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The 28 July 2015 rapid landslide at Ha Long City, Quang Ninh, Vietnam

Abstract From 26–28 July, heavy rainfall occurred in Quang Ninh province causing flooding, debris flows and landslides. It was the largest disaster triggered by torrential rainfall in Vietnam in 2015. The immediate economic loss in Quang Ninh is estimated to be about VND 2000 billion (US$92 million). Seventeen people were reported dead, 1,459 households were evacuated and at least 30 houses were destroyed. Eight of the victims died when a landslide buried three houses at Cao Thang ward, Ha Long City. We undertook field investigation and ring-shear simulations to study the initiation mechanism and behaviour of the landslide. The rainfall-induced pore-water pressures were estimated using the Slope-Infiltration-Distributed Equilibrium (SLIDE) model developed by Sassa et al. (2010) and Liao et al. (2010, 2012). The ring-shear apparatus (ICL-1) was used to simulate the soil failure, formation of sliding surface and steady-state motion of the landslide. Landslide dynamic parameters obtained and estimated from ring-shear tests were used in the integrated simulation model LS-RAPID to simulate landslide motion. The results demonstrate that the LS-RAPID model predicts a similar hazard area to that observed in the field investigation. In addition, the time of landslide occurrence estimated from the rainfall record and the LS-RAPID simulation is close to the time of occurrence reported by local inhabitants.

Introduction

Landslides are one of the most dangerous geohazards in Vietnam which mainly occur during heavy rainfall during tropical typhoons (Duc 2013; Tien Bui et al. 2016). The northern mountainous area is one of the most landslide-prone regions in the country (Tien Bui et al. 2013, 2016; Hung et al. 2016). In particular, on 28 July 2015, around 01:00 local time, a catastrophic landslide occurred at Cao Thang ward, Ha Long City, Quang Ninh province, Vietnam (Fig. 1). The landslide claimed 8 lives and destroyed 3 houses. Total rainfall measured at a number of gauging stations in Quang Ninh province during 26–30 July showed the highest readings in the last 40 years (CCNDPC 2015). The cumulative rainfall from 19:00, 27 July, until 07:00, 28 July was 296 mm at Bai Chay weather station in Ha Long City (CCNDPC 2015). Figure 2a, b presents a UAV image of the affected area and a longitudinal section of the Ha Long landslide. This section is based on a digital surface model (DSM) generated from post-landslide UAV images and a pre-landslide 5-m topographical map. The maximum landslide depth is 6.0 m (vertical). The objective of this research was to understand the initiation mechanism and behaviour of the landslide triggered by the extreme rainfall in Ha Long. In this paper, we specialised in laboratory testing with pore-water pressure and landslide motion modelling techniques to better understand the timing and mechanisms of landslide failure.

Site location and sampling

Ha Long City is located in the center of Quang Ninh province where there is complex and diverse coastal topography including hills, deltas and islands. It is a highly urbanised and rapidly growing city (population 221,580 in 2010). Much of the population live in hilly terrain prone to landslides and debris flows. The north and north-east are covered by hills, containing the 70% of the city's area. The altitude ranges from sea level to 504 m.

Ha Long has a tropical coastal climate with two seasons. A summer season lasts from May to October; the winter from November to April. The average annual precipitation is 1800 mm with 80–85% of the annual average falling in summer, especially in July and August.

A geological map of part of Ha Long city (Fig. 3) illustrates that the landslide area consists of Triassic age conglomerates, gritstones, sandstones and thin lenses of coal.

The Bai Chay weather station in Ha Long City recorded a total rainfall of 387 mm between August 27 and 28. Especially, the cumulative rainfall in the 12 h between 19:00 h, 27 July and 07:00 h, 28 July was 296 mm. The main triggering factor of the Ha Long landslide was this intense rainfall in a short time period.

On 10 September 2015, Japanese and Vietnamese researchers investigated the landslide area. Two samples were taken from the landslide headscarp as shown in Fig. 3 and sent to the International Consortium on Landslides (ICL) laboratory in Kyoto University for testing. The soils in the landslide source area were characterised by a series of standard geotechnical tests (Table 1). There is a brown layer above black layer. The materials are weathered gritstone including sand and silt. The black layer contains more fines than the brown layer. From the grain size distribution (Fig.3), the brown sample had the particles with the mean diameter D_{50} = 1.06 mm, uniformity coefficient U_c = 363.8 and the grains ranging from sand to clay size. It is sand with >12% fines. The black sample had the mean diameter D_{50} = 0.20 mm. The density of brown and black samples was 26.5 and 26.7 kN/m³. Permeabilities of the black and the brown samples are 4.50×10^{-7} and 3.62×10^{-3} m/s, respectively. Due to permeability change between the two layers, the sliding surface may have occurred at the base of the brown sand layer. The brown sand sample was used in the ring-shear tests to study the initiation mechanism and motion behaviour of the landslide at Ha Long triggered by heavy rainfall.

