 6). Sliding debris from the landslides destroyed a local road segment and filled up the Lau stream, causing an increase of

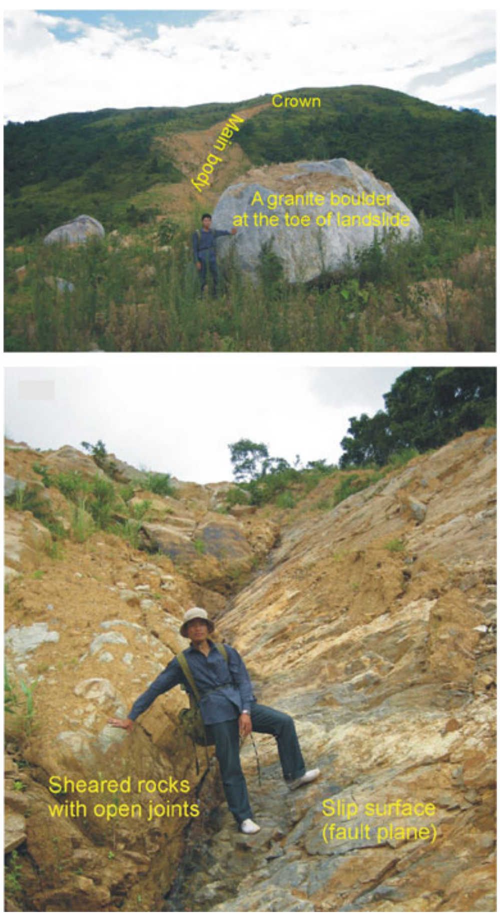

Fig. 6 A large landslide in Lang Chom commune

Fig. 7 Landslides in Ka Bung commune

Table 2 Geotechnical properties of residual soils

Soil type Property	Residual soils from different bedrocks SC (Xa Lam Co formation)	SW (Van Canh complex)	ML (Deo Ca complex)
Number of test	5	2	13
Grain sizes (%)			
5–10 mm	1.5 (1–5.6)	0	0.5 (1–4)
2–5 mm	6.2 (4–10.6)	1.0 (0–2)	6.7 (1.5–11)
1–2 mm	8.4 (6–11)	7.0 (2–12)	8.9 (5–15)
0.5–1 mm	14.2 (12–17)	19.5 (5–34)	15.8 (11–22)
0.25–0.5 mm	17.3 (11–22)	30	15.8 (10–30)
0.1–0.25 mm	14.6 (7–34.5)	31.5 (18–45)	7.7 (2.8–10)
>0.1 mm	37.8 (12.5–47)	11.0 (4–18)	44.6 (39–56)
Water content (%)	20.2 (18–24)	19.3 (18.5–20)	19.6 (13–25)
Wet density (g/cm^3)	1.84 (1.66–1.92)	1.68 (1.64–1.72)	1.87 (1.78–1.94)
Dry density (g/cm^3)	1.53 (1.34–1.62)	1.41 (1.37–1.45)	1.56 (1.47–1.68)
Specific gravity (g/cm^3)	2.71 (2.7–2.72)	2.68 (2.66–2.7)	2.73 (2.7–3.7)
Void ratio	0.77 (0.668–0.017)	0.90 (0.86–0.95)	0.75 (0.606–1.399)
Porosity (%)	43.34 (40–44.6)	47.43 (46.2–48.6)	42.67 (37.7–53.8)
Saturated degree (%)	71.4 (63.7–78.8)	57.1 (56.2–58.1)	71.6 (47.6–85.5)
Liquid limit (%)	45.5 (31–56)		50.9 (31–77)
Plastic limit (%)	30.4 (23.6–36.1)		31.9 (23.6–49)
Plasticity index	15.1 (6.5–21.6)		19.16 (7.4–28.1)
Consistency	−0.61 (−1.12÷−0.08)		−0.63 (−0.73÷−0.37)
Hydraulic conductivity (m/s)	2×10^{-5}	5×10^{-5}	3×10^{-6}
Angle of internal friction (deg.)	28.1 (26.6–30.8)	32.5	28.8 (24.6–33.3)
Cohesion (KPa)	16.4 (11–21)	5.0	15.2 (10–25)

