DERIVING LANDSLIDE DAM GEOMETRY FROM REMOTE SENSING IMAGE AND RAPID HAZARD ASSESSMENT

Jia-Jyun Dong [*a] *,Yun-Shan Li* [b] *and Wen-Shung Li* [c]

[a] Associate Professor, Graduate Institute of Applied Geology, National Central University,
300, Jhongda Rd., Jhongli, Taoyuan 32001, Taiwan; Tel: + 886-3-4224114;
E-mail: jjdong@geo.ncu.edu.tw

[b] Graduate student, Graduate Institute of Applied Geology, National Central University,
300, Jhongda Rd., Jhongli, Taoyuan 32001, Taiwan; Tel: + 886-3-4227151#65853;
E-mail: prettypatty7639@hotmail.com

[c] Graduate student, Graduate Institute of Applied Geology, National Central University,
300, Jhongda Rd., Jhongli, Taoyuan 32001, Taiwan; Tel: + 886-3-4227151#65853;
E-mail: zzxx72106@yahoo.com.tw

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ABSTRACT: The blockage of a river by landslide could induce upstream (rising backwater) and down stream (dam breaching with outburst flood and debris flow) impacts. Since the related hazards might occur soon after a landslide damming the river, promptly taking a measure based on the rapid assessment is crucial. However, the dam geometry, which relevant to the hazard evaluation, is not available for most of the cases. This research proposed a procedure utilizing the orthophotos from remote sensing images, digital terrain model (DTM), and GIS to rapidly evaluate the dam geometry. First, the location of a landslide dam can be identified from the satellite images. Secondly, the elevation of dam crest can be determined based on the orthophotos (after dam forming) and DTM (before dam forming). Accordingly, the dam geometry and potential hazards associated with the formation of landslide dams could be assessed rapidly. The proposed procedure for estimating the elevation of dam crest is validated by a real case (Namasha landslide dam) in Taiwan. The elevation of dam crest derived by the proposed procedure is similar to that from profile leveling after the formation of the landslide dam. Based on the evaluated dam geometry, the dam breakage induced hazards can be assessed within three hours after the orthophotos are available. The case history successfully illustrated the satellite images and the DTMs could be efficiently served as the useful data for decision maker on the action of hazard mitigation soon after the formation of a landslide dam.

1. INTRODUCTION

Based on a data set of 204 cases, Peng and Zhang (2011) documented that half of the landslide dams failed within a week. Regarding the catastrophic disasters caused by outburst floods and debris flows, which frequently occur soon after the forming of a natural lake, rapidly assessing the hazards related to the landslide-dam breaking is essential (Schuster and Costa, 1986). Generally, the hazard from a landslide dam-break flood of an existing landslide-dammed lake can be expressed as the product of the probability for an outburst flood from the dammed lake and the probability of spatial (downstream) impact by an outburst flood (Korup, 2005). The probability for an outburst flood from the dammed lake and its spatial impact are associated with the dam stability and peak flow of the outburst flood, respectively. Currently, the geomorphic approach is widely used to correlate the river, dam, water-storage characteristics with the landslide dam's stability (Costa and Schuster, 1988; Ermini and Casagli, 2003; Korup, 2004; Dong et al., 2009; Dong et al., 2011) and the peak outflow rate from breaching of landslide dams (Walder and O'Connor, 1977; Costa, 1985; Costa and Schuster, 1988; Peng and Zhang, 2011). However, the dam geometries such as dam height, length, width and volume, which are critical factors relevant to the hazard evaluation, are difficult to obtain within a week for most of the cases. How to derive the dam geometry quickly is therefore become an important issue from the hazard mitigation viewpoint.

