Application of High-Resolution SAR Satellite Images to Landslide Disasters
- Report on landslide-dam formation and collapse events in the Kii Peninsula, Japan and Ambon, Indonesia -

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We attempted to establish a method for quickly determining (monitoring) the state of disaster when any large-scale landslide disaster occurs by interpreting high-resolution SAR satellite images, which can be acquired even at night or during bad weather, in Japan and overseas. We identified the locations of many landslide dams sooner than by other methods by interpreting SAR satellite images acquired at the time of the Typhoon Talas (Typhoon 12) disaster that occurred in the Kii Peninsula of Japan in September 2011, and utilized these as data for preliminary investigations. In July 2013, we quickly observed the collapse of a large-scale landslide dam on Ambon Island, Indonesia, using SAR satellite images, estimated the state of collapse using a DEM created from analysis of satellite stereo-pair images, and provided the information to the Indonesian government. In this paper, these two cases for which high-resolution SAR image interpretation was actually used at the time of disaster are reported.

Key words: landslide dam, SAR image, interpretation, emergency search

1. INTRODUCTION

It is important to acquire a complete overview of a large-scale landslide disaster in order to respond appropriately. However, it is very difficult to obtain complete information about a disaster if the disaster-hit area is in a mountainous region, if the disaster occurs at night or in bad weather conditions, or if it occurs over a wide area. In such cases, monitoring the disaster using high-resolution synthetic aperture radar (SAR) satellite images, which can be acquired even at night or during bad weather, is very effective.

We were able to find the locations at which multiple landslide dams had formed earlier by interpreting SAR images than by using other methods when Typhoon 12 struck the Kii Peninsula in September 2011 and utilized these SAR data, for the first time in Japan [*Hayashi et al.*, 2012], as the basic data for early investigation of an actual landslide disaster. We also used SAR images to monitor the formation and collapse of landslide dams on Ambon Island, Indonesia in July 2013 and quickly provided the Indonesian government with information about the state of the disaster.

Therefore, we report here the first cases of actual use of high-resolution SAR interpretation in Japan and in a different county for urgent response to a landslide disaster.

2. SEARCH FOR LANDSLIDE DAMS CREATED BY TYPHOON 12 IN KII PENINSULA IN SEPTEMBER 2011

2.1 Response to landslide dam disasters by interpretation of satellite SAR images

When danger is expected as a result that a large-scale landslide dam occurred, the Japanese government must implement the landslide disaster emergency investigation based on the Sediment Disaster Prevention Act. So we intended to find the locations at which multiple landslide dams had formed earlier by interpreting SAR images than by using other methods when Typhoon 12 struck the Kii Peninsula in September 2011. We interpreted data from the German high-resolution SAR TerraSAR-X satellite (wavelength: X band; polarized wave: HH; shooting mode: strip map; resolution: approx. 3 m; observation width: approx. 30 km in the east–west direction × approx. 50 km in the north–south direction; angle of incidence: 39.21°; ascending orbit; SAR irradiation from the west; process level: GEC (geo-coded, ellipsoid corrected)) acquired on September 5, 2011, after Typhoon 12 had passed, to locate landslide dams.

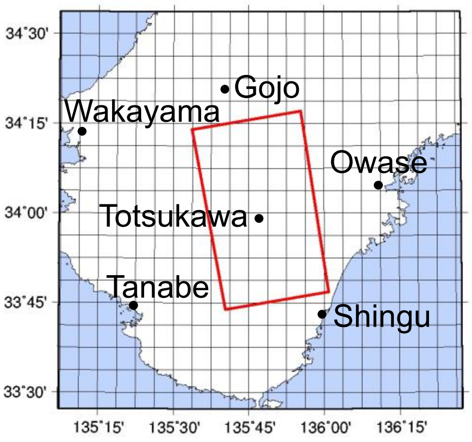

Fig. 1 Area of SAR image

Table 1 Timeline of the emergency search

<u>**September 5, 2011**</u>
Around 01:30 Requested TerraSAR-X observations
14:00 Identified only the Nagatono landslide dam due to thick clouds
17:53 Acquired the TerraSAR-X image
At this time, location information for the Nagatono landslide dam was sent to engineers (approximately 10 team members) for interpretation.
Around 21:00 Began interpreting the SAR image
The engineers confirmed the Nagatono landslide dam, looked for the same pattern of the dam, and found six high and four low reliability points over a period of approximately 4 h.

