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Recent rainfall-induced rapid and long-traveling landslide on 17 May 2016 in Aranayaka, Kegalle District, Sri Lanka

Abstract A rapid and long-traveling landslide was triggered at Aranayaka, Kegalle district, Sri Lanka on 17 May 2016 by exceptionally heavy rainfall associated with a slow-moving tropical cyclone. The precipitation that accumulated within the last 3 days from May 14 to 17 reached 446.5 mm. The landslide mass traveled over an approximately 2-km distance killing 127 people and destroying 75 houses. To deduce the failure mechanism of the Aranayaka landslide, shear behavior of two samples taken from the initial landslide area were examined through ring-shear tests. The first sample (S1) was taken from the weathered soil layer on the left scarp of the landslide. The second sample (S2) was taken from the weathered granitic gneiss at the bottom of the depression in the middle part of the landslide area. The layer was affected by intense tectonic crushing and subsequent deep weathering. A high value of shear resistance at steady state was measured on the sample S1 while the sample S2 obtained a much smaller steady state shear resistance. This indicated that the sliding surface of the landslide was located in the weathered granitic gneiss associated with the sample S2. A series of computer simulations of this landslide was then carried out given the soil parameters from the ring-shear tests and pore-water pressure ratio estimated from the rainfall records using the “SLIDE” model. In the simulation, the landslide initiated from the middle part of the source area, close to the location from where sample S2 was taken. Moreover, the time of occurrence from the simulation was similar to that observed in the real event. This is a very important information to assess further rapid landslides in areas with similar conditions. This study also indicates the importance of selecting soil samples and suggests that the ring-shear apparatus and computer simulations are effective tools to reproduce the process of landslides.

Keywords Aranayaka landslide · Rainfall-induced landslide · Ring shear apparatus · Computer simulation · LS-RAPID · Landslide risk assessment

Introduction

Sri Lanka, being located in one of the tropical monsoon climate zones, is a geological-hazard-prone country in South Asia. Especially in the country’s mountainous regions, landslides have been a major natural disaster recently. According to the statistics of the National Building Research Organization (NBRO), ten districts in Sri Lanka are particularly prone to landslides. These districts cover approximately 30% of the total land area of the island and are occupied by about 35% of the country’s population (Fig. 1 left). Landslide density in these districts is around 1–2 landslides per square kilometer Fig. 1 (left) shows the locations of landslides before 2017 (red points) and in 2017 (blue points) in the ten landslide-prone districts (pink colored areas). Figure 1 (right)

shows that over the past 14 years from 2003 to 2017, a total of 1000 lives were lost in 3653 landslide events. In particular, 420 landslides in 2016 and 450 landslides in 2017 were responsible for 151 and 262 deaths, respectively.

Cyclone Roanu, which was formed on May 15, 2016, and consolidated as it moved along the east coast of Sri Lanka, brought heavy rains to the whole nation. Many landslides were triggered in Kegalle and Kandy districts from the night of May 16 till the morning of May 17 (as reported by JICA Survey Team 2016). Among those rain-induced landslides, the Aranayaka landslide that occurred in Kegalle district on 17 May (WGS: 7°9′19.22″ N, 80°25′50.06″ E) (yellow star in Fig. 1) was the deadliest—destroying 75 houses and killing 127 people. Aranayaka landslide is unique in that it is much bigger in terms of its size and travel distance than the other rain-induced rapid long-traveling landslides (RRLs). The number of extremely large RRLs is limited because a large landslide of this type can only occur when certain hydro-geological conditions are met.

As the members from the International Consortium on Landslides (ICL), the authors conducted the first and second field surveys in Aranayaka in 2017, 1 year after the event in cooperation with the National Building Research Organization (NBRO), Ministry of Irrigation and Water Resources and Disaster Management of Sri Lanka. One of the aims of the field surveys is to examine the feasibility of a currently planned new Sri Lanka-Japan Joint Project, “Development of Early Warning Technology of Rain-Induced Rapid and Long-Travelling Landslides in Sri Lanka.” The results will be applied to a Japanese government program, SATREPS (Science and Technology Research Partnerships for Sustainable Development), that promotes international joint research, structured as a collaboration between the Japan International Cooperation Agency (JICA) under the Ministry of Foreign Affairs of Japan (MOFA) and the Japan Science and Technology Agency (JST) under the Ministry of Education, Culture, Sports, Science and Technology of Japan (MEXT). Another objective is to pave the way for the Sri Lanka-Japan joint landslide investigation to mitigate the risk of landslides in Sri Lanka. During the surveys, a quadcopter Unmanned Aerial Vehicle of DJI Phantom 4 was used to take aerial photographs for photogrammetry to extract 3D information of the Aranayaka landslide and its surrounding region.

In this paper, simulations of the Aranayaka landslide mass movement were conducted using LS-Rapid, a software for rapid run-out simulations (He et al. 2014; Sassa et al. 2018), using the data from undrained high-stress loading tests using a ICL-2 ring-shear apparatus (Sassa et al. 2014a, b; Dang 2015). The geometry of the slip surface was deduced assuming that the

