Disaster Report

Sediment-related Disasters in Petrópolis, Brazil, on February 15 and March 20, 2022

*Hideto OCHI [1], Yoshifumi SHIMODA [2],Yosuke NISHIO [2] and Rafael Pereira MACHADO [3]

[1] Sabo Planning Division, Sabo Department, Ministry of Land, Infrastructure, Transport and Tourism
(2-1-3 Kasumigaseki, Chiyoda-ku, Tokyo 100-8918, Japan) & JICA Expert
*Corresponding Author, E-mail : ochi-h2x7@mlit.go.jp
[2] Yachiyo Engineering Co., Ltd. (CS Tower, 5-20-8, Asakusabashi, Taito-ku, Tokyo 111-8648, Japan)
[3] Ministry of Regional Development (Esplanade of Ministries, Block E, Room 706, Brasília/DF-CEP 70 067-901, Brazil)

The municipality of Petrópolis was hit by heavy rains on February 15 and March 20, 2022 resulting sediment-related disasters. The disaster on February 15, 2022 was caused by heavy rain 253 mm which fell in 3 hours, resulting in 238 fatalities. The disaster on March 20, 2022 was caused by 548 mm/24hr of rainfall which lasted longer than that of February 15, 2022, resulting in seven fatalities. These heavy rains triggered more than 370 landslides, making it the worst disaster ever recorded in the municipality. This report provides an overview of the disaster and the characteristics of four of these more than 370 landslides as examples.

Key words : sediment disaster, landslide, heavy rainfall, Brazil, Petrópolis

1. INTRODUCTION

The municipality of Petrópolis, located in the mountainous region of the state of Rio de Janeiro, Brazil (**Fig. 1**) experienced disasters caused by torrential rains on February 15 and March 20, 2022. According to information from the municipality, more than 370 landslides were confirmed in the municipality, 238 fatalities in the February 15 disaster and 7 fatalities in the March 20 disaster were confirmed. This series of disasters was the worst ever in the municipality of Petrópolis, exceeding the 2011 disaster that claimed 73 fatalities and the 1988 disaster that claimed 171 fatalities [*Satriano*, 2022]. Most of fatalities were caused by rainfall-triggered landslides. There were a few fatalities from flooding that occurred in urban rivers.

The municipality of Petrópolis is composed of five districts, namely Petrópolis, Cascatinha, Itaipava, Pedro do Rio, and Posse. The series of disasters occurred in Petrópolis District (**Fig. 2**) (Area : 143 km^2) in the southern part of the municipality, where the population is concentrated.

The authors, who were in Brazil for the technical cooperation project "Capacity Development Project for Structural Measures against Sediment Related Disaster for Resilient Cities" (commonly called as the "Sabo Project") funded by Japan International Cooperation

Fig.1 Location map of Petrópolis

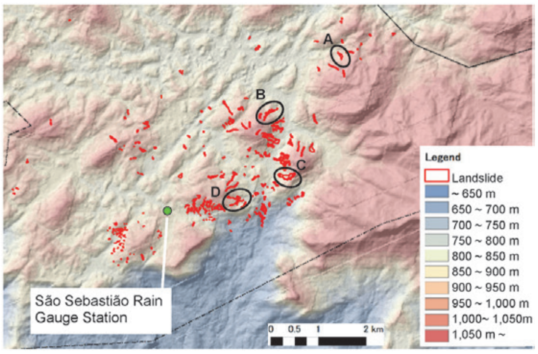


Fig.2 Distribution of landslides and elevation classification in Petrópolis District created from ALOS World 3 D − 30 m. (Information on the landslide was added using city-created data. A-D in the figure are the locations of the sites shown in Fig. 10.)

Agency (JICA), conducted a survey mainly from the air at the request of the Ministry of Regional Development on February 17, immediately after the first disaster. Furthermore, on May 5 and June 24, 2022, several months after the disasters, the authors visited the municipality of Petrópolis to conduct field investigations at four of the landslides, and to interview municipality government officials regarding the disaster situation. This paper reports the results of these investigations.