Fig. 1 Location map of the Ha Long landslide

Methodology

SLIDE model

To simulate rainfall-induced landsliding, pore-water pressure changes need to be estimated. Based on the research of Montarasio and Valentino (2008) and Liao et al. (2010), the Slope-Infiltration-Distributed Equilibrium (SLIDE) model can estimate the pore-water pressure from rainfall intensity using the simple assumption that the water depth in a column in an infinite slope is changed by the balance of rainfall infiltration (assuming all rain infiltrates into the ground) and the drainage outflow from the column. Figure 4 presents the concept of the SLIDE model. The water from the rainfall penetrates into the soil layer and a saturated layer is formed above the bedrock, allowing groundwater to flow through the slope. When the water supply from the ground surface exceeds that of the groundwater discharge from the saturated layer, the groundwater level and associated pore-water pressures will increase. Conversely, the groundwater level (pore-water pressure) will decrease when the infiltration of rain is less than that of the groundwater discharge from the saturated layer. According to Liao et al. 2010, pore pressure (ΔU) acting at the sliding surface can be expressed by Eq. 1:

$$\Delta U = m.H.\gamma_n.\cos^2\beta, \qquad (1)$$

and changes in the ratio of groundwater layer to the soil layer pressure (m) is calculated by Eq. 2

$$\begin{cases} m_1 = 0 \\ O_t = K_t.\sin\beta.m_t.H.\cos\beta.\Delta t \\ \Delta m_t = \dfrac{(I_t - O_t)}{n.H.(1-S_r)} \\ m_{t+1} = m_t + \Delta m_t \end{cases}, \qquad (2)$$

where ΔU is the pore-water pressure, m is ratio between the depth of the soil layer and the depth of the groundwater layer, t is time, Δt is time interval, m_1 is initial value of m and m_t is calculated at each time step. O_t represents the water outlet of a finite portion of a slope of finite length L. I_t is rainfall intensity, and K_t is average permeability of the soil layer, H is landslide depth, n is porosity, β is slope angle and S_r is degree of saturation (Liao et al. 2010).

The SLIDE model is a simplistic model that neglects certain effects such as transpiration from trees and vegetation, and the initial unsaturated infiltration process, but provides an appropriate model for use in computer simulation.

We used rainfall intensity at the Bai Chay weather station to study the rainfall that induces the Ha Long landslide and pore-water pressure response to the rainfall was calculated using the SLIDE model. We used an average soil permeability of 0.00362 m/s, a saturation of 83%, a soil thickness of 6 m, a slope angle of 16° and a porosity of 41%.

The excess pore-water pressure ratio (r_u) during the heavy rainfall period was calculated as the landslide trigger factor in a LS-RAPID simulation. It was expresses as: $r_u = \Delta u/\sigma$

where σ is total normal stress acting on the potential sliding surface $\sigma = H.\gamma.\cos^2\beta$ (γ is unit weight of soil $\gamma = 19.2$ kN/m³).
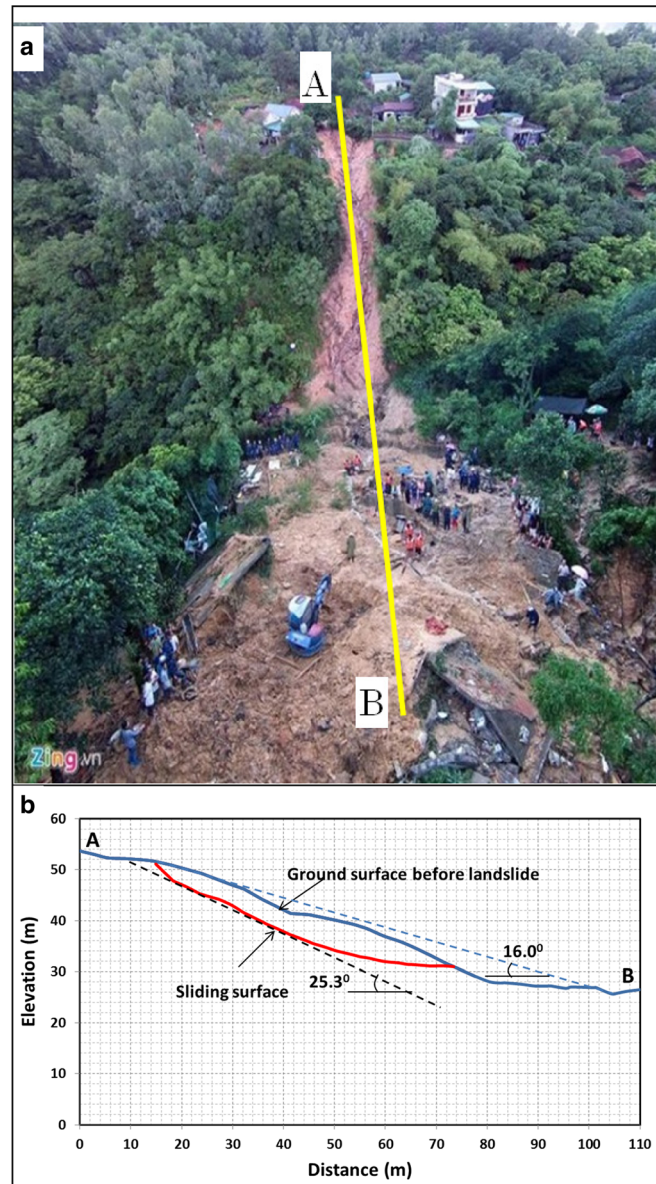
Fig. 2 UAV image (modified from Zing) (**a**) and *A*–*B* longtitudinal cross section of Ha Long landslide (**b**)

