1. INTRODUCTION

As a direct result of continuous rainfall, following a small landslide occurring at about 18:30 on October 22, 2015, a large landslide occurred at about 2:00 am local time on October 23, 2015, on the left slope of the Garcia River, southern Blumenau, State of Santa Catarina-Brazil at about 2:00 am on Friday, October 23, 2015. The landslide appeared to be controlled by the high-intensity rainfall of 80 mm/2 days and duration rainfall of 354 mm/month in addition to unfavorable geological and geomorphologic settings. Landslide debris destroyed 4 houses at the base of landslide slope and completely dammed the Garcia River with a crest height of about 6.0 m above the streambed. Shortly after the landslide dam formed, the dam was filled completely with water and subsequently failed due to overflow and erosion. By the time of our site visit, the Garcia River has been partially blocked with an estimated water level of about 4.5 m above the streambed, creating a small potential for flash flooding and debris flow at the blockage. On December 3 to 4, 2015, Japan International Cooperation Agency (JICA) carried out an on-site survey, in response to the request of the Department of Geology and Natural Risk Analysis of Blumenau Municipality. The objective of the technical survey was to analyze the risk of landslides and provide some geotechnical recommendations for emergency measures and restoration countermeasure works relative to landslide dam.

Key words: hazard analysis, mass movement, landslides dam, geotechnical investigation, Blumenau, Brazil.

The landslide debris struck the community of Willy’s Rancho at the base of the landslide slope, seriously damaging 4 houses and temporarily damming the Garcia River. The landslide debris travelled downslope and partially into the Garcia River, and completely blocked the original course of the Garcia River, leading to changed flow course around the base of the landslide slope and formed landslide dam with a crest height of about 6.0 m above the riverbed. Shortly after the formation of the landslide dam it was immediately impounded to a depth of about 6.0 m above the valley and a length of about 250 m behind the dam, and then partially failed due to overflow and erosion. By the time of our site visit the Garcia River has been partially blocked at an estimated water level of about 4.5 m above the riverbed in the area of the natural dam.

The landslide debris still accumulates mostly on the
lower part of the landslide slope near the Garcia River. Once the foot part of the landslide debris is eroded and removed by the river flow, the landslide debris would move into the river valley and dam the river again. The downstream populations, specially the closest Progresso community, about 2.5 km from the landslide dam site is thus at high risk from the possible flash flooding and associated debris flow. In addition, the formation of landslide dam would submerge the Santa Maria Road around the landslide site, isolating upstream communities and schools located at approximately 3.0 km upstream of the landslide dam.

In this context, the purposes of this study were to assist and give some guidance and advice to the Department of Geology and Natural Risk Analysis of Blumenau Municipality on the evaluation and treatment of the landslide dam, as detailed below:

1) To discuss possible treatment and monitoring program of the formed natural dam with the Department of Geology and Natural Risk Analysis of Blumenau Municipality;
2) To inspect and observe the formed natural dam and then estimate its stability and potential hazards to downstream;
3) To observe landslide slope and define further instability or potential landslide zones;
4) To suggest geotechnical investigation program for further investigation and evaluations of the formed dam and its source slope;
5) To suggest monitoring system with respect to the formed dam and its source slope;
6) To suggest emergent measures to temporarily stabilize the remaining natural dam; and
7) To suggest restoration countermeasures for landslide control and natural dam hazard mitigation.

2. OUTLINE OF LANDSLIDE DAM OCCURRENCE

2.1 Study Area

The 23rd October 2015 landslide is located on an an east-facing natural steep slope along the Garcia River, about 2.5 km south of the Nova Rússia community (Fig. 1). At the toe of the landslide slope is the Willy’s Rancho community that consists of four families near the Garcia River. The Garcia River, a branch of the Itajaí-Açu River flows in a general north-southerly direction past the landslide slope, turns towards northeast-southwest through the Nova Rússia community and finally joins the Itajaí-Açu River within Blumenau City [Pozzobon et al., 2015].

The Santa Maria Road, a sole access to upstream communities runs generally along the Garcia River. The road is approximately 3 to 5 m higher than the riverbed in the vicinity of the landslide slope. At the impoundment of the landslide the road was locally submerged, leading to temporarily closed traffic. In addition, a water source site is located near the level of the Garcia River around the Nova Rússia community. The water source site supplies approximately 25% domestic water of Blumenau. The upstream landslide dam and subsequent flash flooding, as well as debris flow, pose a significant threat to the water source site.