If the DTMs (Digital Terrain Model) of a landslide site are available before and after the dam formation, the dam geometry can be easily evaluated from the GIS (Geographic Information System) platform. Usually, only the topography before the newly formed landslide dam is available. High resolution airborne LiDAR has been successfully utilized to evaluate the geomorphological characteristics of large landslides and related dams (e.g. Chang et al., 2006; Chen et al., 2006). However, to produce the DTM from LiDAR is still time consuming regarding to the requirement for first-order assessing the related hazards of a landslide dam. Dong et al. (2011) utilized aerial photographs and 5 m DTMs before the dam formation and after dam breaching to evaluate the geometry of a partly breached landslide dam. Hydrology analysis, laboratory work and extensive field-investigation results are used to reconstruct the dam geometry successfully. Because of the time constraint, detail field and desk works are nearly impossible. Could it be possible to derive the dam geometry with adequate accuracy only from remote sensing images, DTM, and GIS? To what extends the resolutions of remote sensing image and DTM affect the evaluation results of dam geometry? How much time is required to evaluate the hazards of landslide dam for the first-order estimation? To answer those questions, this research proposed a procedure utilizing the orthophotos from remote sensing images, DTM, and GIS to evaluate the dam geometry. A landslide dam case in Taiwan (Namasha landslide dam) is used to demonstrate the influence of the data resolutions on the dam geometry determination and down stream hazard evaluation. In addition, the required time for assessing the outburst flood induced hazards is evaluated.

2. NAMASHA LANDSLIDE AND RELATED DAM

In Aug. 2009, Typhoon Morakot brought intense rainfall to southern Taiwan. Hourly rainfall records from the nearby Jiashian #2 rainfall stations indicate a total of 2138 mm of accumulated rainfall during Aug. 7-11, 2009. The peak hourly rainfall intensity was 95 mm/h, and the rainfall duration was 99 hours. The heavy rainfall triggered 17 large landslides that resulted in the formation of dams (Chen and Hsu, 2009). One such landslide dam, Namasha landslide dam, was located at the Minshan village, Southern Taiwan; Figure 1 (a)). The Namasha landslide dam can be identified from a high-resolution aerial photograph taken by the Aerial Survey Office, Forestry Bureau, Taiwan after Typhoon Morakot (Figure 1 (a); X: 120°44’39.44’’ and Y: 23°19’39.49’’). The 1:50,000 scale geologic map (Sung et al., 2000) is shown in Figure 1 (b). Miocene Changchikeng Formation outcropped at the landslide site. The landslide area is about 138 ha. The debris formed a fan and mainly deposited on the channel of Cishan River.

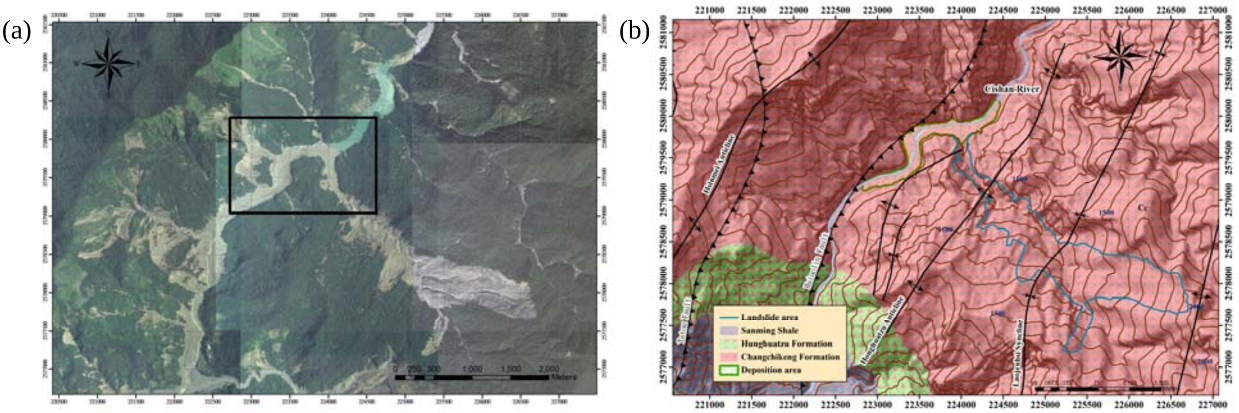

Figure 1. (a) Namasha landslide and landslide dam at the Minshan village, Southern Taiwan. This high-resolution aerial photograph was taken at Aug. 24, 2009, about two weeks after the typhoon. The black square represents the area of Figures 2 and 3. (b) The 1:50,000 scale geologic map near the Namasha landslide dam site.

To evaluate the related hazards of the landslide dams, the dam geometry is essential. Usually, it is difficult to get the post-event DTM soon after the formation of a landslide dam. To estimate the dam geometry quickly, a procedure using the post-event orthophoto from remote sensing image and DTM before the landslide dam formation is suggested. The used remote sensing images and DTMs, as well as the proposed procedure, are described subsequently.