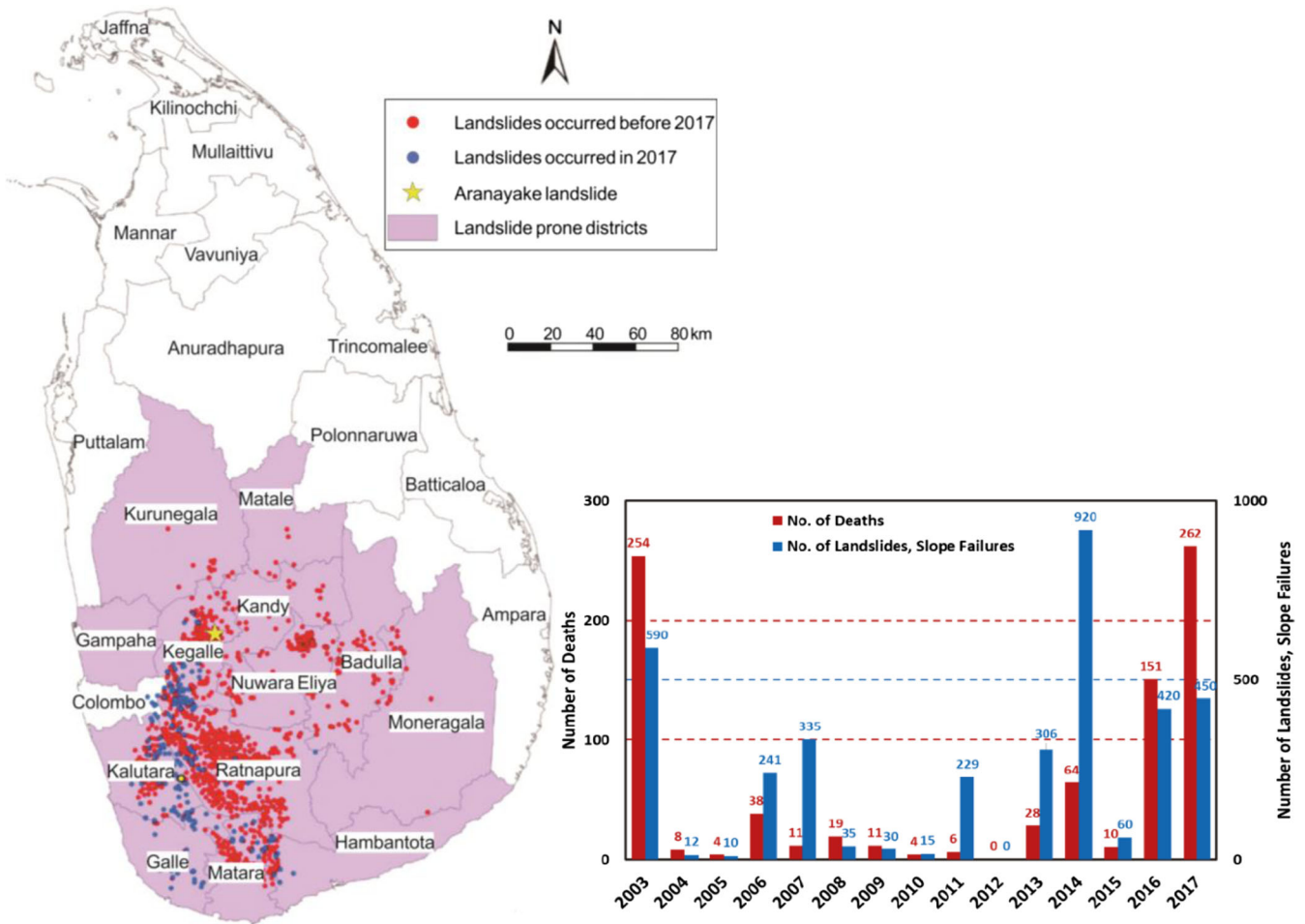


Fig. 1 General information about landslides occurring in Sri Lanka (from NBRO). **a** Location of landslides that occurred before and in 2017, landslide prone districts, and location of 2016 Aranayaka landslide, and **b** number of lives lost due to landslides in the period from 2003 to 2017

sample S2 was taken exactly from the right depth and by comparing digital elevation models (DEMs) of the slope before and after the landslide event. Buildup of the pore-water pressure was estimated by using the SLIDE (Slope-Infiltration-Distributed Equilibrium) model (Montarasio and Valentino 2008; Liao et al. 2010; Loi et al. 2017) using hourly rainfall data over the period from May 14 to 17, 2016 as its input.

Field investigation and soil sampling

According to the JICA survey team report, the instability observed started as a small landslide high on the hillslope at around 4:30 PM on May 17, 2016, and developed into a more substantial failure that traveled over an extremely large distance. Using the terminology defined by Varnes (1978), the landslide is considered as a complex movement with evidence of bedrock exposed in the area. The mobile material appears to be deeply weathered soil and the displaced material appears to have turned into a highly mobile flow that has channelized (Petley 2016).

Figure 2 shows an overview of the Aranayaka landslide with locations of two sampling points (S1 and S2) and destroyed houses. The latter were identified by comparing two Google Earth images taken on 11 February 2017 (after the landslide event) and on 7 November 2014 (before the landslide event). Two cross sections along lines A1–A2 and B1–B2 in Fig. 2 are shown in Fig. 3. The brown-colored parts are the estimated landslide masses. The slope angle of the sliding surface in the source area was estimated to be 35° and the average apparent friction angle, which is the inclination of the line connecting the top and the toe of the entire stretch of the landslide, was about 15°. The maximum depth of the sliding surface was estimated to be about 25 m. The landslide mass traveled at least 2 km.

The geological map of the study area (Fig. 4) shows rocks covering the area include quartzite, biotite hornblende garnet gneiss, gamet silimanit biotite gneiss, granitic gneiss, and charnockitic gneiss. The entire extent of the landslide is covered by granitic gneiss and biotite hornblende garnet gneiss. The two sampling locations (S1 and S2) are within the weathered granitic gneiss.