Figure 5 shows the relationship between rainfall intensity and pore-water pressure ratio from 0 0:00 h on 26 July 2015. The maximum pore-pressure ratio is 0.41.

Ring-shear simulator

Samples taken from the landslide area were tested in a ring-shear box (Sassa et al. 2004). The normal and shear stresses acting on the potential sliding surface were reproduced in the shear box. When stresses became high enough to trigger sample deformation, a shear surface developed within the shear box, and the rotary lower half of the shear box started to displace. During the shearing process, the ring-shear

apparatus measured excess pore-water pressure, mobilised shear resistance and shear displacement. Two tests were conducted on the brown sample. The test program is present in Table 2.

An undrained monotonic shear stress-controlled test was conducted at a normal stress of 95 kpa. This corresponds to the landslide initiation in the field. Normal stress was increased to 95 kPa at a rate of $\Delta\sigma = 1$ kPa/s in the drained condition. After consolidation, the shear box was then changed to the undrained condition, and shear stress was increased at a rate of $\Delta\tau = 0.5$ kPa/s. When the effective stress path reached the failure line, the sample deformation
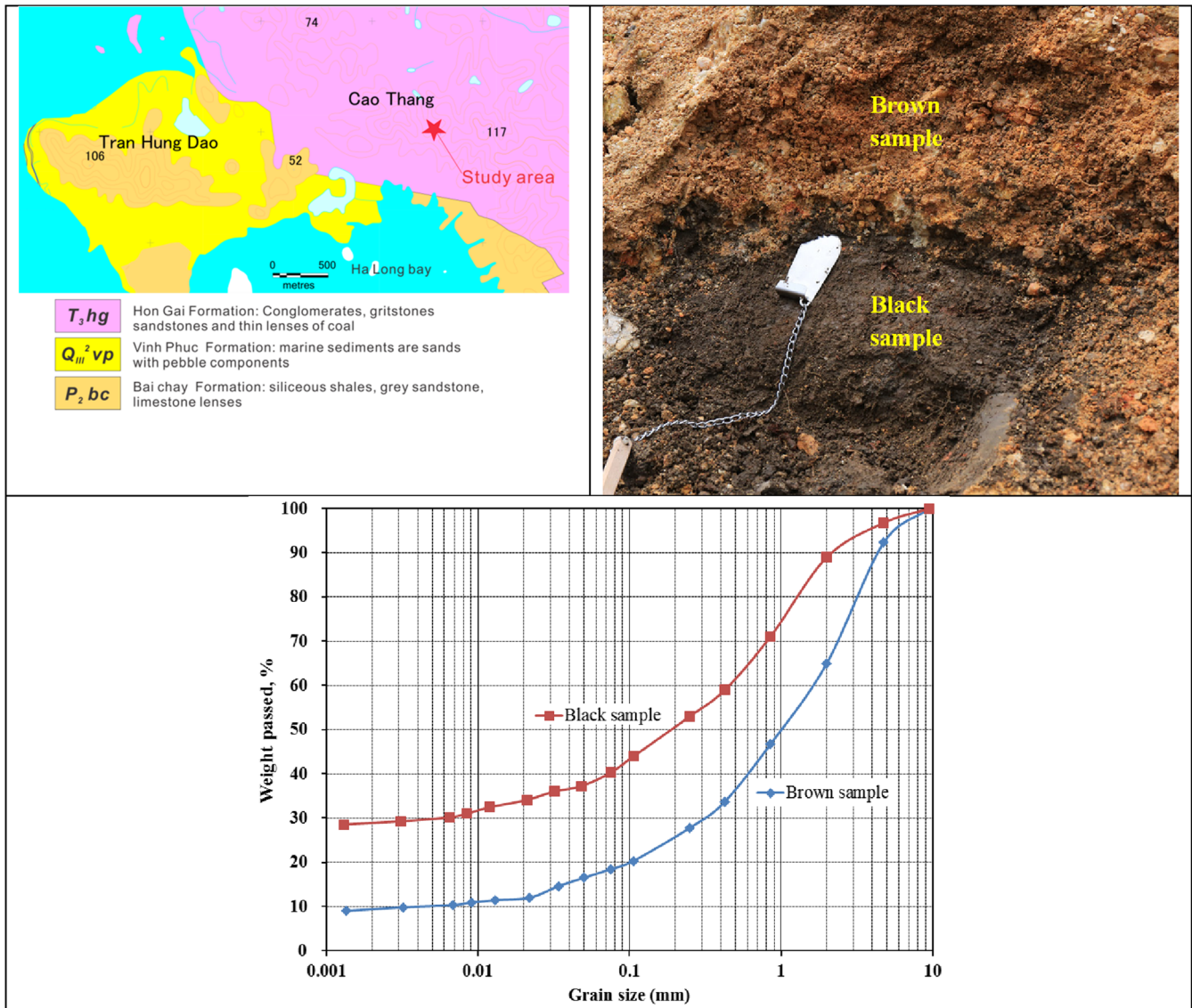
Fig. 3 Geological map of study area and sampling