28.1 (26.6–30.8)—average (minimum–maximum)

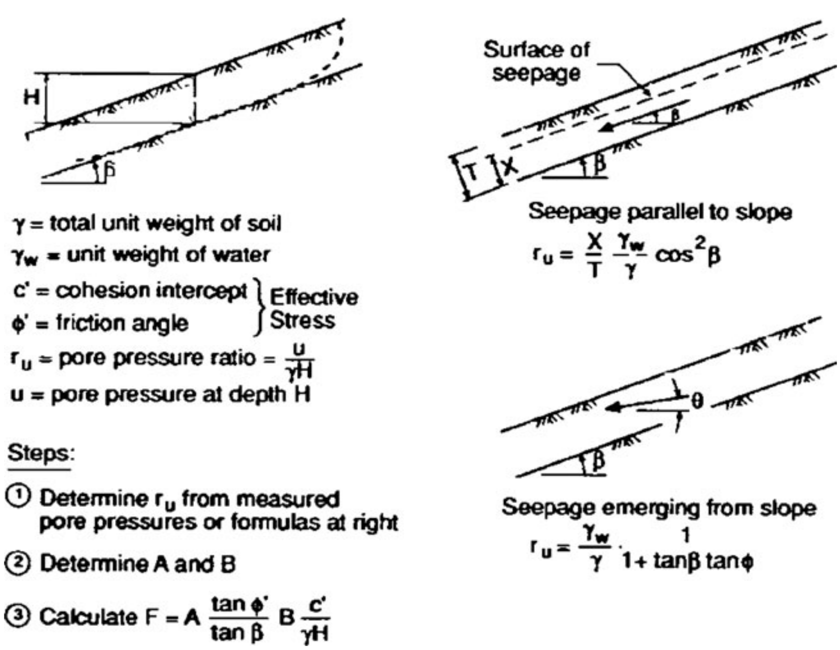

Fig. 8 Illustration of infinite-slope-analysis method (taken from Duncan 1996)

2–3 m in the stream water level (per communication with local people). Fortunately, there were no debris flows due this phenomenon.

At the same time, in Ka Bung commune (the opposite site of the mountain), there was a series of large landslides (Figs. 5 and 7). The thickness of residual soils in these landslides is 6–9 m and slope angles are 28–32°. The average volume of these landslides is 20,500 m^3. The landslides took place far from residential areas and did not cause any fatalities. Many other landslides and rockfalls were also triggered by rainfall along local routes and on rocky mountains with steep slopes on 15 December 2005.

Geotechnical properties of residual soils and stability analysis
Based upon the results of laboratory testing, the residual soils were classified into three types: silt (ML), clayey sand (SC), and well-graded sand (SW). Silt and clayey sand are dominant in the residual soils of the Deo Ca complex and the Mang Yang, Xa Lam Co formations. Well-graded sands are common in the weathering crust of the Van Canh complex. The geotechnical properties of the soils are shown in Table 2.

As can be seen in Table 2, residual soils of clayey sand and silt have a rather high natural degree of saturation (almost above 70 %), although samples were taken in the dry season. The main reason for this is the frequently high atmospheric moisture. Such