2.2 Records of Past Instability and Landslide Dam Formation

On the basis of discussion with the Department of Geology and Natural Risk Analysis of Blumenau Municipality and review of available data and reports, the past slope instability and landslide dam formation is summarized below:

1) In 2011, two small landslides occurred on the same slope (refer to Fig. 2 below). They occurred along the channelized parts of the slope. The two landslides are shallow and presumably due to the erosion of surface water flow. No landslide dam was formed from the 2011 landslide.

2) The October 2015 landslide is bigger than the 2011 ones in size (refer to Fig. 2 below). It came down in twice; namely, first small landslide and second large landslide (refer to Fig. 3 A).

3) The first small landslide occurred down at about 6:30 to 7 pm on October 22, 2015 and formed a landslide dam. The landslide dam was overtopped and the impounded water flowed over the road and bridge in the vicinity of the Rancho community at about 8 pm on the same day. The height of the landslide dam formed by the first landslide is estimated to be 3 to 4 m above the riverbed.

4) About 7 hours later, at 2:00 am on October 23,
2015, the large landslide occurred and formed a larger landslide dam with a crest height of about 6.0 m, which completely dammed the Garcia River.

5) The larger landslide dam was completely filled with water within 5 hours since the formation of the landslide dam.

6) The dam immediately failed due to overflow and subsequent erosion and still blocked partially the river.

7) By the time of field visit (December 4th, 2015) the river has been partially blocked with an estimated water level of about 4.5 m above the riverbed.

Besides, the October 2015 landslide not only damaged 4 houses at the base of the landslide slope and also leaded to changed course of the Garcia River (Figs.3A & 3B). The landslide debris still accumulates mostly along the Garcia River.

2.3 Geological and Geomorphological Settings

Geologically, the landslide slope is located on the southern border of the Itajaí Basin (Santa Catarina state – Southern Brazil). The basin is an asymmetric basin, elongated approximately in the N 60 E direction. The Itajaí Basin is considered as a peripheral foreland basin related to the Dom Feliciano Belt. It presents an excellent record of the Ediacaran period, and its upper parts display the best Brazilian example of Precambrian turbiditic deposits [Basei et al., 2011]. Moreover, the southern border contact of the Itajaí Basin is predominantly tectonic, with the basal units being overthrust by banded tonalitic-granodioritic gneisses of the São Miguel Complex and by the metavolcano-sedimentary rocks of the Brusque Group [CPRM, 2014].

The landslide slope is located within the sedimentary rocks of the Gaspar Formation (Fig.4). The Formation Garcia corresponding to interspersed sandstones and shales with layers of conglomeratic sandstones, conglomerates and volcanoclastic rocks source. The Formation Gaspar, defined as
superimposed on the Formation Garcia, corresponds to the conglomerates, sandstones with subordinate portions of arkoses medium to fine.

As shown in Fig.4, the most important aspect of regional geological structures is the presence of the thrusting faults of northeast-southwest strike and the folds of northeast-southwest axis. Furthermore, other four systems of faults are present and they are 1) NE-SW fault, NNE-SSW fault, NW-SE fault and NNE-SSW fault. Satellite image interpretation using Landsat 7 (Fig.5) also shows that three preferred lineaments are clearly visible in the vicinity of the Nova Rússia landslide, namely, 1) NE-SW, 2) N-S and 3) NNW-SSE.

These geological structures largely contribute to the shearing/fracturing/weathering of sedimentary rocks, creating a geological setting in promoting deep-seated slope instability.

According to site observation, as described in the next section, abundant landslide and talus deposits widely and thickly cover the landslide slope with an estimated thickness of 2 to 5 m; this evidence indicates that the region, including the landslide slope, is geologically active.

Geomorphically, the landslide is situated at immediate downstream of narrow deep V-shape valley, about 20 to 25 m wide at the level of the riverbed. The landslide slope, about 200 m high, are very steep, about 35 to 40 degrees at the lower slope and 40 to 45 degrees at the upper slope.

As stated above, geologically active area together with steep narrow valley provides a high potential for forming the landslide dam.

2.4 Site Observations

The geologic materials comprising the landslide dam were derived from the sandstone and conglomerate rocks that forms the western wall of the Garcia valley. These materials range in particle size from clays to boulders with a max size of 2 to 3 m. At the time of field work, there was no flow of water along the original course of the river, instead, through the newly formed course; this indicates that the geological materials formed the landslide dam has low permeability and that no water flows through continuous voids in the dam (Figs.6 A & 6 B).