3 REMOTE SENSING IMAGES AND DTMS

In this study, orthophotos from high-resolution aerial photograph and 5 m DTM (provided by the ASOFB; Aerial Survey Office, Forestry Bureau, Taiwan) were used to evaluate the dam geometry. In addition, the orthophoto from FORMOSAT-2 satellite image and 40 m DTM, were also used to assess the influence of the data resolution on the dam geometry determination. The images and DTMs used were shown in Figure 2.

4. THE PROPOSED PROCEDURE AND EVALUATED DAM GEOMETRY

First, the location of a newly formed landslide dam can be identified easily by satellite images when a clear image is available. The breaching point of the Namasha landslide dam is at E: 224034 and N: 2579895 (TWD97). Accordingly, the catchment area of the Namasha landslide dam can be determined as 210 km^2 using the DTM on the GIS platform (eg. ArcHYDRO tool).

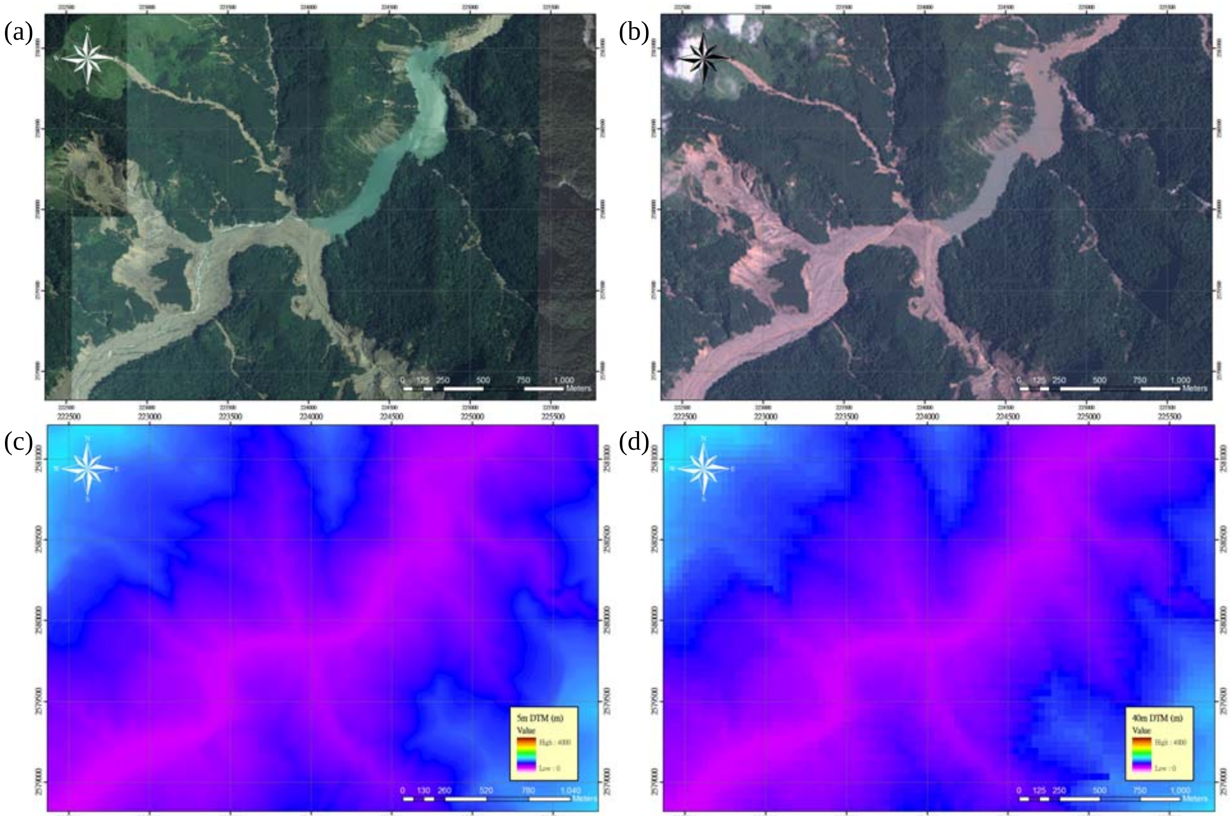

Figure 2. Orthophotos from (a) high-resolution aerial photograph (same image as Figure 1 (a)) and (b) FORMOSAT-2 satellite image (taken at Aug. 15, 2009); DTMs with (c) 5 m and (d) 40 m resolution.