and pore-water pressure were recorded until 10 m of shear displacement had been achieved.

The Ha Long landslide was triggered by heavy rainfall which can be simulated using the ring-shear apparatus. In order to observe the effect of pore-water pressure generation carefully, the initiation of the slope failure was simulated. Firstly, the sample was saturated ($B_d = 0.98$), then consolidated to 95 kPa normal stress and 45 kPa shear stress in a drained condition.

Integrated simulation model LS-RAPID

LS-RAPID is an integrated computer model that can simulate the initiation and motion of a landslide using soil parameters obtained from the ring-shear results. This simulation model was developed from the geotechnical model for the motion of landslides (Sassa et al. 2010)—its improved simulation model and new knowledge obtained from a new dynamic loading ring-shear apparatus (Sassa et al. 2004, 2010).

Table 1 Basic geotechnical test results of the two samples

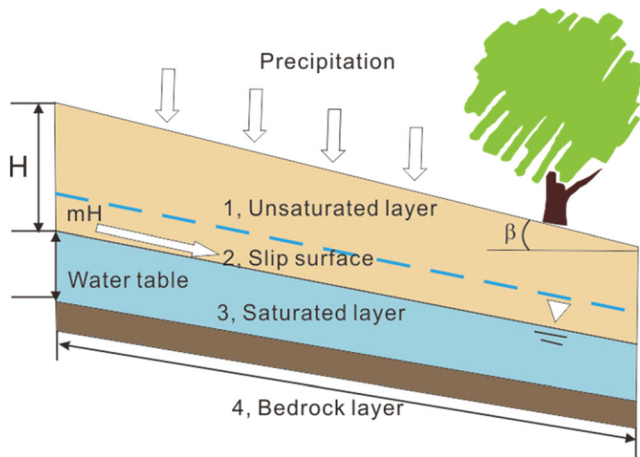| Sample	Moisture (%)	Unit weight (kN/m^3)	Density (kN/m^3)	Permeability (m/s)
Black sample	26.6	18.7	26.5	4.50×10^{-7}
Brown sample	21.2	19.2	26.7	3.62×10^{-3}

Fig. 4 Schematic illustration of water infiltrating an infinite slope (from Liao et al. 2010)

It is difficult to simulate both landslide initiation and motion in a single model. Thus, the state from the initiation of the landslide to its occurrence was simulated using slope stability analysis, while the motion of the landslide was simulated using landslide run out analysis. Ring-shear test results were input into the LS-RAPID as the landslide's dynamic parameters. The parameter information was described as follows:

(1). The steady-state shear strength, the peak friction angle and the friction angle during motion ($\phi_{p=}$ 38.0°) were obtained from the undrained stress-controlled test.

(2). The shear displacement to achieve shear-strength reduction was estimated from the undrained stress-controlled test. The critical shear displacement for the start of strength reduction (DL) and the start of steady state (DU) were obtained from shear stress and shear displacement graph.

(3). Lateral pressure ratio is k 0.5–0.7. The authors assumed the lateral ratio to be 0.5 in the top of the slope, 0.6 in the landslide body and 0.7 in the lower part.

(4). Pore-pressure generation rate B_{ss} was 0.8–0.9 in the landslide area and 0.3 outside the landslide area. It was 0.95 in the marsh area (inside of yellow line in Fig. 8a)

(5). The unit weight of the brown sand sample was 19.2 kN/m³.

Test results and discussions

Undrained monotonic shear stress-controlled test
Figure 6 presents the stress paths and time series data for the brown sand sample. The measured steady-state shear resistance was 6 kPa. The friction angle of the peak failure line and friction during motion were 38.0° and 35.6°, respectively.

Pore-water pressure-controlled test
The preparatory stage was to reproduce the initial stress on the slope (the corresponding slope angle is 25.3°), and is shown as a black line in Fig. 7.