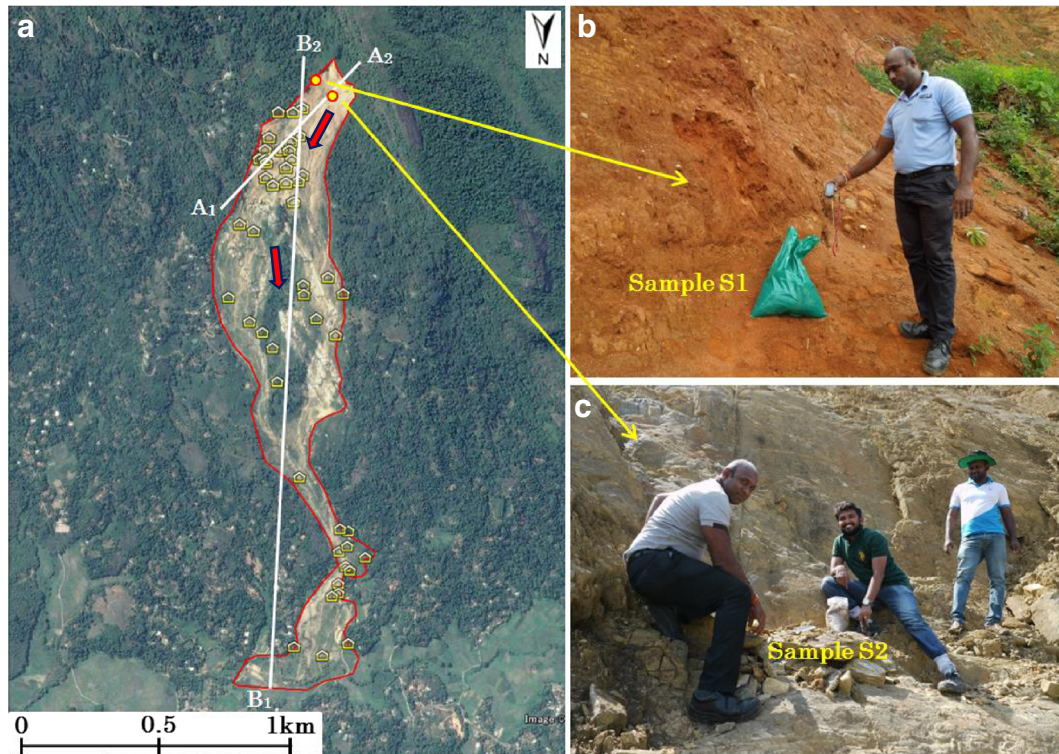


Fig. 2 Overview of Aranyaka landslide with sampling locations and cross section lines. a Google Earth image of the Aranyaka landslide with identified destroyed settlements (image was taken on 11 February 2017), the red arrows indicate the sliding direction, b photo of sampling point S1, and c photo of sampling point S2

Two soil samples were taken from the source area for laboratory tests (Fig. 2). In the first survey, soil sample S1 was taken from the toe part of the exposed scarp on the left side of the source area. The results of the ring-shear test on this silty sand did not indicate that the material would cause a rapid and long-traveling landslide. The investigation team conducted a second field survey to the material in which the sliding surface landslide was formed. The investigation was focused on the bottom of the middle depression part of the initial landslide area. Sample S2 was taken from the weathered granitic gneiss layer, which was affected by intense tectonic crushing and deep weathering. The shear behavior of S2 was quite different from that of S1. After the failure, a rapid and large pore pressure generation and rapid drop down of the shear resistance was observed. It showed that the S2 material could have been the causative material of this large rapid and long-traveling landslide, as will be shown later.

Grain size distributions of the collected samples from this landslide are shown in Fig. 5. These distributions were obtained following the American Society for Testing and Materials (ASTM) standards. Sample S1 consists of 60.14% sand and 39.86% silt while sample S2 consists of 97.26% sand and only 2.74% silt.

Ring shear testing

As mentioned above, two soil samples, taken from the landslide source area as shown in Fig. 2, were sent to Kyoto, Japan for laboratory testing. Sample S1 was taken from the weathered soil

exposed on the left scarp of the landslide. Sample S2 was taken from the bottom of the source depression where the sliding surface was presumably exposed. Dynamic landslide parameters of these two samples were measured through a series of ring shear tests at the UNITWIN laboratory at Kyoto University (Fig. 6). Detailed information of the ring-shear apparatus and testing processes are presented in Dang (2015) and Sassa et al. (2014b).

As the first sample (S1) includes a large amount of fine grained silty material with low permeability, a slow shear speed was to be applied to accurately observe pore water pressure buildup. First, the sample was saturated and consolidated under 500 kPa of normal stress which corresponds to a depth of about 25 m. Then, an undrained shear displacement controlled test was conducted with a constant shearing speed of 0.05 mm/s. The stress path obtained from this test is shown in Fig. 7a, in which the friction angle at failure (ϕ_p) was found to be 40° and the steady-state shear resistance (τ_{ss}) was 250 kPa. This high value of steady-state shear resistance indicates that the rapid and long-traveling landslide observed could not have occurred in this soil layer.

The second sample S2 is a sandy soil with higher permeability than that of Sample S1, and thus an undrained monotonic stress-controlled test was conducted under the same normal stress of 500 kPa. The shear stress was increased at the constant rate of 1 kPa/s. Samples were sheared until the shear displacement reached 3 m (pink colored line in Fig. 7b) and the steady state conditions were obtained. In this test, a friction angle (ϕ_m) of 39° , steady state shear