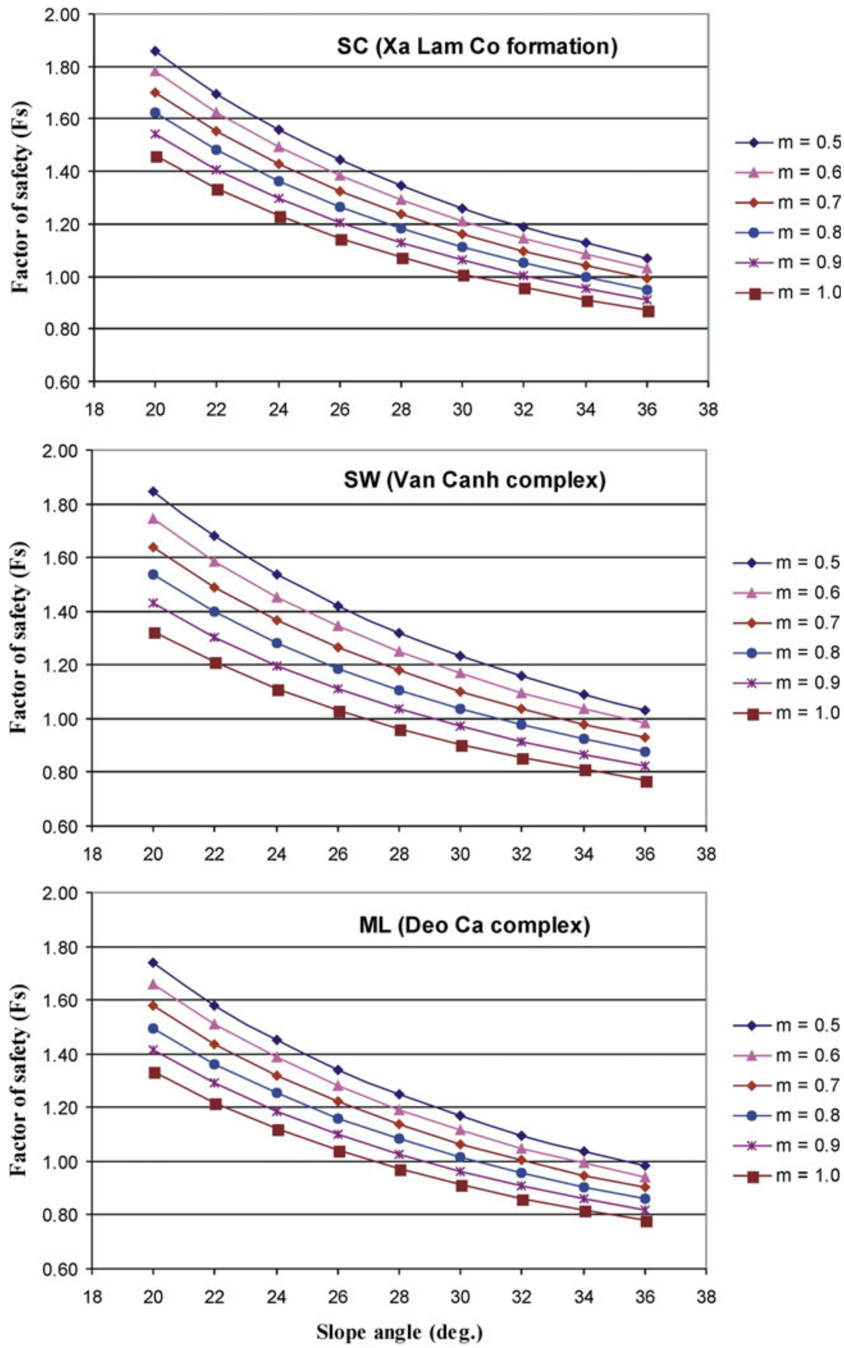

Fig. 9 Relationships between slope angle, saturated fraction, and factor of safety for various residual soils

Table 3 Monthly rainfall in Van Canh with different return frequency (mm) (Huong 2004)

Month	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
P=5 %	112	65	130	128	276	212	183	184	410	1,015	1,132	656
10	79	49	91	103	233	183	158	153	358	891	987	537
20	49	33	54	76	188	150	128	121	299	754	822	410
25	40	28	43	67	173	138	118	109	278	705	763	366
50	18	12	13	35	123	92	78	69	199	528	541	213
75	11	2	0	11	86	51	44	36	131	380	347	94
80	10	0	0	6	79	41	36	29	115	347	303	69
90	10	0	0	0	63	17	16	13	77	268	194	13
95	9	0	0	0	54	1	1	2	48	211	111	1

permanent saturation may reduce the effect of rainfall as a trigger of slides. Saturated hydraulic conductivities of the soils ranged from 3×10^{-6} to 5×10^{-5}m/s in the most torrential rains, which occurred on 23 and 27 October 2005, the maximum rain intensity was 12 mm/h (equivalent to about 3×10^{-6}m/s). Thus conductivities are rather high in comparison to rain intensity in the study area, and rainwater can easily infiltrate into the slopes, increasing the degree of saturation of the soils, and reducing slope stability.