<u>**September 6, 2011**</u>
Around 01:30 Finished the interpretation
Around 02:00 Sent the location information to the Kinki Regional Development Bureau
Around 10:00 Identified the Akadani and Kuridaira landslide dams by helicopter based on the location information
Evening Press release regarding implementing the landslide disaster emergency investigation based on the Sediment Disaster Prevention Act

<u>**September 8, 2011**</u>
Issued the landslide disaster emergency information
Gojo city and Totsukawa village issued evacuation orders to residents and residents evacuated.

The range of shooting is shown in **Fig. 1**, which is centered around Totsukawa village in Nara prefecture. Rain from the typhoon fell until the morning of September 4; a timeline of image interpretation after this date is shown in **Table 1**.

For the interpretation, we referred to municipality boundary GIS data, ALOS pan-sharpen images preceding the disaster, and a 10-m mesh DEM of the Geospatial Information Authority of Japan. As in this case, it is necessary for proper interpretation of high-resolution SAR satellite images to collect information related to the disaster, such as the results of helicopter and ground investigations, reference information such as optical satellite images acquired before the disaster, news reports, etc. This information can enhance the interpretation of images and assist in comprehensively judging whether or not a landslide dam has formed.

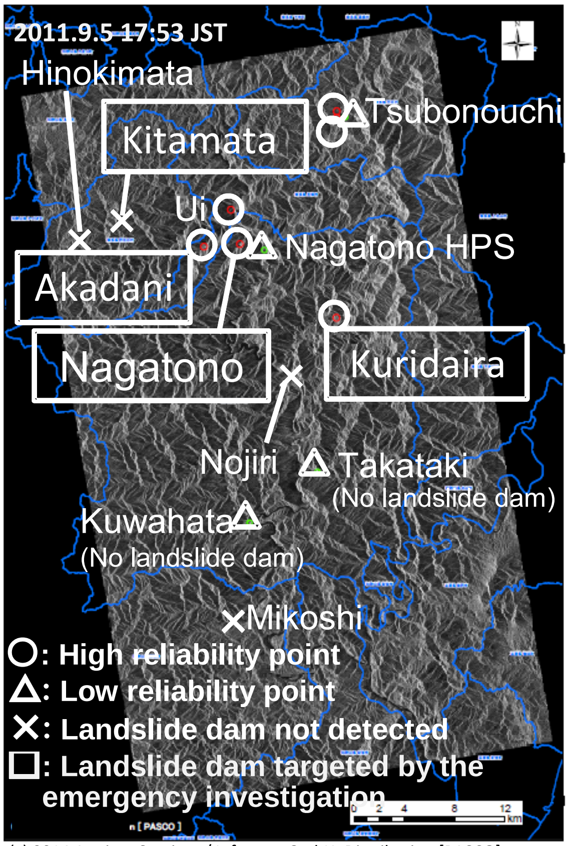

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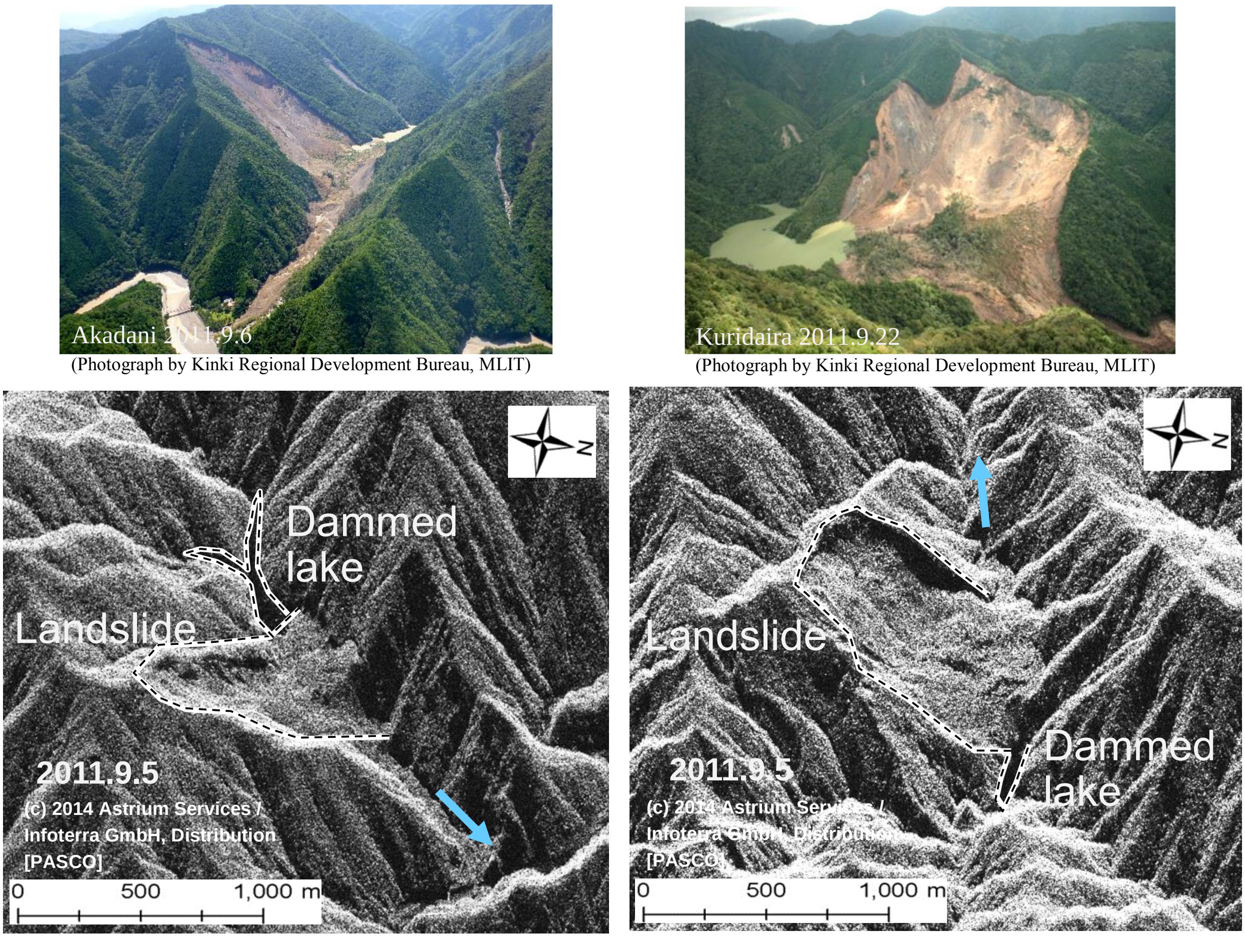
Fig. 2 Detected landslide dam candidates and evaluation of detection

By interpreting the satellite SAR images, six locations with high reliability (including the Nagatono area) and four locations with low reliability were extracted as locations where landslide dams had formed, as shown in **Fig. 2**.



Akadani Kuridaira

Fig. 3 Enlarged images of landslide dams targeted by the emergency investigation under the sediment disaster prevention act

As a result of the extraction of this time, it was confirmed that landslide dams had formed at all six of the high-reliability locations, including the Akadani and Kuridaira areas, which became the subject of an emergency investigation (**Fig. 3**). Additionally, a landslide dam (Tsubonouchi) and a large-scale slope failure were found from the four low-reliability locations.

However, four landslide dams and large-scale slope failures (Kitamata, the subject of an emergency investigation, Hinokimata, Nojiri, and Mikoshi) could not be extracted because of the direction of radar irradiation, the angle of incidence, and so forth. It is considered that such overlooking of landslide dams are mostly caused by small scale of a landslide dam and a dammed lake, or early overflow from the dam, or shadowing of a mountain, or layover of a slope by image property.