The observation results around the landslide slope are summarized below:

1) The landslide main scarp is straight, generally parallel with the original course of the Garcia River (Fig.7), indicating translational slide.
2) The landslide mainly involved colluvial deposits and the underlying highly weathered sandstone (Fig. 8 A). Three sets of joints, J 1 to J 3 (Fig. 8 B) well develop in the sandstone that forms the landslide slope. The landslide is a large translational rockslide that is controlled by geostructures in view of geological setting, as described before.

3) The landslide was estimated to travel downslope about 80 to 100 m from the height of the landslide main scarp (Fig. 7). The landslide debris mostly accumulates on the lower part of the landslide slope along the newly formed course of the Garcia River (Fig. 7) except for a limited volume that was eroded and removed due to the landslide dam failure.

4) Above the landslide main scarp, some minor scars are observable (Fig. 7). In addition, personnel from the Department of Geology and Natural Risk Analysis of Blumenau Municipality observed the presence of two sets of newly formed cracks on the upslope of the landslide, that is, a) N 30 W to N 45 W, and b) N 20 E. Especially the crack with a strike of N 30 W to N 45 W is generally parallel with the direction of the landslide main scarp; this indicates that the movement of the landslide contributes to the instability of the upslope.

5) A bundant spring water flows out between the colluvial deposits and the underlying bedrocks during rainfall. The contact between the colluvial deposits and the underlying bedrocks is geologically weak and a potential sliding surface in terms of strength and permeability. Because of the typically shallow depth (2 to 5 m thick), the colluvial deposits are particularly susceptible to rapid saturation from infiltration of surface runoff, direct infiltration of precipitation, groundwater seepage, or a combination of these sources of water. Shallow colluvial landslides are considered to be much likely to occur on the upslope of the slope.

In addition, abundant distribution of colluvial deposits around the landslide slope and its upslope indicates that the slope or area is geologically active – a frequent site of landslide and rockfall.

3. ASSESSMENT OF LANDSLIDE DAM HAZARD

3.1 Stability of the Remaining Landslide Dam

The geological materials of the landslide dam contain various sizes of particles, ranging from clays to big boulders. Especially fine-grained fractions such as clays and gravels are particularly susceptible to erosion and removal by flow water, as evident from the failure of the landslide dam due to overflow and erosion.

The remaining landslide dam is considered to be highly susceptible to erosion and removal little by little by the flow water of the river, especially by high-water-level flooding.

3.2 Stability of the Present Landslide Debris

As described previously, the present landslide debris travelled approximately 100 m downslope and accumulates along the river bank. Because of large displacement, the sliding surface has dropped into the level of residual strength and the present landslide debris is thus at critical condition.

The following three cases would contribute to instability of the present landslide debris:

1) The base part of the present landslide debris along the river is eroded and removed by the flow water of the river and surface water.

2) Landslide materials from the upslope slide down and accumulate on the head part of the present...
landslide debris.

3) Surface water collected from the upper slope of the present landslide debris flows into the sliding surface through the landslide main scarps.

3.3 Stability of the Slope above the Present Landslide

In 2013, the CPRM produced the Susceptibility Map of Landslides and Floods for the Municipality of Blumenau. The area of New Russia was indicated with high susceptibility to mass movements. Plus, the following facts or evidence observed at the site strongly suggest that the upper slope be particularly susceptible to further landslide and slope failure:

1) New open cracks on the upper slope were observed to be parallel with the main scarp of the present landslide; this indicates that the movement of the present landslide has served to destabilize the upslope of this landslide.

2) Abundant spring water flows out between the colluvial deposits and the underlying weathered sandstones, as observed on the main scarp face of the landslide; this indicates that potential sliding surface is present geologically between the colluvial deposits and the underlying weathered sandstones in terms of permeability and strength and that the colluvial deposits are much likely to slide down and extend progressively from the lower part to upper part of the slope.

3.4 Potential for Future Landslide Dam Formation

On the basis in the field investigation, as described above, we can envision three possible scenarios for future formation of landslide dam at the same landslide site, as follows:

1) A severe rainstorm, for example, as big as that in November 2008, could cause a high-water-level flooding. The flow water of such flooding would erode the base part of the present landslide debris near the river, disturbing the stability of the landslide debris; consequently, the present landslide debris would move down and then dam the river again. This scenario is considered to be much likely to occur, but could only form a small landslide dam, which is the same in size as before, with a crest height of 5 to 10 m.