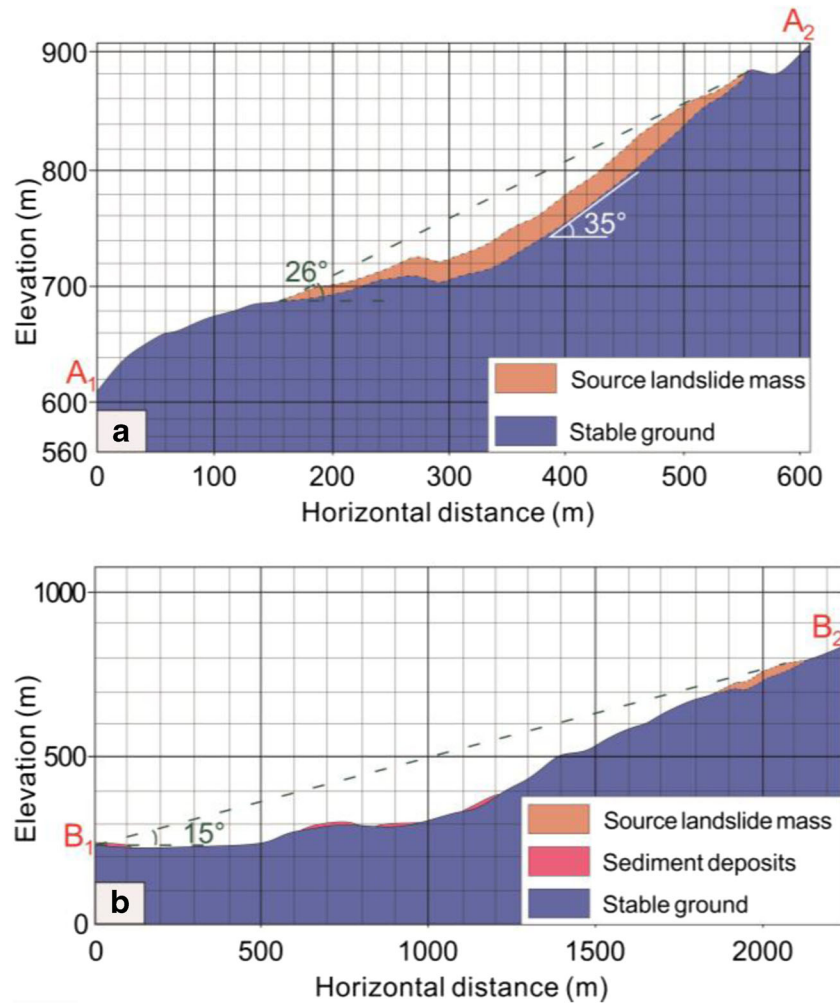


Fig. 3 Cross sections of Aranayaka landslide through **a** source area along A1–A2 (Fig. 2) and **b** volume enlargement area along B1–B2

resistance (τ_{ss}) of 30 kPa, shear displacement at peak strength (DL) of 6 mm, and shear displacement for the initiation of steady-state shear resistance (DU) of 1000 mm were obtained (Fig. 7c, d). Given this very small value of the steady-state shear resistance, it is no wonder that this sandy material (S2) could have been causative for the rapid and long-traveling landslide in Aranayaka. Therefore, the soil parameters from sample S2 are used in the LS-RAPID model to simulate the Aranayaka landslide movement.

Aranayaka landslide simulation

Numerical simulations of the Aranayaka landslide mass movement were conducted using LS-RAPID, a software for landslide run-out simulations. The simulation used the soil parameters obtained from the ring-shear tests and pore water pressure ratio estimated from a “SLIDE” model. The basic concept and flowchart of the LS-RAPID are shown in Fig. 8. Starting from the beginning, the steps are (1) generation of topographical DEM data, (2) creation of sliding surface topography, (3) definition of soil parameters, and (4) setting the simulation conditions (i.e., pore-water

pressure ratio, seismic data). More details of the software are available in Sassa et al. (2010) and Sassa et al. (2018) and manuals for the software can be found in He et al. (2014), and Sassa et al. (2018). This program assumes that vertical column elements compose the landslide mass. Each mass is accelerated by all forces exerted on it from its surrounding columns. These forces include the self-weight (W), seismic forces, lateral pressures acting on its side walls (P), basal shear forces from the bottom (R), normal stress at the base (N), and pore-water pressure acting at the base (U).

This rapid and long-traveling landslide in Aranayaka was triggered by intense rainfall. According to the JICA survey team report, daily precipitation in the northeastern and central regions of Sri Lanka varied from 200 to 373 mm. In particular, record-breaking precipitations were recorded in Kegalle and Kandy districts. Handessa and Weweltalawa weather stations, which are located 18 km northeast and 15 km southwest of the Aranayaka landslide site, respectively, recorded the peak rainfalls on May 15, around 1.0 to 1.5 days before the landslide occurred. Rain gauges at Handessa and Weweltalawa recorded