Secondly, contours with different elevations from DTM can be generated. Overlap the contours on the orthophoto through the GIS platform one by one. The elevation of the best fitted contour to the water-land boundary of the dammed lake on the orthophoto indicates the water surface elevation of the lake. If the landslide dam overtopped, the water surface elevation will identical to the elevation of the dam crest at the breaching point. Figure 3 shows the elevation of water surface and the breached point on the dam crest is about 800 m. Notably, since the image has been taken northward, the water-land boundary on the southward bank could be covered by tress.

Figure 3. A contour with elevation of 800 m generated from the 5-m DTM which best fit the water-land boundary identified from the high-resolution aerial photograph.

Thirdly, reference points of the dam crest could be identified from the boundary of vegetant and bare land. Figure 4 shows several blue circles with blue numbers indicating the reference points related to the elevation of the dam crest. Accordingly, the contours of the dam crest can be extrapolated (brown lines) from the elevation of the reference points and the dam shape can be estimated. It is notable that the landslides or erosion occurred on the river banks could seriously affects the elevation determination for the dam crest. Efforts should be made to carefully extract the influence points of landslide and erosion on the river banks and the induced errors could be minimized.

After the formation of the Namasha landslide dam, seven profiles (A1-A7 in Figure 4) were selected to monitor the elevation changes of the channel by Forestry Bureau, Taiwan (National Cheng Kung University, 2010). To validate the proposed procedure for determining the dam geometry, the profile leveling results at 2009 Oct. 29 (about 2 months after the dam forming) were used to compare the results deriving from image and DTM. Figure 5 shows the seven profiles with the results from leveling (red short dash lines) and from the proposed procedure (blue long-short dash lines). The induced errors of the estimated elevation of the dam crest are general less than 10 m. It is illustrated that the rapidly evaluated dam shape agrees well with the leveling results. Base on the evaluated elevation of the dam crest and the pre-event 5-m DEM, the dam height is 60 m. The cross-river length and along-river width of the dam is 180 m and 2200 m, respectively. The volume of landslide dam is about 8.9×10^6 m^3. From the pre-event 5-m DEM and the elevation of breaching point, the maximum lake volume is 8.9×10^6 m^3 (neglected the influence of sediments from the upstream of the dam after the Typhoon Morakot). Notably, the dam height, length and width are the dimension of the landslide dam passing through the breaching point.

5. DISCUSSION

5.1 Assessing the Down Stream Hazards Using the Evaluated Dam Geometry

The hazard induced from the outburst flow of dam breaking is related to the failure probability of the dam (i.e., the susceptibility) and the spatial impact of the peak flow (Korup, 2005). The landslide-dam hazard then can be assessed by a matrix combined with landslide-dam failure probability and the spatial impact of the peak flow to the down stream (Yang et al., 2011). The failure probability of the landslide dams $P_f = e^{-L_s} / (1+e^{-L_s})$ with different dam geometry can be calculated using Logistic model (Dong et al., 2011) as follows:

$$L_s = -2.22\log(A) - 3.76\log(H) + 3.17\log(W) + 2.85\log(L) + 5.93 \qquad (1)$$

where A(m^2), H(m), W(m), L(m) are the catchment area at the upstream of landslide dam, dam height, width and length, respectively.