2) A heavy rainfall triggers a shallow landslide on the upper slope; and the landslide materials would move down and load on the head of the present landslide debris, similarly disturbing the stability of the present landslide debris and consequently leading to the formation of landslide dam. Similar to the above-mentioned scenario, this scenario has a big chance of occurrence and thereby forms a small landslide dam with a crest height of 5 to 10 m.

3) As a result of a severe rainstorm, a simultaneous movement of a huge landslide (refer to Fig.2 before) and the present landslide debris would occur. This scenario is the worst possible, but is considered to have a small chance of occurrence. This scenario would form a large landslide dam with a crest height of 20 m or more, and therefore has a significant hazard to downstream in terms of major flash flooding and debris flow.

Because the catchment area is very huge, about 60 km², and narrow valley; once formed, such landslide dam would be immediately filled with water within several hours and then catastrophically fail, as observed in October 2015.

In addition, the nearest settlement downstream from the landslide dam is the Progresso community (Fig.1 above), which is 2.5 km distant.

Although the gradient of the Garcia River from the landslide site to the nearest downstream Progresso community is gentle, averaging 2 to 3%, there is sufficient water and sediment/debris in the impoundment of a large landslide dam, assumed to be 10 high or more, as discussed above, to cause a major flash flooding and debris flow that could reach the Progresso community.

4. GEOTECHNICAL RECOMMENDATIONS AND SUGGESTIONS

4.1 Geotechnical Recommendations and Suggestions

Listed below is a prioritized list of actions to mitigate future landslide dam hazards to downstream populations.

1) Installation of Water Level and Rain Gauges

Install, immediately, one water level gauge and one rain gauge in the landslide site.

At the time, the water level gauge needs to be at about 80 to 100 m upstream of the landslide dam. If available, another water level gauge should be installed at immediate downstream of the nearby bridge. Fig.9 shows the tentative locations of water level gauges.

In addition, rain gauge shall be installed within the village above the Santa Maria Road around the landslide dam.

Seeing as no water level and flooding information are available in the Garcia River, alert water levels for the landslide dam site are tentatively determined in view of the previously formed landslide dam as follows:

1) Normal water level: 3.0 to 4.0 m above the present riverbed
2) Warning water level: 6.0 m above the present riverbed.
3) Evacuation water level: 8.0 m above the present riverbed

Warning water level assumes that a landslide dam with a crest height of about 6.0 m, similar to the height of the previous landslide dam, has a limited hazard/threat to downstream populations, as shown evidently from the formation and failure of previous landslide dam.

Similarly, evacuation water level assumes that a large landslide dam with a crest height of 8.0 m or more poses a significant hazard to downstream populations once failed.

The above-mentioned tentative alert water levels at the landslide dam site should be estimated and improved as rainfall and water level information is collected from the installed equipment.

Furthermore, the cancellation of warning must be discussed with municipality technicians and then decided. The criteria for the cancellation of warning are tentative as follows:

- No precipitation for over 24 hours is confirmed; and
- The drawdown of water level as low as the normal water level is checked from the results of monitoring and observation for over 24 hours.

(2) Construction of Inspection Paths

As stated above, the landslide debris accumulating along the Garcia River and landslide slope are at critical conditions, and therefore, regular inspection by visual observation and simple measurement should be conducted to early recognize the abnormal phenomena, collapse, deformation or crack, which could avert a disaster.

The regular inspection shall focus on the landslide debris area and the upslope of the landslide areas, especially paying more attention to deformation and cracks on slopes, as well as small collapses and springs (amount and location number). The results of inspection shall be recorded and filed as a database.

The inspection should be conducted basically after rainfall. The points to observation/inspection and records are listed as follows.

On the landslide area and its upslope
(a) Head scarp
(b) Cracks, subsidence, depressions
(c) Small collapse
(d) Distribution and amount of spring water, etc.

And on the present landslide debris area
(a) Deformation
(b) Base of the bulge
(c) Scour of surface water and water flow
(d) Spring water and conditions of drainage

In addition, to supplement the regular inspection/observation, we recommend installing Displacement Measurement to monitor the amount of crack opening, as shown in Fig.10. Also, the Displacement Measurement can be utilized in an emergency if an extensometer cannot be installed because of large displacement.