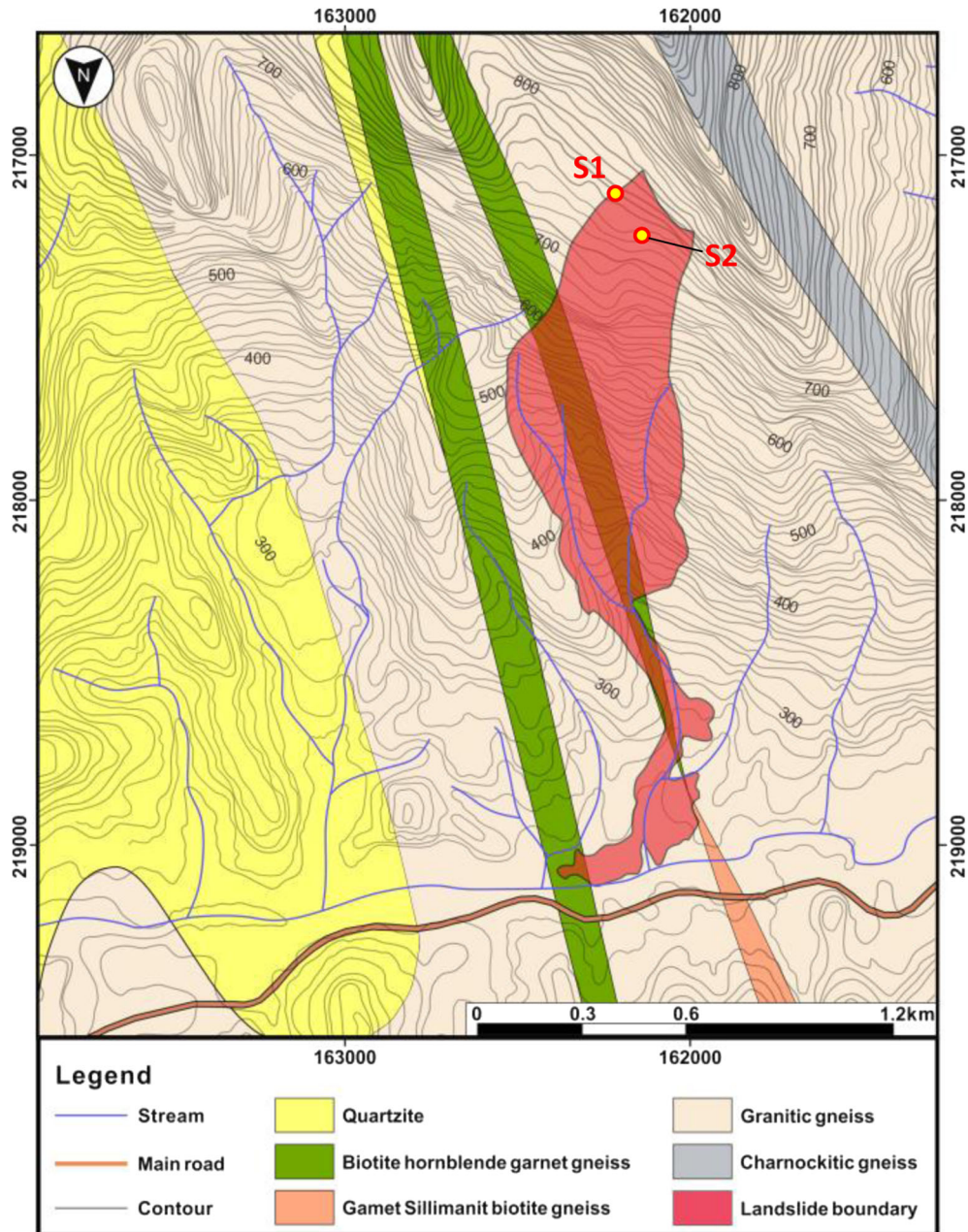


Fig. 4 Geological map of the Aranayaka landslide area with two sampling points (S1 and S2)

the accumulated precipitations of 300 mm and 400 mm, respectively, for the last 3 days immediately before the landslide occurrence. It was remarkable that a total of 446.5 mm of rainfall had accumulated within the last 3 days from May 14th to 17th at the weather station R27 of NBRO, which is 3.5 km west of the landslide site.

Because neither the ground water lever nor pore water pressure within the landslide mass were measured in-situ, the pore water pressure buildup was estimated by using a SLIDE (Slope-Infiltration-Distributed Equilibrium) model (Liao et al. 2010; Loi et al.

2017). Pore-water pressure acting at the sliding surface is expressed in this model by Eq. 1:

$$\Delta U = m \cdot H \cdot \gamma_w \cdot \cos^2 \beta \quad (1)$$

where ΔU is the pore-water pressure, m is the ratio between the depth of unconfined aquifer and the thickness of the soil layer, γ_w is the unit weight of water, and β is the slope angle. m varies with rainfall intensity, and is given by Eq. 2:

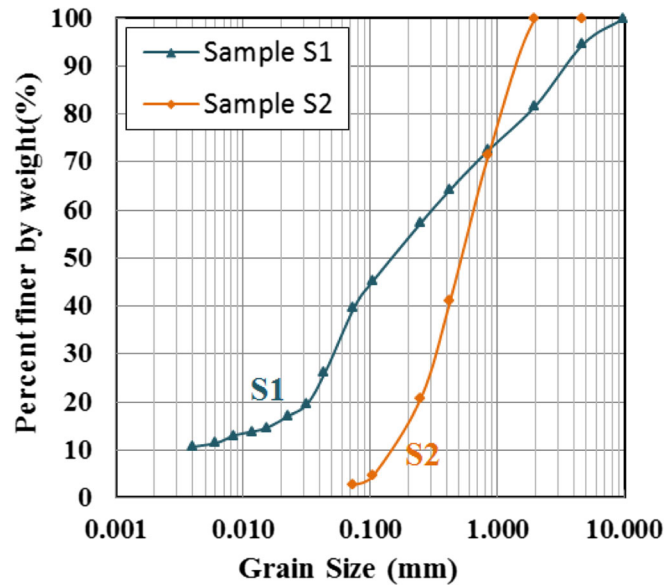


Fig. 5 Grain size distribution curves for samples S1 and S2

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

where m_1 is initial value of m , t is time, Δt is time increment, and m_t is calculated at each time-step. O_t is the water outlet of a finite portion of a slope of finite length L . I_t is rainfall intensity and, K_t is the significance of global drainage capability due to both intrinsic soil permeability and the presence of numerous preferential down-flow ways (Liao et al. 2010).

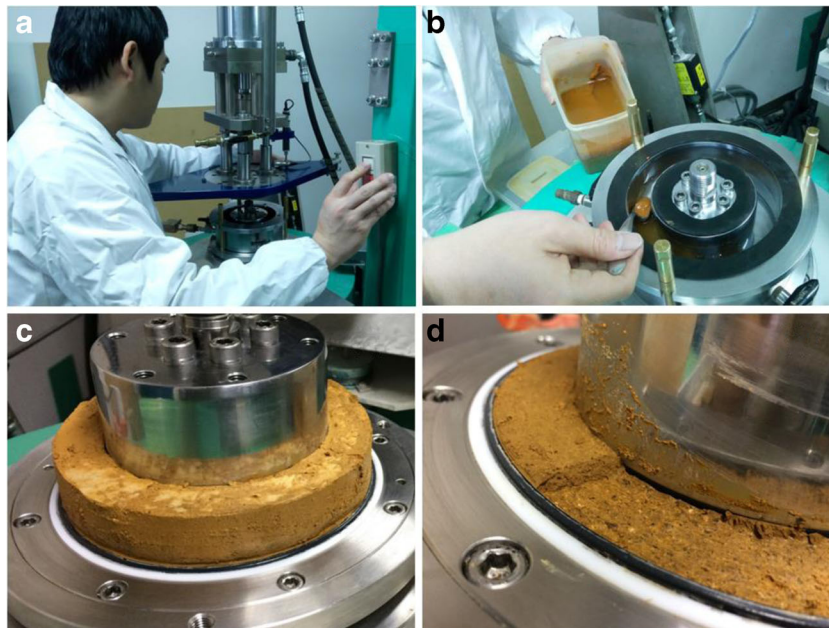


Fig. 6 Photos of ring-shear testing on Aranayaka sample (S1). a Set-up of the ring-shear apparatus, b Placement of the soil sample into the shear box, c Sample after removal of the upper part of the shear box, and d Shear zone after undrained monotonic stress controlled test