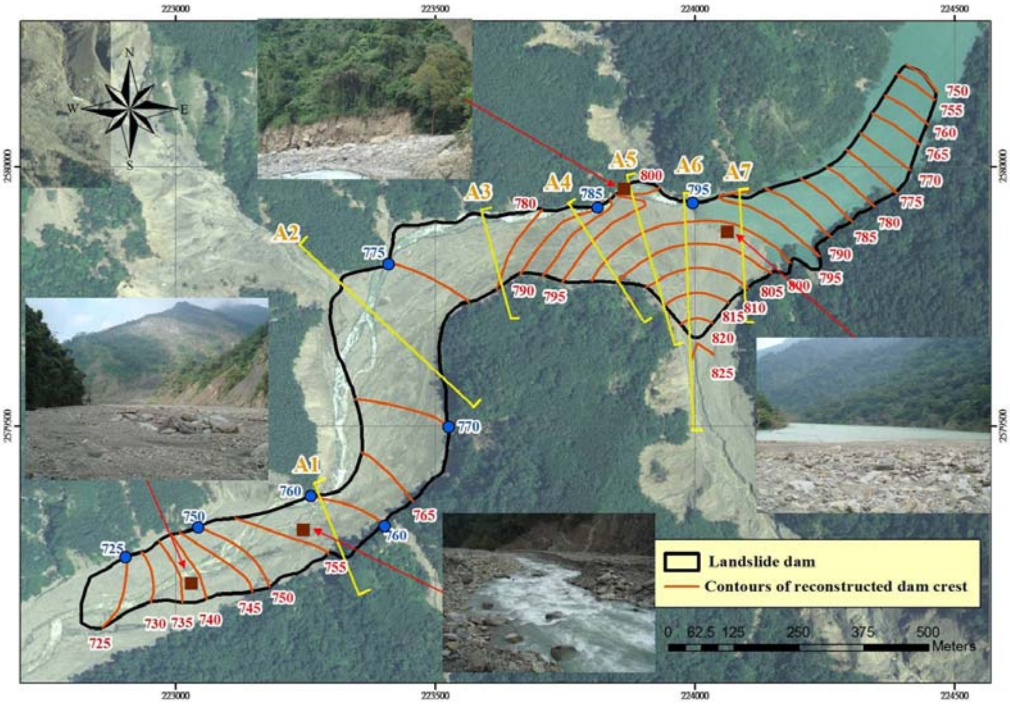

Figure 4. The rapidly evaluated dam shape. The brown lines are the contours of the estimated dam crest.