In order to simulate the pore-pressure-induced landslide process, the water pressure was gradually increased at a rate of Δu = 0.4 kPa/s up to 95 kPa. Failure occurred at a
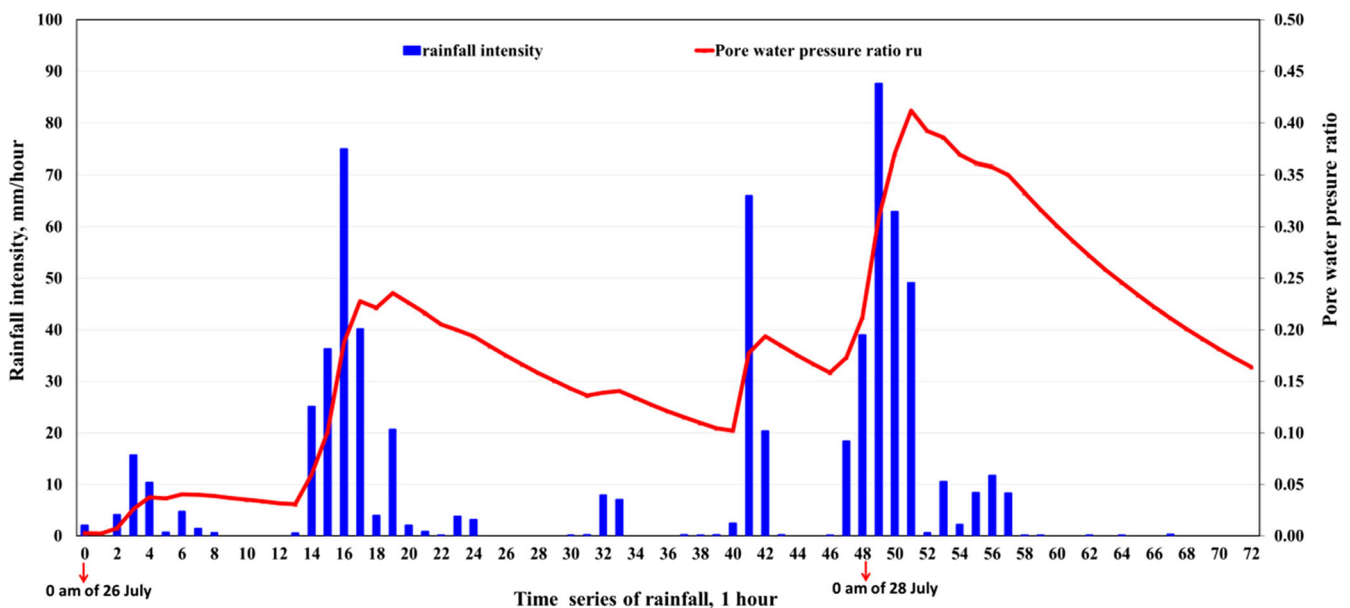

Fig. 5 Pore-water pressure calculation by the SLIDE model from the rainfall record monitored at the Bai Chay weather station for each 1 h from 0:00 h on 26 July 2015

Table 2 Test program

Sample	Test	Consolidation stage Normal stress (kPa)	Shear stress (kPa)	Shear stage Shear stress increment rate (kPa/s)	Pore-water pressure increment rate (kPa/s)	Drainage
Brown sample	Undrained monotonic shear stress-controlled test	95	0	0.5		Undrained
Brown sample	Pore-water pressure-controlled test	95	45		0.4	Undrained

pore-water pressure of 32 kPa at a pore-water pressure ratio $r_u = 32/95 = 0.34$. The friction angle at failure was 36.3°. To monitor the water pressure during shearing, the pore-water pressure supply valve was closed after failure occurred. Figure 7 shows the stress path going down the failure line during motion with a friction angle of 32.0° during motion. After closing the pore-water pressure supply valve, the pore-water pressure was quickly generated to close the normal stress during shearing. The shear resistance is reduced and reached steady state with high speed