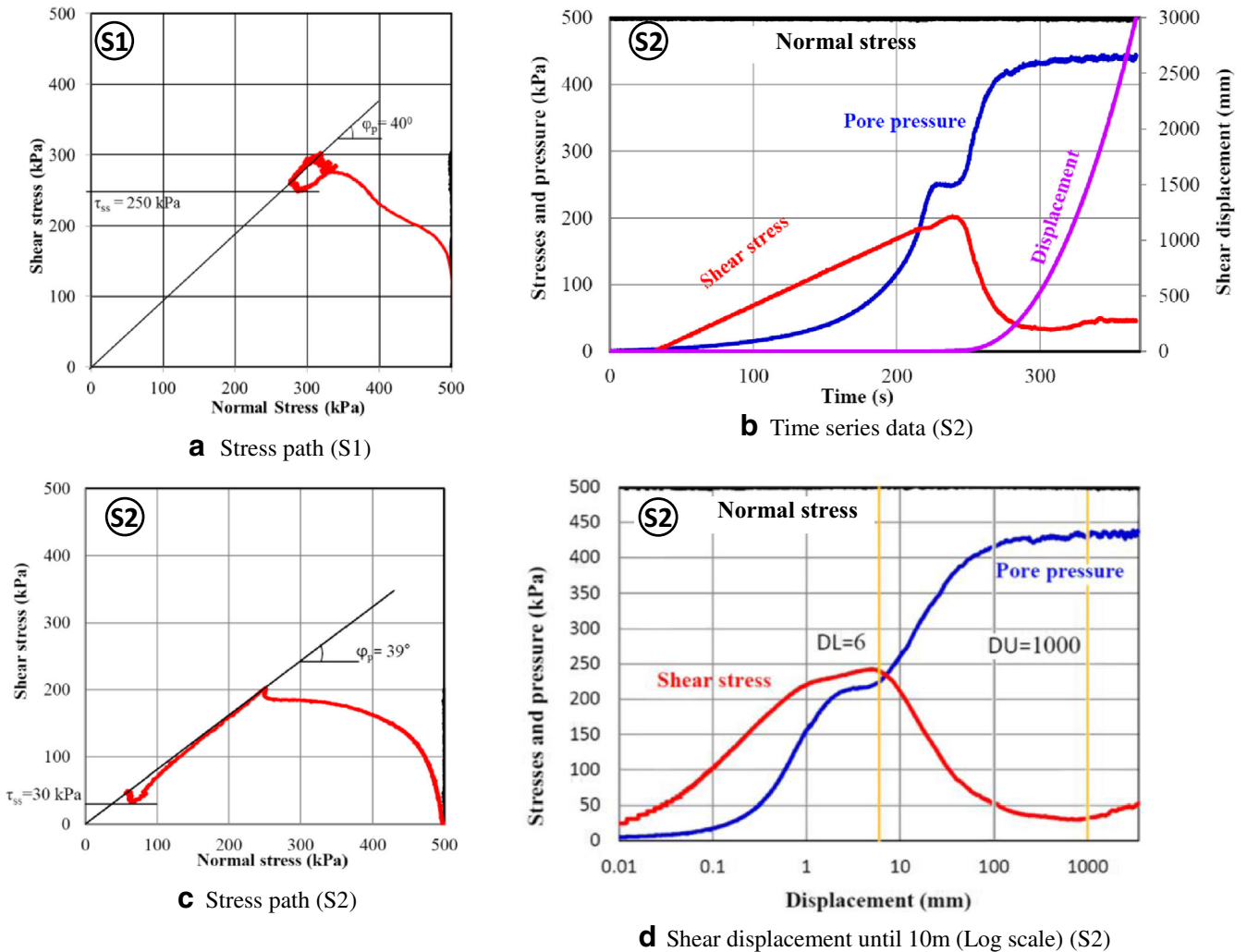


Fig. 7 Result of the ring-shear tests on the Aranayaka samples of S1 and S2 with initial normal stress of 500 kPa. **a** Stress path of undrained shear displacement controlled test on sample S1 sheared at a constant rate of 0.05 mm/s. **b** Time series data, **c** stress path, and **d** shear displacement of undrained monotonic stress-controlled test ($\Delta\sigma = 1$ kPa/s) on sample S2

Hourly rainfall data from 10:00 PM (IST) on May 14 to 11:00 PM (IST) on May 17, 2016 were used as inputs to the SLIDE model to estimate the pore-water pressure buildup. Due to the about 25 m thickness of the landslide mass, the pore-water pressure ratio continued to increase even after peak values of hourly rainfall of 20.75 mm and 23.25 mm were reached at 11:00 AM on May 15 and 12:00 AM on May 16, respectively. The hourly rainfall reached a third peak of 26.75 mm at 2:00 PM on May 17, and pore-water pressure ratio reached its maximum value of 0.28 at 4:00 PM on May 17. This time almost exactly coincides with when the Aranayaka landslide took place (Fig. 9). Therefore, the simulated pore water pressure buildup was used as the input to LS-RAPID.