2. OVERVIEW OF THE DISASTERS

2.1 Topography

The municipality of Petrópolis is located approximately 68 km north of the municipality of Rio de Janeiro, on a plateau of the Atlantic shield between 800 m and 1,000 m above sea level (**Fig. 2**) in the mountains along the southeastern coast of Brazil, called Serra do Mar. The topography of the municipality of Petrópolis can be roughly classified into mountains, hills formed by the dismantling of mountains by weathering and erosion, and rocky outcrops, with few flat areas (**Fig. 3**). In Petrópolis District where the series of disasters occurred, there are many hills and mountains with specific heights ranging from 50 to 200 meters above the valley floor. The landslides occurred on the slopes of these hills, rocky outcrops and mountains, striking residential areas on the slopes and lower part of slopes (**Fig. 4** and **Fig. 5**). Most of the landslides were shallow landslide with a narrow width relative to their length, originating around the knick point near the top of the slope. In the case of **Fig. 5**, shallow landslide occurred on the weathered surface layer of a granite outcrop at the top of the hill. From the air observation, most of the landslides were shallow landslide on the slopes, and there were very few cases that could be considered as debris flow.

The slope classification map created from ALOS World 3D - 30 m (hereafter referred to as "AW3D30m") combined with the distribution of landslides in Petrópolis District is shown in **Fig. 6**. Using satellite imagery, each landslide was divided into collapsed

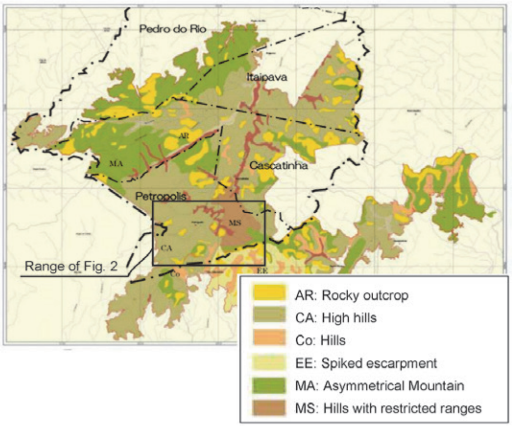


Fig.3 Geomorphological map of Petrópolis. Administrative boundaries were added to the map of *Prefeitura Municipal de Petrópolis* (2016).

Fig.4 Landslides on a hill in the southern part of Petrópolis District.

Fig.5 Landslides on a hill with rocky outcrops in the eastern part of Petrópolis District.

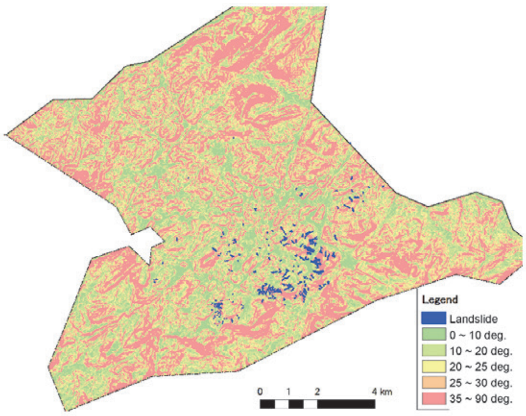


Fig.6 Distribution of landslides and slope classification in Petrópolis District created from ALOS World 3 D − 30 m. (Information on the landslide was added using city-created data.)

slope and deposited debris. The average gradient of collapsed slope was 30.4 degrees (calculated from AW 3D30m), and the average collapsed slope area was 1,600 m^2.

2.2 Geology

The municipality of Petrópolis is located on the Atlantic shield with Precambrian basement rocks [*Kamitani*, 1984] consisting of granitoid (Rio Negro Unit), migmatite (Rio Negro Unit), and Serra dos Órgãos batholith of granitic origin (**Fig. 7**). Field investigations revealed that the granite forming the hills and mountains had developed parallel cracks on the surface, where there was a risk of bedrock collapse. The weathered residual soil covering the granite was as thin as 1 ～ 2 meters and lateritized.

2.3 Rainfall

The municipality of Petrópolis belongs to the tropical climate zone. Rainfall is concentrated from October to March, with an average annual rainfall of 1,383 mm [*Instituto Nacional de Meteorologia*, 2013]. However, according to the data observed at São Sebastião rain gauge station (**Fig. 2**) of National Center for Natural Disaster Monitoring and Alert (CEMADEN) located in the vicinity of the landslide-prone area in the Petrópolis District, the rainfall that caused the February 15 disaster was 253 mm/3hr, and the rainfall that caused the March 20 disaster was 548 mm/24hr. Therefore, about half of the region's annual precipitation fell during this series of disasters.