of shearing. This result indicates that the sliding surface liquefied as has been observed by other researchers (e.g. Sassa et al. 2004, 2010; Wang et al. 2005; Okada et al. 2007; Dang et al. 2016). The sliding-surface liquefaction is key concept of landslide dynamics. The grains in the shear zone were crushed during shearing, and a high pore-water pressure is generated by reduction of volume (Sassa et al. 2004, 2010; Okada et al. 2007). This test may have reproduced the rapid and fluidised motion of Ha Long landslide.
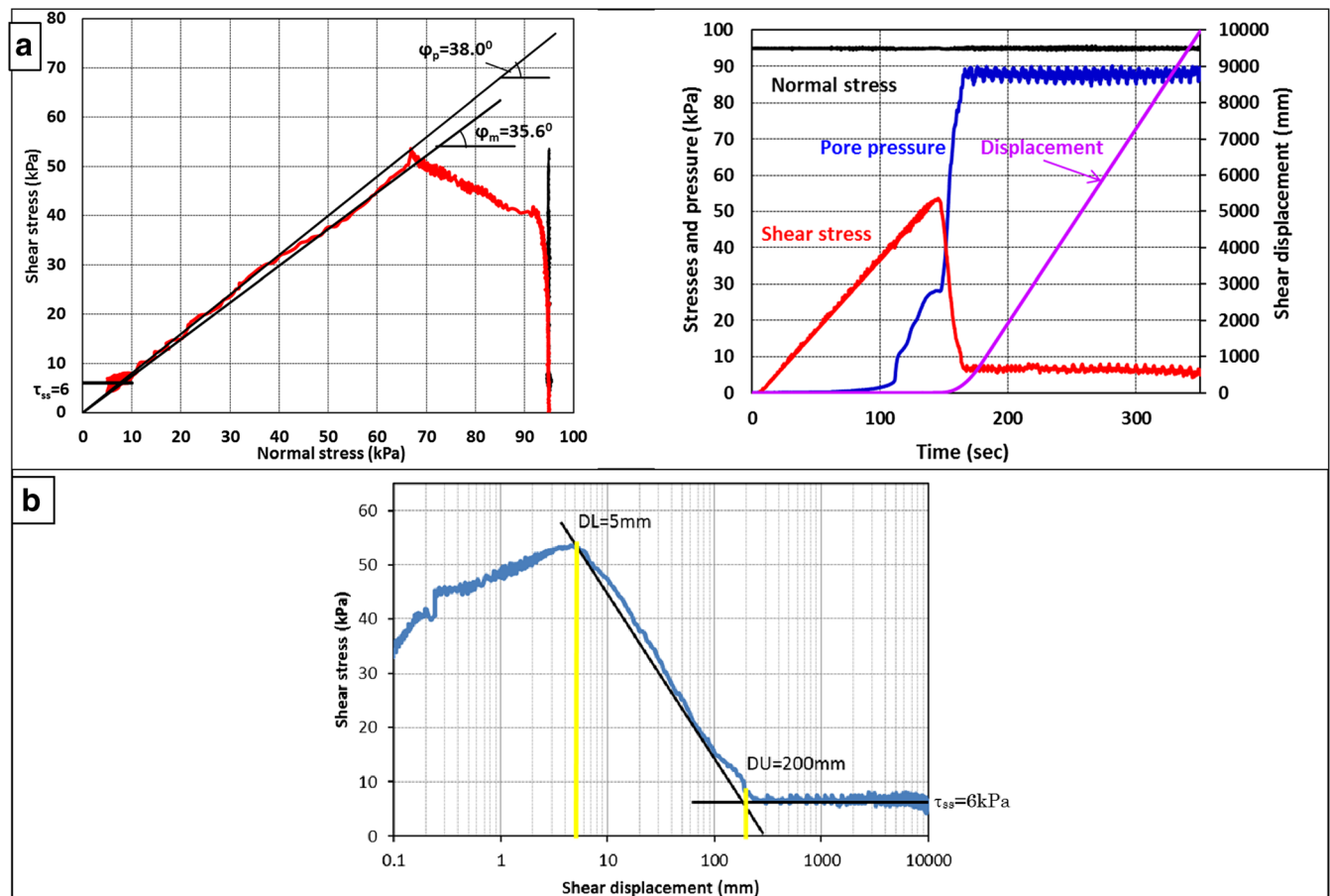

Fig. 6 Undrained monotonic stress-controlled test on the brown sand sample ($B_d = 0.95$, normal stress = 95 kPa $\Delta\tau/s = 0.5$ kPa/s). Stress path and time series data (**a**) and relationship between shear stress and shear displacement (**b**)
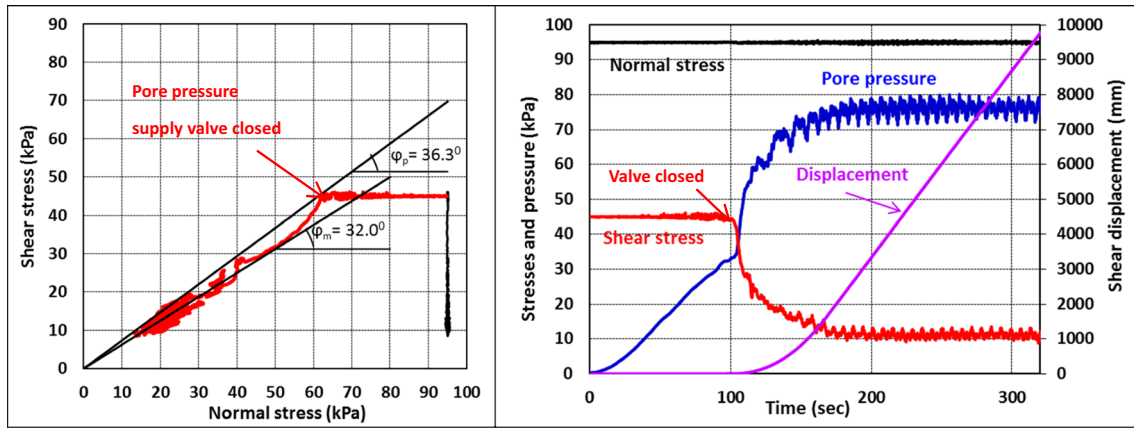
Fig. 7 Pore-pressure-controlled test on the brown sand sample ($B_d = 0.98$)