The infinite-slope-analysis method was employed for the stability analysis. It quantitatively analyzes the effect of soil saturation on the stability of those slopes where potential for translational slides exists (Duncan 1996). The analysis assumes the slip surfaces are long compared to their depth, and it ignores the driving force at the upper end of the sliding mass and the resisting force at the lower end (Fig. 8). The method requires a procedure with three steps:

1. Determination of the factor of safety (Fs) using the following equation:

$$\mathrm{Fs} = \mathrm{A}(\tan\varphi'/\tan\alpha) + \mathrm{B}(\mathrm{c}'/\gamma/\mathrm{H})$$

where H is the depth of soil measured vertically from the slope surface to the surface of sliding; φ' and c' are the effective strength parameters; α is the slope angle; and γ is soil density.

2. Determination of parameters A and B from the following equations:

$$A=1-(r_u/\cos^2\alpha)$$

$$B=1/(\sin\alpha\cdot\cos\alpha)$$

where parameter A accounts for the pore pressure acting normal to the sliding surface and parameter B accounts for the shear resistance along the sliding surface.

3. Determination of r_u, the pore pressure ratio, as follows:

$$r_u=(X/T)(\gamma_w/\gamma)(\cos^2\alpha)$$

where X is the thickness of the soil mantle that is saturated, T is the total thickness of the residual soil mantle, and γ_w and γ are the water and soil densities, respectively.

Based upon field observations made during this study, seepage was considered to occur parallel to the slope face. In the analysis, the saturated fraction of soil mantle ($m=X/T$) was considered to range from 0.5 to 1. Three types of residual soils (clayey sand, well-graded sand, and silt) are taken into the calculation. As observed at the recorded landslides, depths from the slope surface to the surface of sliding (H) in the soils of clayey sand, well-graded sand, and silt are 3.5, 1.5, and 4.0 m, respectively. Strength parameters are average values of φ' and c' (Table 2).

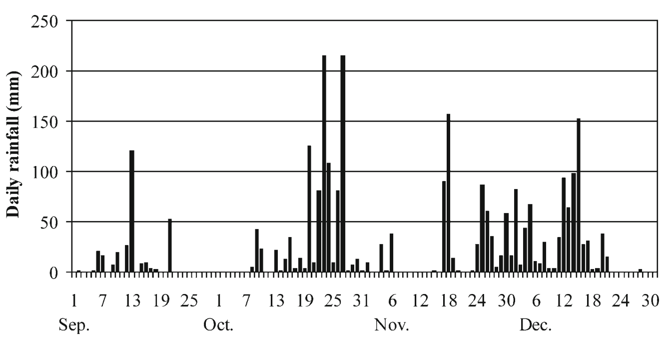

Fig. 10 Rainfall from 01 September 2005 to 31 December 2005

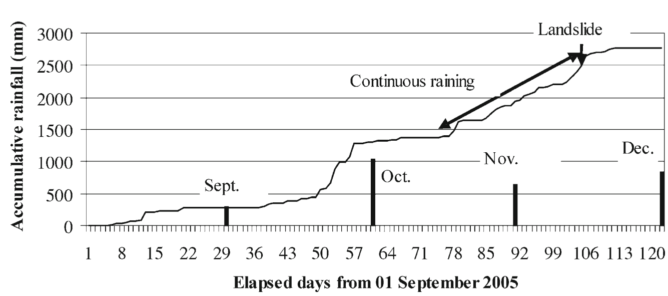

Fig. 11 Monthly and accumulative rainfall

Table 4 Affecting factors and scores of landslide susceptibility

Factor Susceptibility	Slope angle	Distance to fault (m)	Slope aspect[a]	Factor score	Total score
Low	<20°	>1,000	>20°	0	0–2
Medium	20–28°	500–1,000	10–20°	1	3–4
High	28–36°	250–500	<10°	2	5–6
Very high	>36°	<250		3	7–8

[a] The absolute difference between strikes of slope face and fault plane

The results are shown in Fig. 9 and display the relationships between Fs and slope angle at various values of saturated fraction (m). As can be seen in Fig. 9, a slope of well-graded sand and silt at an angle of more than 28° is unstable when fully saturated, meanwhile a 36° slope can fail if half of the soil mantle is saturated. Meanwhile, a saturated slope of clayey sand is unstable at an angle of more than 30°. The results match well with actual observations, where failures occurred at slope angles of 28–31°. However, the phenomenon of rainfall-induced slope failure depends not only on soil properties but also on topographical and geological characteristics which contribute to the existence of a potential sliding surface.