Figure 8 shows the hourly rainfall at São Sebastião rain gauge station from February 14 to 18, 2022. Rainfall was concentrated in a four-hour period from 15 : 00 to 19 : 00. The maximum hourly rainfall was 115.2 mm (from 16 : 30 to 17 : 30) and the maximum 2-hourly rainfall was 196.2 mm (from 16 : 30 to 18 : 30). This maximum 2-hour rainfall of 196.2 mm was higher than the monthly average rainfall for February in Petrópolis (185 mm). Photos taken by a resident at 17 : 44 in Petrópolis District show the occurrence of a landslide, which suggests that the landslide occurred around the time when the peak of rainfall intensity was recorded.

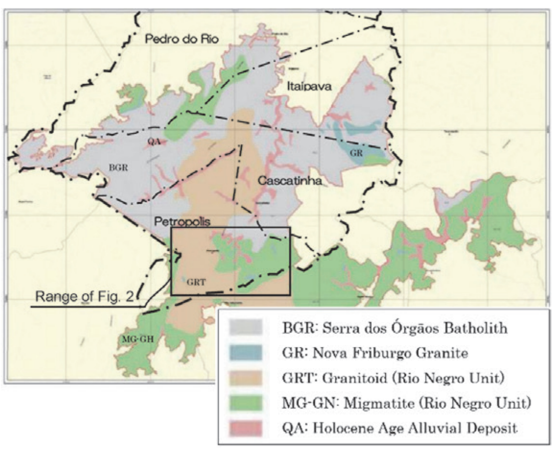


Fig.7 Geological map of Petrópolis. Administrative boundaries were added to the map of *Prefeitura Municipal de Petrópolis* (2016).

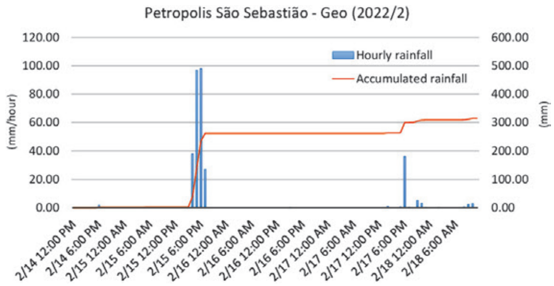


Fig.8 Hourly rainfall at São Sebastião rain gauge station for February 14～18, 2022 organized from CEMADEN observation data.

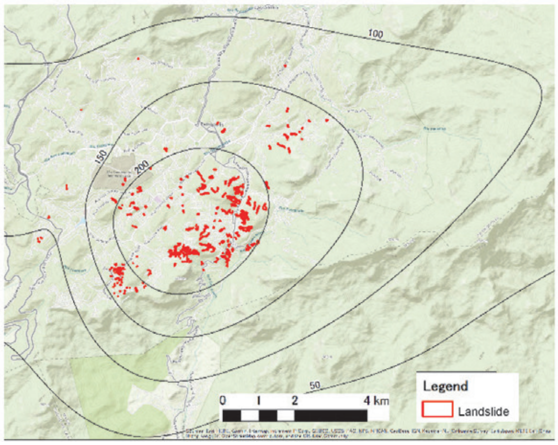


Fig.9 Isohyetal map of 3-hour rainfall on February 15, 2022 from 15 : 30 to 18 : 30 organized from CEMADEN observation data.

Figure 9 shows an isohyetal map of 3-hour rainfall from 15 : 30 to 18 : 30 on February 15, 2022, organized from CEMADEN's 14 rain gauge stations in the municipalities of Petrópolis and Magé. It shows that landslides were concentrated in the area where the 3-hour rainfall exceeded 200 mm/3h. In addition, most of the landslides were contained within the range where rainfall exceeded 150 mm/3h.

3. DETAILS OF INDIVIDUAL LANDSLIDE

Among the landslides that occurred in Petrópolis District, we were able to visit and carry out investigation four sites (**Fig. 10**) where the scale of damages were relatively large. Name of the sites were designated as Sites A through D from north to south. Details of the mass movement and damages at each

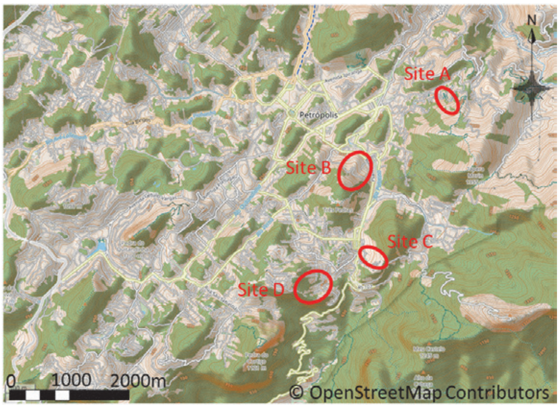


Fig.10 Location map of Site A－D where field investigation was carried out.