Results of the landslide simulation are shown in Fig. 10. The bright green line is the periphery of the landslide source area. The

blue colored dots represent soil columns at rest, while the red colored dots are soil columns in motion. The landslide mass movement was initiated by increasing the pore water pressure ratio, r_u , from 0 to 0.28, as was shown in Fig. 9. Both the increments of the pore-water pressure buildup (Points A, B, and C) and the corresponding snapshots of landslide mass movement are shown in Fig. 10. At 0 s (Point A in Fig. 9), Fig. 10A is the initial condition when both the rainfall and pore water pressure ratio were set to zero. At around 40 h after the simulation started, r_u rose up to 0.20, and a small localized failure began to appear in the middle of the source area as shown by red-colored points in Fig. 10B. As the time went on, the local failure continued to expand. When r_u reached 0.28, 66 h 06 m after the simulation started (around 4:00 PM on 17 May 2016), the initial landslide mass was about to become detached from the source area (Fig. 10c), similar to the field observations. Then, the landslide

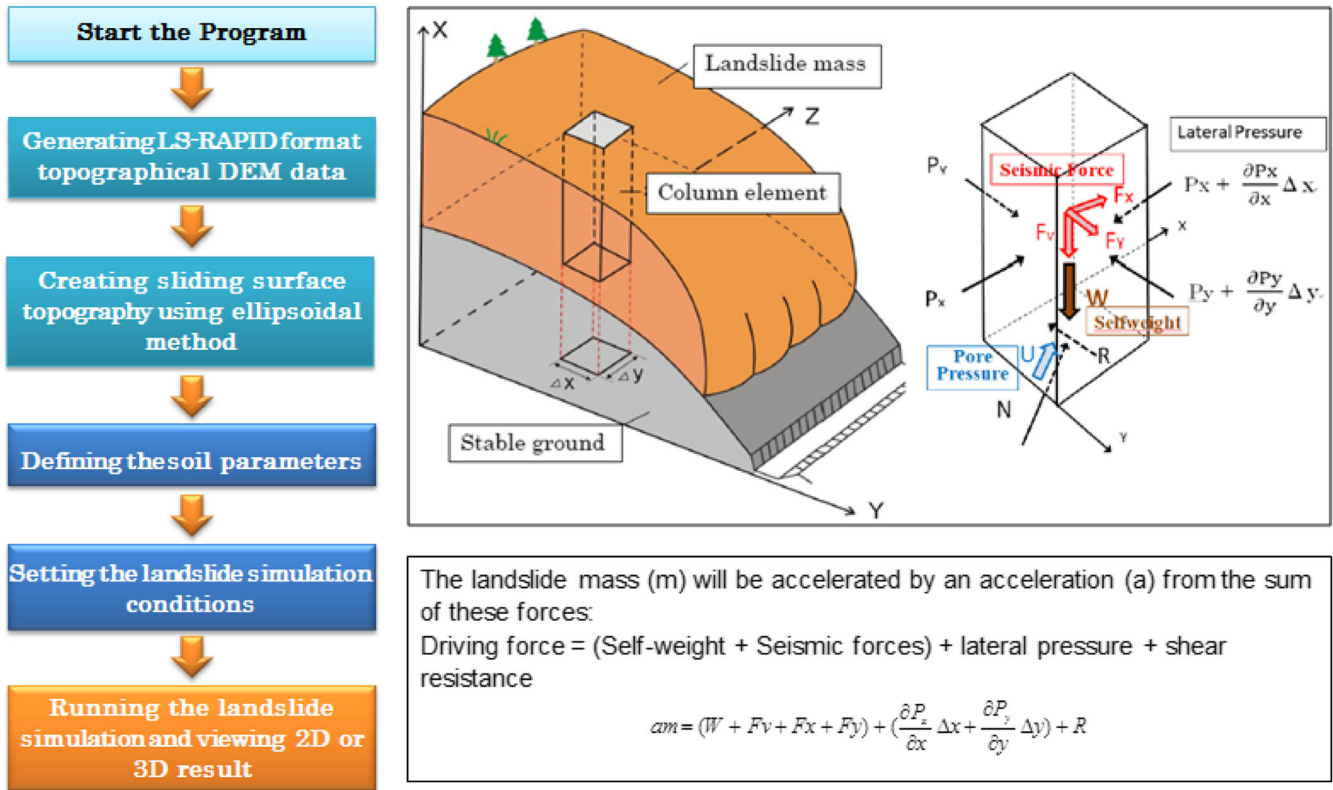


Fig. 8 Flowchart of the computer simulation by LS-RAPID (left) and the basic concept of the LS-RAPID model (right) (from Sassa et al. 2018)

mass in the simulation continued moving down the valley over a period of 2 min before it stopped completely at 66 h 08 m. From the simulation, the total landslide volume and the vertical maximum depth of the landslide were calculated to be 1,237,280 m³ and

26.2 m, respectively. As seen, the numerical simulation could successfully reproduce the movement of Aranayaka landslide in terms of the time of occurrence, travel distance, and the whole run-out process.

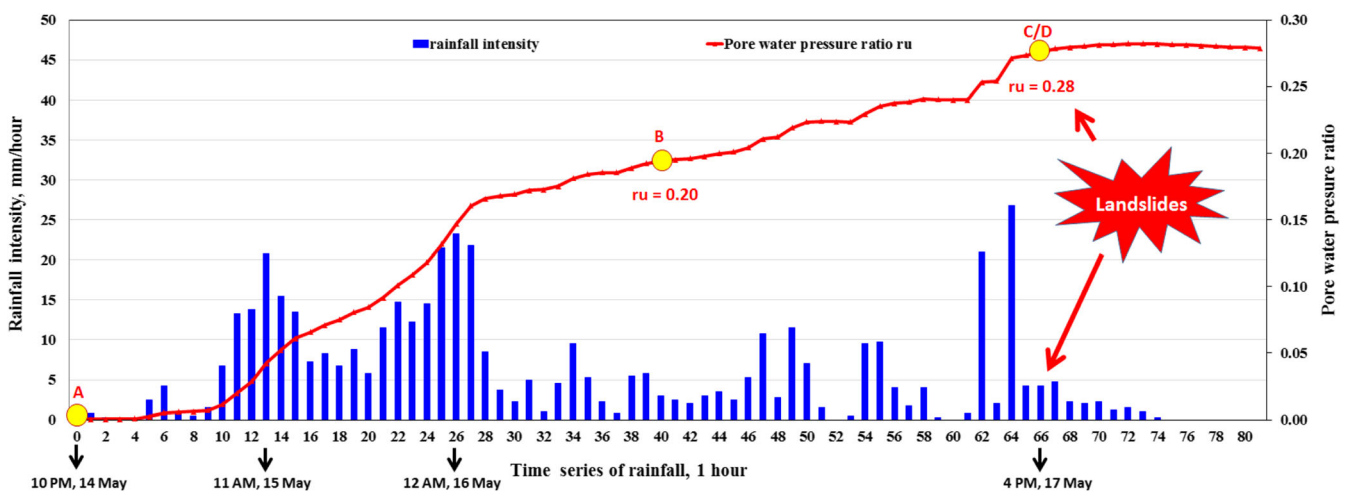


Fig. 9 Hourly rainfall and calculated pore water pressure ratio in the Aranayaka landslide area from 14 to 17 May 2016; A, B, C, and D correspond to the landslide simulation results in Fig. 10