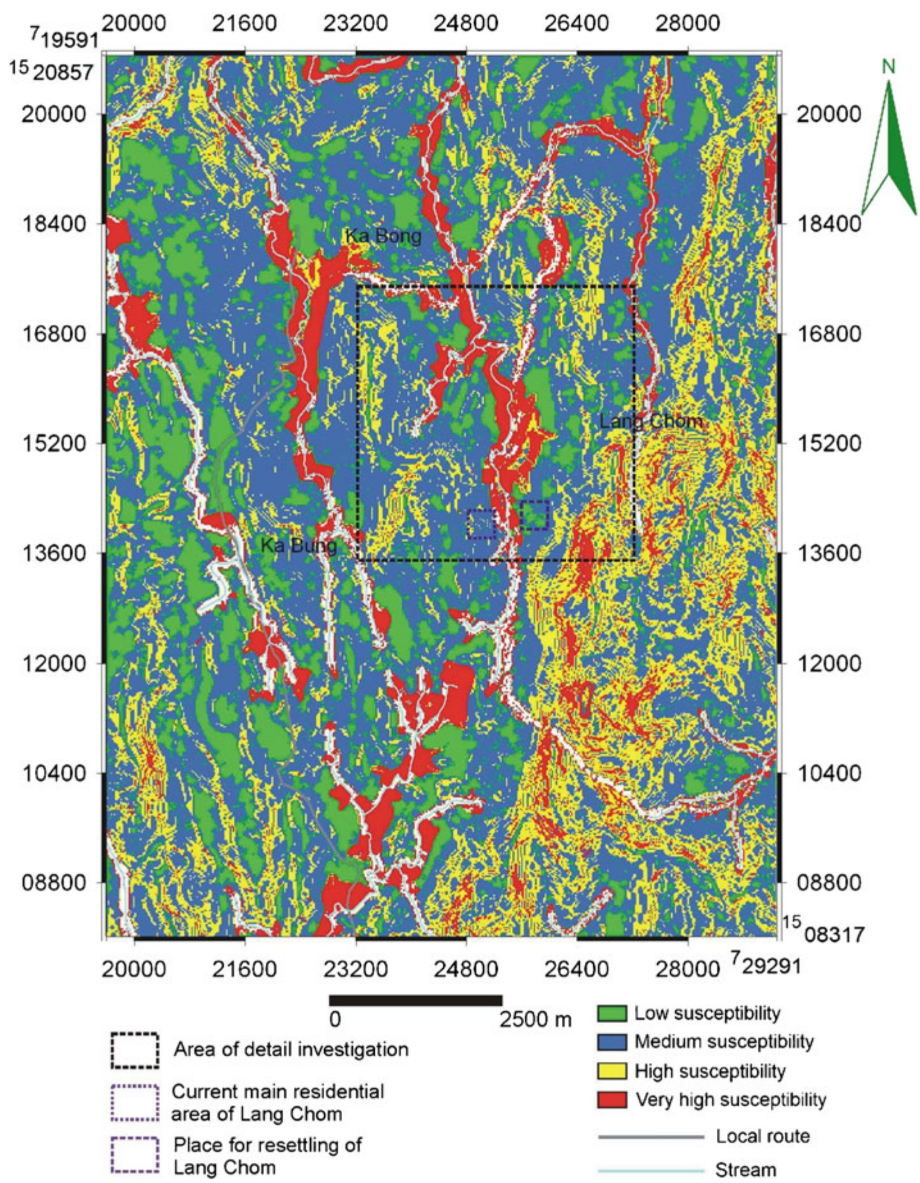

Fig. 12 Landslide susceptibility

Landslides triggered by heavy rainfall

To determine an empirical relationship between rainfall and landslides, the daily rainfall data from September to December 2005 was taken into account. Total rainfall in September 2005 was 287.3 mm, a normal figure in comparison to other years. In October 2005, the figure was 1,016.8 mm which is larger than the normalized rainfall with a frequency of 5 % (1,015 mm, Table 3). Therefore the rainfall in October 2005 was above the value for a 20-year return period. The number of rainy days in this month was 20 days continuously. In particular, the rainfall in 3 days (23–25 October) reached to a total of 566.5 mm (Fig. 10). However, no large landslides occurred during that month. The rainfall in November and December 2005 was 627.6 and 829.0 mm, respectively (Fig. 11). The rainfall in November 2005 is also a normal event. But the rainfall for December 2005 is very remarkable, and has a return period of 50 years. Therefore, all of the large landslides occurred in a month with an extraordinary high amount of rainfall. The unusual high amounts of rainfall in October and December make a total rainfall of 2,766 mm in the fourth quarter of 2005 which is likely to have a return period of 100 years.

The above results show that the landslides occurred after 3 months of heavy rain from September to December 2005. Heavy rainfall at the beginning of wet season (September and October) increased the water content of the soils but could not trigger landslides. In fact, the rainfall in October 2005 was even larger than in December 2005. As the results of slope stability analysis, we can predict that landslides were triggered when the slopes were almost saturated. The antecedent rainfall in October and November made soils and rock joint surfaces wetter, conditions that are more favorable for later showers to induce landslides. The total rainfall that triggered landslides was 1,260 mm, which occurred after about 1 month (17 November–15 December 2005) of heavy rains.

Comments on loud noises

Loud booms accompanied some of the large landslides in Van Canh district and caused a lot of anxiety among local people. According to local eyewitnesses, when a large landslide occurred there was a loud noise following by weaker ones. On hearing these noises some local people considered that a severe earthquake would come or "the angel of mountain was angry". Natural slope failures in Vietnam often occur in remote areas where the local knowledge is limited, and the people are unaware of possible early indications of a landslide. It increases risk in landslide-prone areas. Local authorities therefore need a scientific explanation of the phenomenon to enhance residents' awareness.