Fig.11 View of the landslide Site A in Caxambu Neighborhood from the air.

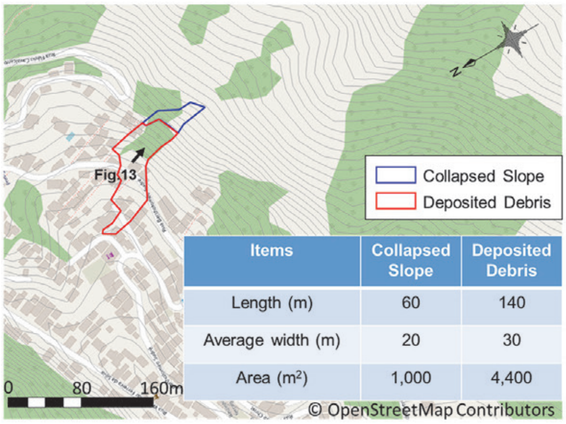


Fig.12 Topography and information of the landslide at Site A in Caxambu Neighborhood. The green hatching in the figure represents forest covers. This definition on the green hatching is the same in Figs. 14, 19 and 21.

Fig.13 Situation of the landslide at Site A in Caxambu Neighborhood.

site are described below.

3.1 Site A in Caxambu Neighborhood

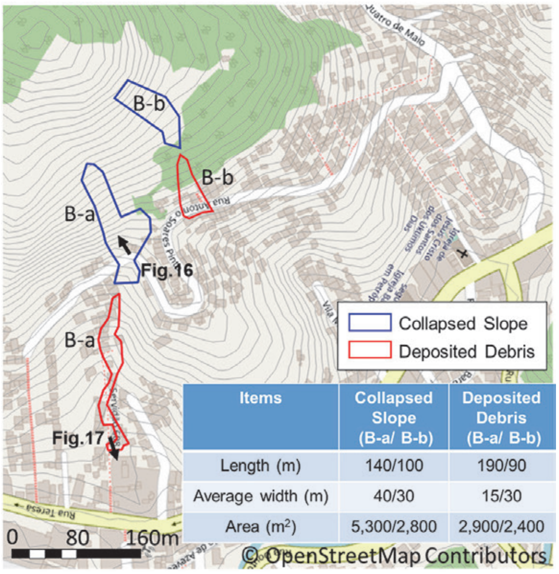
The landslide Site A shown in **Fig. 11** occurred on the north slope located at coordinates lat 22° 30'26.90"S. long 43° 9' 31.08" W. in Caxambu Neighborhood. The average gradient of the collapsed slope was approximately 30 degrees as read from the contour lines, and the length, average width and area of the collapsed slope were approximately 60 m, 20 m and 1,000 m^2 respectively, according to the satellite image. The length, average width and area of the deposited debris were approximately 140 m, 30 m and 4,400 m^2 respectively (**Fig. 12**). Visual inspection of both sides of the collapse site revealed that cracks parallel to the slope had developed in the granitic bedrock (**Fig. 11** and **Fig. 13**). The bedrock was covered with less than 1 m of weathered residual soil with vegetation including tall trees. The diameter of the collapsed rock was 2 to 3 meters.

According to a municipality government official, the vegetation on the collapsed slope was similar to that of the adjacent land, the collapse was probably caused by groundwater from short-term heavy rainfall. The official also said that the slope may have been saturated, because a person who lived in the affected house posted a video taken at the time of the disaster on a social networking site showing a large amount of water flowing indoors.

Even though the collapsed layer thickness of weathered residual soil was less than one meter, about 10 houses were destroyed at the foot of the slope where debris had deposited. The collapsed slope was long and constant, and its base rock had cracks parallel to the slope, which allowed the collapsed material to reach the foot of the slope without slowing it down. This may have been the cause of the significant damage.