Application of LS-RAPID and SLIDE model to the 2015 Ha Long landslide

Triggering factors

The amount of heavy rainfall needed to trigger the 2015 Ha Long landslide was calculated using the SLIDE model. This pore-water pressure ratio was then input into LS-RAPID as a graph of triggering factor.

Landslide dynamics parameters

The parameters used in the computer simulation are listed in Table 3.

The simulation result of the Ha Long landslide is presented in Fig. 8. The pink line is the calculated sliding mass distribution area. Then, the pore-water pressure ratio was increased and local failure started from the middle of the slope when r_u reached 0.34 at 01:30′:00″ (28 July). At 01:55′:39″, r_u reached

0.36 and the whole landslide mass was formed and moved down. At 01:55′:49″, the landslide mass reached a maximum velocity of 13.3 m/s. At 02:10′:19″, movement had ceased. Using the image taken by UAV (Fig. 8f) as the real case, the landslide movement in the computer simulation is similar to it. Based on information from local inhabitants, the Ha Long landslide took place around 01:00 local time on 28 July. The landslide is modelled to have occurred at 01:30′:00″ (Fig. 8b). Allowing that the rainfall input into the model has an hourly resolution, the estimated time of landslide occurrence from the LS-RAPID simulation is remarkably close to the actual occurrence time.

Conclusion

Rainfall-induced landslides and debris flows resulted in a great disaster in Ha Long. The main objectives of this research were to study the initiation mechanism and behaviour

Table 3 Parameters used in LS-RAPID simulation

| Parameters	Value	Source
Steady-state shear resistance (τ_{ss}, kPa)	6	Test data
Lateral pressure ratio ($k = \sigma_h/\sigma_v$)	0.5–0.7	Estimated
Friction angle at peak (ϕ_p, degree)	38.0	Test data
Cohesion at peak (c, kPa)	5	Estimated
Friction angle during motion (ϕ_m, degree)	35.6	Test data
Shear displacement at the start of strength reduction (DL, mm)	5	Test data
Shear displacement at the start of steady state (DU, mm)	200	Test data
Pore-pressure generation rate (B_{ss})	0.3–0.95	Estimated
Total unit weight of the mass (γ_t, kN/m³)	19.2	Test data
Unit weight of water (γ_w, kN/m³)	9.8	Normal value
Triggering factor		
Pore-water pressure ratio in the potential shear zone (r_u) during rain	0–0.45	Estimated from SLIDE model
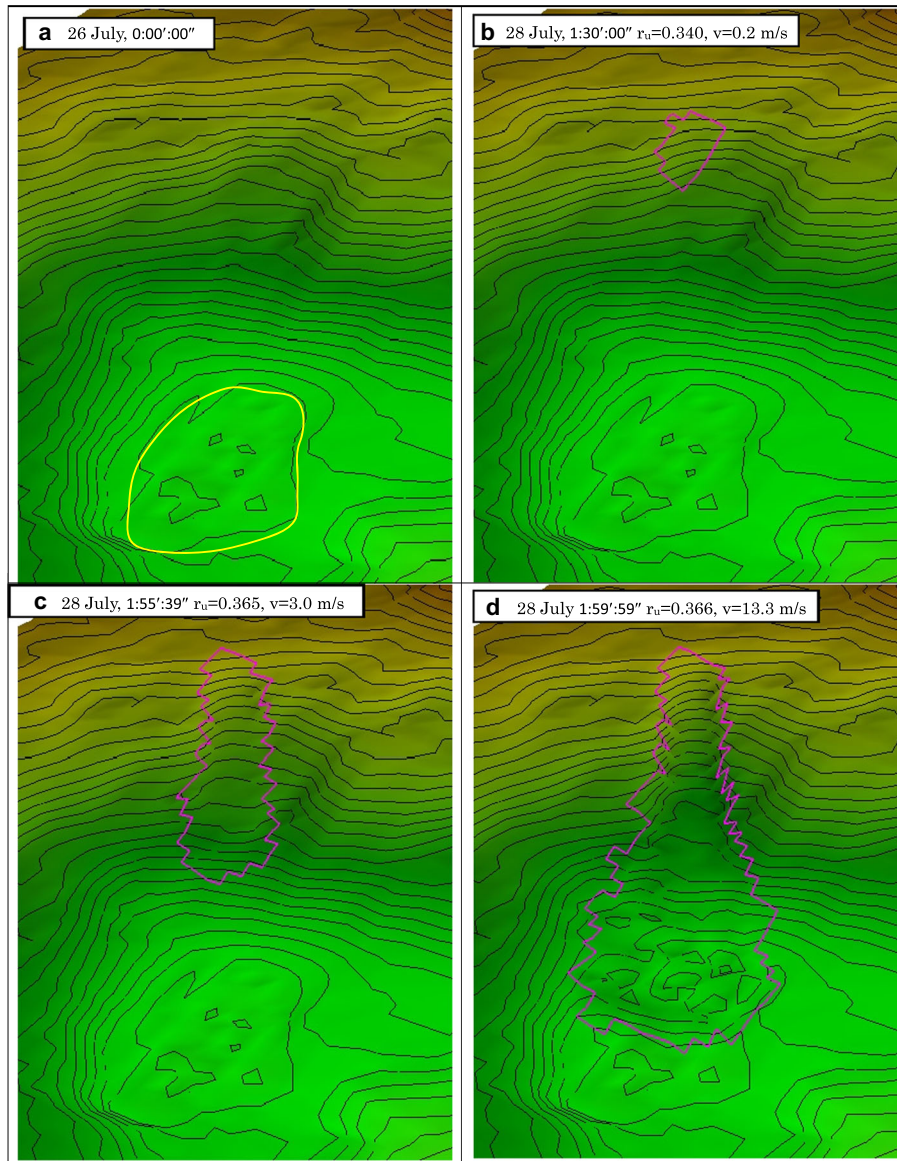
Fig. 8 Simulation result of Ha Long landslide