(3) Emergency Measures

The following emergency measures should be immediately performed to maintain the stability of the landslide debris:

1) Gabion wall + geotextile along the base of the landslide debris. In order to minimize and control erosion of the landslide debris by the flowing water of the river, a gabion wall of about 2 to 3 m in height should be constructed along the residual landslide dam (Fig.11).

2) Temporary ditch on the upslope of the landslide. The ditch covered with plastic sheet should be provided on the upslope of the landslide to control or prevent flowing of surface water into the landslide debris.

(4) Installation of Ground Extensometer

It is necessary to install 2 to 3 ground extensometers on the upslope of the landslide, across a crack or
depression in a row (Fig.12). Ground extensometers can be used to continuously monitor and record the movement of a potential landslide by recording the change of a distance between two points on a ground surface. Very useful information about the movement characteristics of a landslide can be obtained by continuing the monitoring through a rainy season. It can be used to find the causal relationship between the continuous movement and rainfall.

At the landslide site, these ground extensometers can be utilized to early find and warn the landslide hazard on the upslope. Information regarding standard values is not available in Blumenau; some standard values that have been widely used in Japan are revised and selected conservatively as tentative standard values for this site [Ayalew et al., 2011; JICA, 2015], as shown in Table 1. These standard values should be improved as rainfall and displacement information is collected from the installed equipment.

Monitoring data are not only used to activate warnings, but their continuous analyses also help to improve and update the designated critical values themselves. In addition, the ground extensometer can also be used for disaster management during the construction of restoration.

Table 1 Attempt to standardize the values related to the soil extensometer. Source: JICA (2015).

| Alert level  | Standard value | Observations                      |
|--------------|----------------|-----------------------------------|
| Normal       | Less than 1mm/h |                                   |
| Attention    | 1 – 2mm/h       | Reinforcement of periodic inspection |
| Alert        | 2 – 4mm/h, and 10mm/24h |            |
| Evacuation   | Above 4mm/h, and 100mm/24h |       |

(5) Light Laser Measurement Using Non-Prism or Prism Total Stations

Prism Total Station is available in the Department of Geology and Natural Risk Analysis of Blumenau Municipality. We recommend using the equipment to monitor and observe the movement of the present landslide debris and its upslope.

In that it is dangerous or difficult to place Prism in the landslide debris, alternatively, we recommend introducing Non-Prism Total Station (REMOTO 2) from Japan to monitor and observe the movement of landslide debris and its upslope. Available measuring range by REMOTO 2 is about 1,000 m with reflective sheet. [Higuchi et al., 2008]

(6) Geological and Topographic Surveys

It is necessary to hold topographic and geologic surveys for the purpose of restoration countermeasure design and potential large landslide assessment. The geological risk mapping needs to be updated annually since the occupation is extremely dynamic and difficult to control by the municipalities.

(7) Construction of Restoration Countermeasures

It is crucial issue to protect the Garcia River against further landslide dam that would be formed by the present landslide debris or by instability of the upslope. Thus, the following restoration countermeasures are recommendable:

1) Change of the river course, generally along the newly formed course of the Garcia River.
2) Check dam, two to three sites.
3) Embankment loading, in general between the new river course and base of the slope.

The change of the river course into the right side of the original course is to reduce and control the present landslide debris erosion by flowing water of the river and also provide a place for construction of embankment loading.

Check dams is planned to protect river banks from erosion and stabilize the landslide debris foot.

Embankment loading is planned to improve the stability of the present landslide debris by banking.
debris to be excavated for the new river course and by compacting the present landslide debris. In addition, the embankment loading can also provide some places to catch landslide debris from further instability of the slope above the present landslide debris.

The layout and basic design shall be carried out based on the topographic and geologic surveys.

5. CONCLUSIONS

Therefore, this study presented a preliminary assessment and recommendations of Landslide Dam, in the southeast of Blumenau, Santa Catarina State-Brazil, based on field investigations and available data. There is a high potential for future formation of landslide dam at the same site, due either to further movement of the landslide debris toward the river or to a shallow landslide on the upslope of the landslide. The formation of the landslide dam and subsequent flash flooding and debris flow poses significant hazard and risk to downstream populations. It is suggested for geological risk mitigation that geotechnical measures are executed. Disaster management in urban areas also assumes that it is necessary to define very quickly what is most critical within a generally problematic context and that non-structural medium- and long-term measures are also required.

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