3.2 Site B in Vinte e Quatro de Maio Neighborhood

The landslide B-a occurred on February 15, 2022 is located on the northeast slope at a point 400 m to the



Items	Collapsed Slope (B-a/ B-b)	Deposited Debris (B-a/ B-b)
Length (m)	140/100	190/90
Average width (m)	40/30	15/30
Area (m^2)	5,300/2,800	2,900/2,400

Fig.14 Topography and information of the landslide at Site B in Vinte e Quatro de Maio Neighborhood.

Fig.15 View of the landslide Site B in Vinte e Quatro de Maio Neighborhood from the air.

east from 24 de Maio Street into Antônio Soares Pinto Street with coordinates lat 22°31'6.51"S. long 43°10' 23.99"W. in Vinte e Quatro de Maio Neighborhood (**Fig. 14** and **Fig. 15**). This landslide is called "608 landslide" based on the number of the address of the nearby shopping center which is 608 Teresa Street. The average gradient of the collapsed slope was approximately 30 degrees as read from the contour lines, and the length, average width and area of the collapsed slope were approximately 140 m, 40 m and 5,300 m^2 respectively, according to the satellite image. The length, average width and area of the deposited debris were approximately 190 m, 15 m and 2,900 m^2 respectively (**Fig. 14**). The slope where the landslide occurred was a granite outcrop, the surface of which was partially covered by weathered residual soil less than 1 m thick with a dense herbaceous and shrub cover. The slope had two rows of approximately 20-meter-long rockfall prevention nets and a 45-meter-long drainage ditch parallel to the contour line to gather surface water from the slope and direct it into a vertical drain. However, the rockfall prevention nets could not fully capture the falling rocks, and the drainage ditch was partially destroyed by the falling rocks (**Fig. 16**). The collapsed rocks flowed over Antônio Soares Pinto Street in the middle of the slope, destroying houses in the lower part of the slope, and stopped at the wall of a shopping center facing Teresa Street (**Fig. 17**).

According to the municipality government official, there was almost no vegetation near the rockfall prevention nets before the disaster. The reason why the falling rocks were not fully caught by the nets and reached the foot of the slope was because there were more rocks than expected that collapsed and also landslides occurred on the slope outside of the netting area.

Landslide B-b also occurred on the west side of landslide B-a on February 15, 2022 (**Fig. 14**). At that time, the collapsed rocks did not reach the residential

Fig.16 Situation of the collapsed slope at Site B-a in Vinte e Quatro de Maio Neighborhood.

Fig.17 Situation of debris B-a stopped at the wall of a shopping center facing Teresa Street.

area. However, on March 20, 2022, the landslide expanded, causing severe damage to houses in the Antônio Soares Pinto Street area.

According to the municipality government official, after the landslide occurred on February 15 2022, a field survey revealed that there was a risk of the landslide spreading. Therefore, they designated the area included within a 30-degree range on either side downward from the landslide as a remaining mass movement risk area (**Fig. 18**), and ordered residents to evacuate. As a result, although houses were damaged by the expansion of the landslide on March 20 2022, human casualties were avoided.

Fig.18 Remaining mass movement risk polygon, Antonio Soares Pinto Street, Alto da Serra, Petrópolis. Flow direction of collapsed rocks on March 20 2022 was added to the map of Petrópolis Civil Defense.

3.3 Site C in Alto da Serra Neighborhood

The landslide Site C occurred on February 15, 2022 is located on the west slope adjacent to Ferroviarios Street with coordinates lat 22° 31'50.17"S. long 43° 10' 9.35"W. in Alto da Serra Neighborhood. The average gradient of the collapsed slope was approximately 35 degrees as read from the contour lines, and the length, average width and area of the collapsed slope were approximately 100 m, 60 m and 6,000 m^2 respectively, according to the satellite image. The length, average width and area of the deposited debris were approximately 200 m, 70 m and 14,500 m^2 respectively (**Fig. 19**).