At the slip surfaces of landslides, some fractures were recognized in the intact bedrock (Fig. 7d). Although the initial loud noises emanated from the sliding areas, they were not followed by rolling rocks or dust clouds. These sounds may have been the result of intact brittle rock fracturing in the slope. A similar event was recorded in the Afternoon Creek rockslide in the state of Washington, USA (Strouth et al. 2006) and in a catastrophic rockslide–debris avalanche at St. Bernard, Southern Leyte, the Philippines (Catane et al. 2007). The noises that followed may be due to the falling and rolling of rock boulders.

Proposals for counter measures

The population density in Van Canh district is very low. The total land area with potential to slide is 6 km^2 which is 0.7 % of the whole district (Ha 2011). Therefore, expensive structural measures are not necessary. Instead, the measure of resettling vulnerable communes to safer places is much more effective. Detailed investigation in Lang Chom commune showed that the east side of Lang Chom commune was less vulnerable to landslides than the west side, especially downslope of geophysical sections T5 and T6. In this place, residual soils are which weathered from rocks of the Van Canh complex and can be classified as SW. The thicknesses of residual soils is 1–5 m. Slopes are gentle, with angles of 5–10° at the T6 section and 5–15° at the T5 section. A part of Lang Chom commune was resettled in a location downslope of the T6 section.

To define suitable places for resettlement in the whole study area, a score-based method was applied to assess landslide susceptibility. It included four levels of low, medium, high, and very high susceptibility. The study results showed that main factors affecting landslide susceptibility include slope angle and faults. Based on the results of stability analysis (a fully saturated slope can fail at an angle of 28–30°), slope angles are classified into four categories with angles of less than 20°, 20–30°, 30–40°, and more than 40°, respectively (Table 4). The influence of faults includes two aspects. Firstly, the actual distance from the investigated point to a fault, which is categorized into four levels (Table 4). The second aspect was the difference between the strikes of the slope face and the fault plane. Plane failures were considered to occur if the slope face strikes parallel or nearly parallel to the fault plane (±20°) (Wyllie and Mah 2004). It has been called here "slope aspect" and was categorized into three levels, with the absolute value of difference of more than 20°, 10–20°, and less than 10°, respectively.