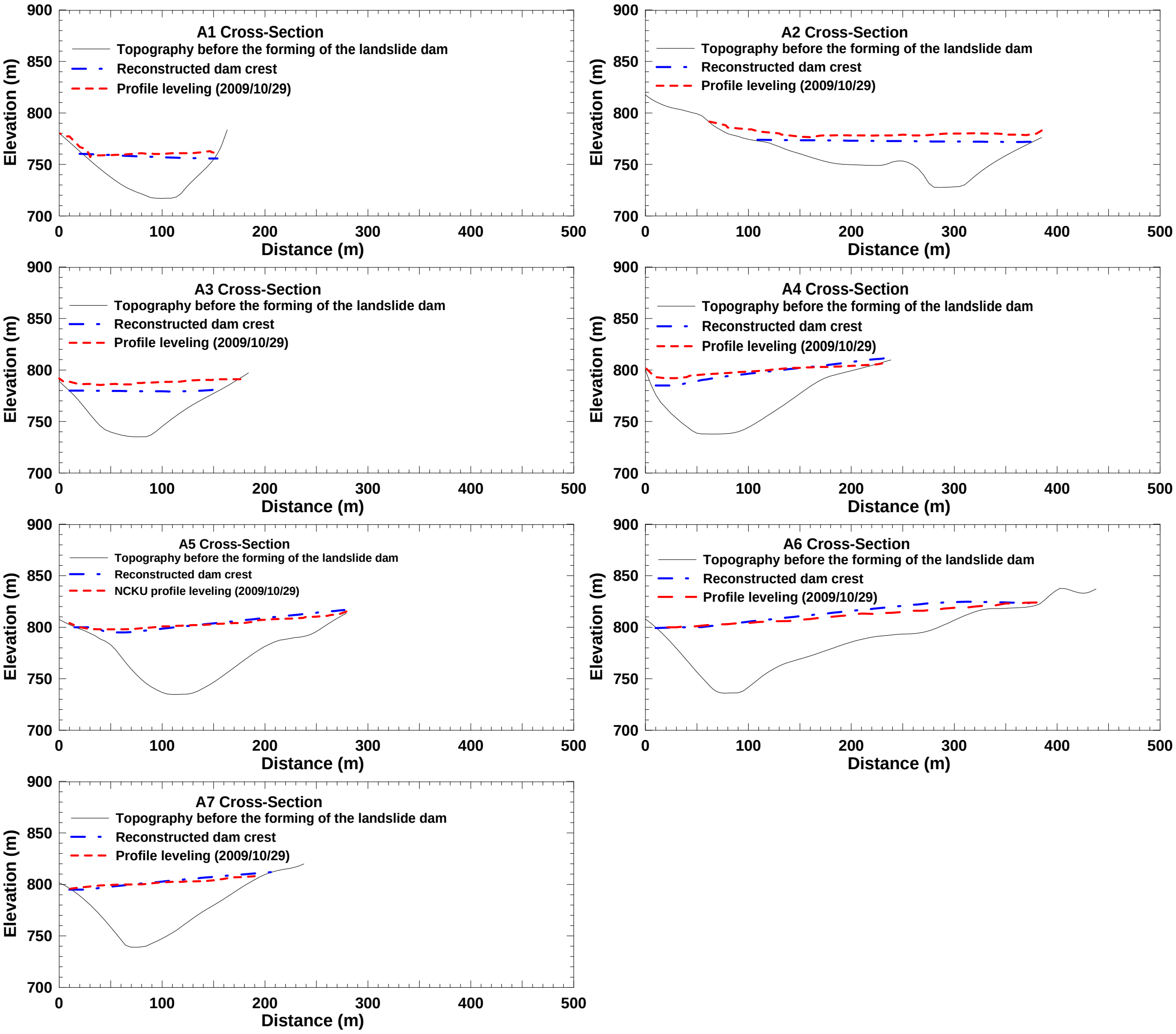

Figure 5. Elevations of the dam crest from leveling (red lines) and estimated by the proposed procedure.

A peak-flow influence ratio (breaching peak-flow divided by the design peak flow) was introduced by Yang et al. (2011) to evaluate the spatial impact of the outburst flood. The design peak flow down stream is available for the main rivers in Taiwan. The peak flow of a breaching landslide dam (Q_p (m^3/s)) can be determined empirically or numerically. For demonstration, this research introduced an empirical equation proposed by Costa (1985) as follows:

$$Q_p = 181(H \cdot V_l)^{0.43} \qquad (2)$$

where V_l (10^6 m^3) is the lake volume. Based on the aforementioned method, the failure probability of the Namasha landslide dam is 90% and the estimated peak flow is 2833 m^3/s. The design peak flow is 2236 m^3/s (Yang et al., 2011). Since the Namasha landslide is high failure probability and high spatial impact, the landslide dam breaking hazard can be categorized as high level.

The Namasha case consumed 3 hours to derive the elevation of dam crest, the relevant parameters and the down stream hazard. Chen et al. (2005) documented the orthophotos from SPOT5 image can be produced in 28 min if an “adaptive patch projection” scheme is adopted for a test site with area of 3600 km^2. That is, once the clear images are available, the dam breaching hazard could be assessed within four hours. The results indicate that the proposed procedure is potentially useful for the first order evaluation of the hazard related to the outburst from landslide dam breakage.

5.2 Influence of the Resolution of the Images and DTMs

The high-resolution aerial photograph is not always available soon after the formation of a landslide dam.

Relatively, the FORMOSAT-2 have an advantage of high spatial resolution (2-m panchromatic and 8-m multispectral) as well as a high temporal resolution (1 day). This study used the 40 DTM and orthophoto from FORMOSAT-2 satellite image (Figure 2 (b) and (d)) to evaluate the influence of resolution of data on the hazard evaluation results. As expected, the required time for hazard evaluation is not significantly influence by the data resolution. The evaluated dam height and dam length are 45 m and 175 m, respectively. Therefore, the failure probability of the dam is 85% while the peak flow of the outburst flow is 2503 m^3/s. About 6% and 12% difference of the susceptibility of dam failure and spatial impact of the outburst flow. It is indicated that the 40 DTM and FORMOSAT-2 satellite image are useful for the first order hazard evaluation of a landslide dam.

6. CONCLUSIONS

This research proposed a procedure utilizing the orthophoto from high-resolution aerial photograph, 5-m DTM and GIS to evaluate the dam geometry rapidly with adequate accuracy. Therefore, the potential hazards associated with the landslide dam breakage could be assessed within three hours if the orthophoto from a remote sensing image is available. The case history of the Namasha landslide dam illustrated that the FORMOSAT-2 satellite image and the 40 m DTM could also be efficiently served as the useful data for decision maker on the action of hazard mitigation soon after the formation of a landslide dam.

7. ACKNOWLEDGEMENT

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