The base rock is granite and is generally poorly weathered, but some areas were discolored due to weathering. As in Site A, the base rock also has overhangs that may be remnants of avulsion and landslide. The base rock was covered with soil less than 1 m thick, where vegetation was dominated by tall trees (**Fig. 20**). A house once existed on a talus deposits in the middle of the slope, but the landslide washed its foundation and everything else away. Today, only gate of the house and a part of concrete pavement remain. According to the municipality government official, the sediment which collapsed in the upper part of the slope swept away the talus deposit as well, resulting in an increase in the amount of sediment which flowed down the lower part of the slope. As a result, many houses were destroyed on the lower part of the slope. Although some residents were able to

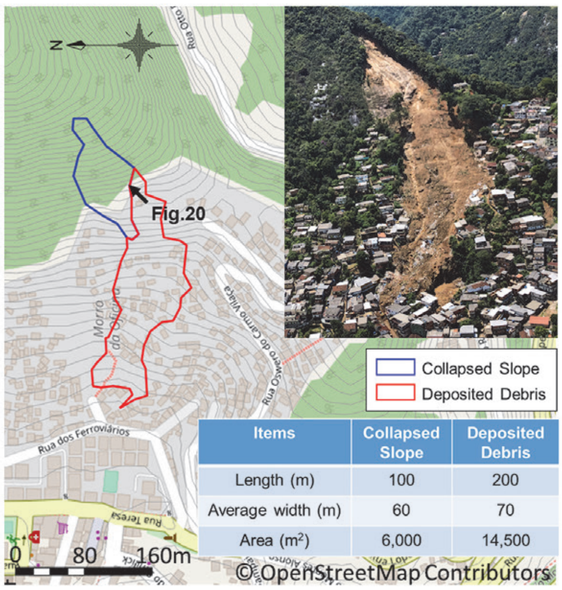


Fig.19 Topography and information of the landslide at Site C in Alto da Serra Neighborhood.

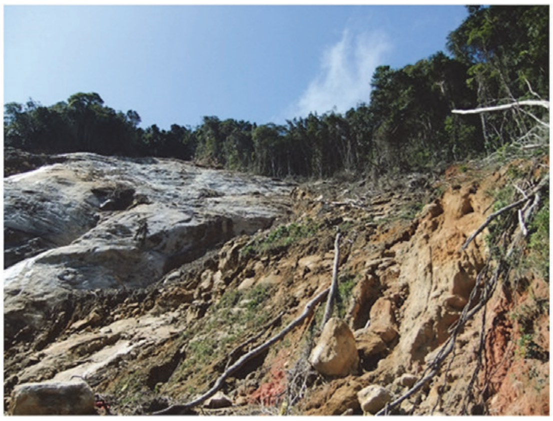


Fig.20 Situation of the landslide at Site C in Alto da Serra Neighborhood.

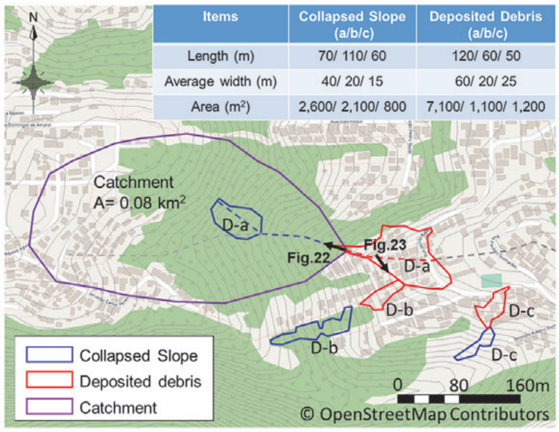


Fig.21 Topography and information of the landslides at Site D in Vira Felipe Neighborhood.

evacuate based on the early warning information issued by the municipality government, this site suffered the most human casualties in the disaster. Possible reasons for this include the relatively wide landslide width, the long debris depositional range due to the steep slope, the large amount of sediment transported by the erosion of talus deposit on the middle of the slope, and the development of residential land up to the slope. The reasons why many people did not evacuate despite the city issued the early warning information may include the possibility that the early warning information was not sufficiently communicated and that many people were under the impression that even if a landslide occurred, the sediment would not reach their houses.

3.4 Site D in Vira Felipe Neighborhood

Three landslides, namely D-a, D-b, and D-c occurred at this Site D in Vira Felipe Neighborhood. The coordinates of each landslide are lat 22° 32’4.15”S. long 43° 10’51.75”W., lat 22° 32’8.88”S. long 43° 10’ 48.80”W. and lat 22° 32’9.60”S. long 43° 10’40.56”W. respectively. Information on these landslides is shown in **Fig. 21**. Of these, the investigation results of the catchment which includes the landslide D-a, where the debris flow likely occurred, are described below.