Thematic maps of slope angle, aspect, and geology were overlaid by using ILWIS software. Pixels with size of 10×10 m were used. Based on the total score of these three factors, landslide susceptibility was divided into four levels with scores of 0–2, 3–4, 5–6, and 7–8 (Table 4). The results are shown in Fig. 12. It showed that areas of very high and high landslide susceptibility occupied only small portions of the area. However, a major proportion was distributed along streams and some routes because of steep excavated slopes. The map also provided an orientation and initial information for selection of resettlement sites.

Fig. 13 Signs of potential landslides in Van Canh district (tension crack and scarp at the top)

Natural slope failure is normally a long-time process. The first sign of instability is a tension crack or scarp at the top of the potential slip surface. It is easy to recognize these signs (Fig. 13) because the local people usually carry out many activities on the slopes such as planting trees and feeding cattle. The signs can help to give an early warning of potential landslides and dangerous areas.

Conclusions

The specific conclusions of this study can be summarized as follows:

1. Natural slope failures in Van Canh district took place as a series of large landslides (20,000–195,000 m^3) that occurred due to a prolonged period of rainfall from early September to the middle of December 2005. Landslides occurred where the slopes were at angles of 28–31° and the thickness of residual soils was more than 3 m. The main slip surface is a fault plane.
2. The travel distance of landslides reached over several hundreds meters, seriously threatening residential areas and fields near the slopes. The effective counter measure is to resettle local people to safe sites and disseminate the early warning signs of potential landslides (such as tension cracks and scarps) in the area to the local people.

Acknowledgment

The author would like to thank very much two anonymous reviewers for their valuable comments. Many thanks to Drs. Mauri and Eileen McSaveney (GNS Science, New Zealand) for English editing and comments. All these contributions have helped a lot to improve the quality of the paper.

References

ASTM (2001a) D 422 Test method for particle size analysis of soils
ASTM (2001b) D 2487 Practice for classification of soils for engineering purposes
Catane SG, Cabria HB, Tomarong CP Jr, Saturay RM Jr, Zarco MAH, Pioquinto WC (2007) Catastrophic rockslide–debris avalanche at St. Bernard, Southern Leyte, Philippines. Landslides 4:85–90
Duc DM (2010) Rainfall-induced landslides in Bac Kan and Binh Dinh provinces. VNU J Sci Earth Sci 26(1):1–10
Duncan MJ (1996) Soil slope stability analysis. Landslides: investigations and mitigation. Special Report, vol 247. Transportation Research Board, National Research Council, Washington, pp 337–371, Chapter 13
Ha NH (2011) Application of GIS and remote sensing for landslide assessment in Van Canh district, Binh Dinh province. Master thesis, Hochiminh city University of Polytechnics, 2011 (in Vietnamese)
Huong NT (editor in chief) (2004) Characteristics of meteorology and hydrology in Binh Dinh Province. (in Vietnamese)
ILWIS 3.0 Academic User's Guide. Unit Geo Software Development, Sector Remote Sensing & GIS, IT Department, International Institute for Aerospace Survey and Earth Sciences (ITC), Enschede, The Netherlands. May 2001
Nadim F, Kjekstad O, Peduzzi P, Herold C, Jaedicke C (2006) Global landslide and avalanche hotspots. Landslides 3:159–173
Schuster RL, Highland LM (2007) The third Hans Cloos lecture. Urban landslides: socioeconomic impacts and overview of mitigative strategies. Bull Eng Geol Environ 66:1–27
Strouth A, Burk RL, Eberhardt E (2006) The Afternoon Creek rockslide near Newhalem, Washington. Landslides 3:175–179
Tam DM (2001) Flooding and landslides at the highways of Vietnam. Proceedings of the International Workshop on "Saving Our Water and Protecting Our Land". Hanoi, 20–22 Oct. 2001. pp 18–27
Wyllie DC, Mah CW (2004) Rock slope engineering: civil and mining. 4th Edition, Taylor & Francis Group, pp. 129–152. Chapter 6

D. M. Duc (✉)
Department of Geotechnics, Faculty of Geology,
VNU University of Science,
334 Nguyen Trai, Thanh Xuan, Hanoi, Vietnam
e-mail: ducdm@vnu.edu.vn