of the Ha Long landslide. The pore-water pressure-controlled test for simulating the initiation of landslide can suggest that Ha Long landslide could occur by increasing pore-water pressure until a pore-water ratio of 0.34. We examined these results in relation to the rainfall event which was known to have triggered the event.

From our study we conclude:

1) The Ha Long landslide occurred in an area where high soil permeability soil (brown layer) overlies lower soil permeability layer (black layer). During heavy rain, the low permeability of the black layer soil allows high pore-water pressures to build up in the brown soil layer above resulting in the Ha Long landslide failure.

2) This research has successfully demonstrated rapid flow failure occurs through the liquefaction of the landslide shear zone due to rapid pore-water pressure rise replicated in the ring-shear testing.

3) The SLIDE model is useful to calculate pore-water pressure from rainfall intensity for use in shallow landslide models.

4) The LS-RAPID model produced a landslide area that was broadly consistent with field investigation results. In addition, the modelled time of landslide occurrence is close to that reported by local inhabitants.

5) Ha Long landslide was small; however, it caused a great disaster. This research contributes to understanding the mechanism of a rapid landslide during heavy rain as a basic knowledge for disaster prevention. It may provide useful information for the local government authorities in Ha Long City for land-use planning in the hilly areas of the city.
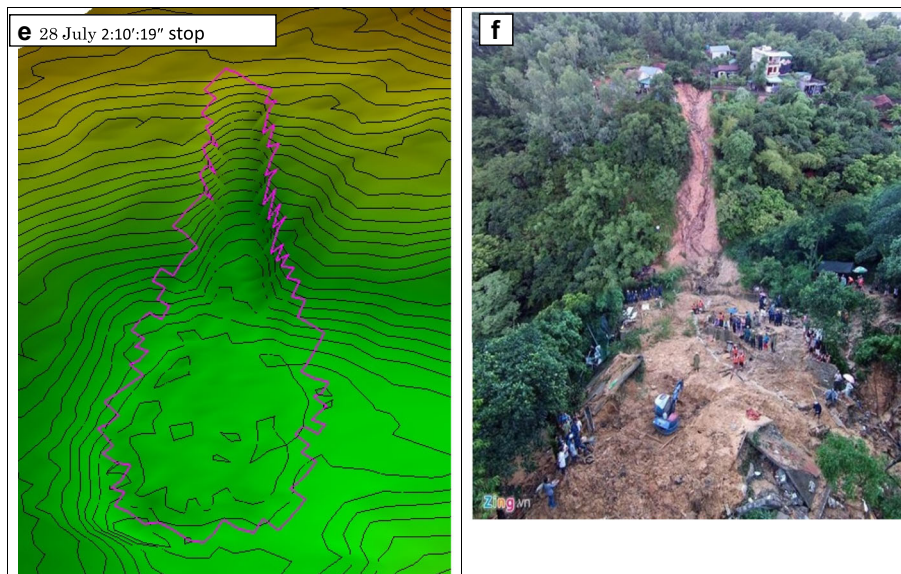
Fig. 8 (continued)

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