The landslide D-a occurred on the left bank slope of the midstream of a drainage basin with a catchment area of 0.08 km^2. The sediment from the landslide flowed down the stream and eroded the streambed to expose fresh base rocks (**Fig. 22**). The sediment also destroyed several houses on the mountain side of Jacinto Rabello Street at the valley outlet. The sediment that flowed down the stream contained boulders and deposited as it fanned out from the valley outlet (**Fig. 23**).

The longitudinal profile of the landslide D-a and its downstream section is shown in **Fig. 24**. The catchment of 0.08 km^2 in area, streambed in the valley

Fig.22 Streambed eroded by debris from the landslide D-a.

Fig.23 Situation of debris containing boulders of 1 m diameter or less deposited downstream from the valley outlet.

section with a gradient of 15 degrees or more, sediment deposition area from the valley outlet with a gradient of 10 to 15 degrees downstream from the valley outlet meet the conditions for the occurrence of debris flows. As of the first week of May 2022, when the field investigation was conducted, it was not possible to observe the debris accumulation structure

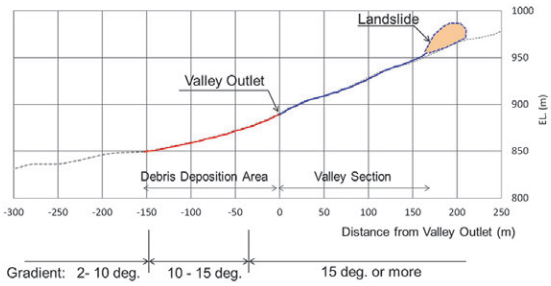


Fig.24 Longitudinal profile of the landslide D-a and its downstream section.

downstream of the valley outlet because most of the deposited debris had been artificially removed. However, the field conditions described above suggest that a landslide-induced debris flow likely occurred at this site. The reasons why the debris flow was stopped at the point around the 10-degree slope may be that the duration of the heavy rain was only about three hours causing relatively small amount of runoff, there were many boulders in the deposited debris, and houses crowded at the valley outlet acted as obstacles.

4. CONCLUSION

The landslides which occurred in the Petrópolis District on February 15 and March 20, 2022 were caused by the existence of cracks in a granitic bedrock parallel to the steep slope and weathered surface layer, and a short period of torrential rain.

In areas where many houses were damaged and fatalities were found, houses were disorderly constructed along valleys and on talus deposits covering steep slopes where there was a high risk of landslide disasters, such as Site B and Site C.

Most of the landslides were shallow landslides in which the weathered surface layer collapsed. However, the mass movement that occurred at Site D-a was a case considered to have occurred landslide-induced debris flow.

The issuance of early warning information and the designation of remaining mass movement risk area by the municipality government are believed to have contributed to the reduction of human suffering.

ACKNOWLEDGMENTS : We would like to thank Petrópolis Mayor Rubens Bomtempo, Civil Defense Director Gil Kempers, and other staff members of the municipality of Petrópolis for their cooperation in guiding us through the field investigation, introducing the site and providing materials. We also acknowledge CEMADEN for providing rainfall data.

REFERENCES

CEMADEN (2022) : Mapa Interativo da Rede Observacional para Monitoramento de Risco de Desastres Naturais do Cemaden [in Portuguese], http : //www 2.cemaden.gov.br/mapainterativo/#, accessed on 05/09/2022

Instituto Nacional de Meteorologia (2013) : Dados climáticos − Petrópolis [in Portuguese], https : //web.archive.org/web/20131205122502 / http : / / www . rio 2016. com / pregamestraining / sites / default / files / petropolis _ pt _ 1. pdf, accessed on 03/03/2022

Kamitani, M. (1984) : Geology and Carbonatite Deposits in Brazil(1), GSJ chishitsu news No. 362, pp. 24-27 [in Japanese], https : //www.gsj.jp/data/chishitsunews/84_10_05.pdf, accessed on 06/06/2022

Satriano, N. (2022) : Com 178 mortos, tragédia em Petrópolis é a maior já registrada na história do município [in Portuguese], https : //g 1.globo.com/rj/rio-de-janeiro/noticia/2022 / 02 / 20 / tragedia-em-petropolis-maior-registrada-na-historia-o-municipio.ghtml, accessed on 04/04/2022

Prefeitura Municipal de Petrópolis (2016) : Plano de Intervenção Ruptura de Encostas − Caetitu 01, pp. 11-13 [in Portuguese]

Received : 13 September 2022
Accepted : 2 November 2022