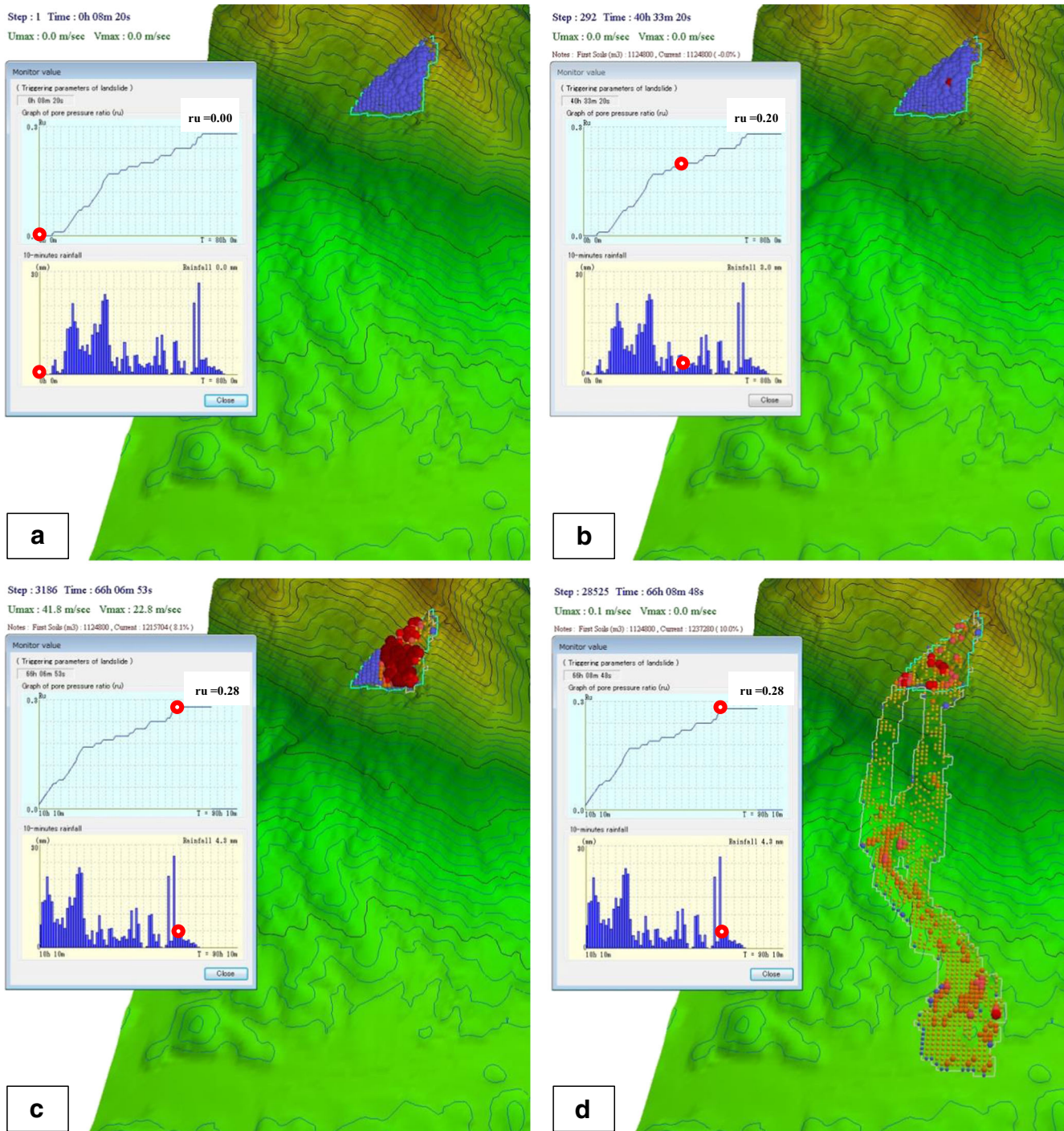


Fig. 10 Results of the computer simulations of the Aranayaka landslide; blue dots represent at-rest soil columns, while red dots represent soil columns in motion

Conclusions

Rain-induced rapid and long-traveling landslides have become more frequent and resulted in many deaths in Sri Lanka. Among those events in the recent past, the deadliest landslide occurred at Aranayaka, Kegalle district, on May 17, 2016 killing 127 people. To better understand the triggering mechanism and the long-traveling nature of the landslide mass, field investigations, including soil sampling, and numerical simulations were carried out.

Two soil sampling locations were examined. The first surface sample (S₁) was taken from the weathered soil layer on the left scarp of the landslide, and the second sample (S₂) was taken from the weathered granitic gneiss rock at the bottom of the depression in the middle part of the initial landslide area. Results from the ring-shear tests on the two samples showed that shear-resistance at steady-state of the sample S₂ was only 30 kPa, extremely small in contrast with 250 kPa shear-resistance observed from the test

conducted on sample S1, indicating that the landslide could have occurred along a sliding surface located in the weathered granitic gneiss from which sample S2 was taken. The computer simulation software, LS-RAPID, was used to simulate the rainfall triggered landslide mass movement with soil parameters provided from the ring-shear tests on sample S2 and the pore water pressure buildup estimated from the “SLIDE” model. The numerical simulation could successfully reproduce the movement of Aranayaka landslide mass in terms of the time of occurrence, travel distance, and the whole run-out process.

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