Although there is limited time for taking measures against a disaster, it may be possible to improve the accuracy of interpretation by interpreting from two ascending and descending orbits, from a different direction of radar irradiation, or from different angles of incidence. Eventually, from the 11 landslide dams formed within the area of the SAR images, seven locations were extracted (Akadani, Nagatono, Kuridaira, Ui, and three locations in Tsubonouchi), four locations could not be extracted, and two locations were mistakenly extracted. The total number of landslide dams formed in Kii Peninsula, including the area outside of the SAR images, was 17 locations.

2.2 Method for searching for landslide dams by interpreting single-polarization SAR images

When searching for the locations of landslide dams using SAR images, the topographic features of landslide dams to be searched are dammed lakes, landslide scar, and colluvium that blocks a river channel. We prepared a checklist (**Table 2**) by summarizing the important points of view during interpretation of standard interpretation criteria based on the actual processes of interpretation at the time of Typhoon 12 in 2011, the characteristics of the SAR images mentioned in 2.1, and the previously mentioned topographic features to be searched [*Udono et al*., 2012]. And, by this check list, we can already carry out interpretation at the time of disaster.

Table 2 Interpretation checklist (single-polarization)

The order of confirmation

Range of confirmation	Check item	Judgment criteria	Evaluation
River channel	Dammed lake	-Is there any dark area assumed to be a dammed lake? -Is the width unnatural compared to the upstream/downstream width? -Is it the water in an artificial structure, such as a dam, intake weir, etc.	
Geographic features of the surrounding area	Gradient of slopes	-Are there any slopes around the dammed lake? -Do the slopes around the area have a steep gradient, which implies occurrence?	
Landslide	Sliding cliff	-Are there any sliding cliffs observed around the dammed lake? -Is there any shadow layover caused by steps around the sliding cliff? -Is the shape of the sliding cliff arc-shaped against the direction of the slope?	
	Interior of the landslide scar	-Is there any shape reminiscent of slope failure beneath the sliding cliff? -Is the shape of the slope failure coherent with the direction of the slope?	
	Colluvium (the area that blocks the river channel)	-Is there colluvium in the landslide scar and at the bottom? -Does the colluvium have a tongue-like shape? -Is the reach of colluvium coherent with geographic features? -Did the area that blocks the river channel form in a way such that the valley was buried? -Is there a reservoir upstream from the area that blocks the river channel? -Are there any shapes of fallen trees or other debris on the colluvium?	
	Scale of landslide	-Is the scale of collapse large enough that it may cause blockage of the river channel?	
	Texture of the image	-Is the surface inside the landslide scar, the colluvium, etc., smoother than the area of forest in the peripheral region?	
Relative location	Relation between the upstream and downstream regions, etc.	-Are there any unnatural points in the relationships among the locations of the sliding cliff, landslide scar, dammed lake, etc.? -Is the reach of the colluvium coherent with the geographic features?	
	Structures around the site	-Is there a split road network in the area around the site? -Is there any situations in which a buried building, etc., is observed?	
Judgment			

The checklist items and points to note for each range of confirmation are explained below.

1) When checking river channels

-Check the dammed lake

Search for dammed lakes formed by landslide dams. It is assumed that dammed lakes appear black, and it is necessary to confirm these areas by comparing the upstream and downstream widths of the river channel and by checking that the water-covered area is not a reservoir of an artificial structure, such as a dam, intake weir, or other.

2) When checking the surrounding geographic features

-Check the gradient of slopes

In order to confirm whether a dammed lake is caused by landslide, it is necessary to check the existence and gradient of slopes in the surroundings.

3) When checking landslide scar

-Check the sliding cliffs

In order to confirm the existence of landslide scar, check the existence of sliding cliffs, the characteristics of the image, shapes, etc.

-Check inside the landslide scar

Confirm whether there is any slope failure shape beneath the sliding cliff and whether the direction of the slope failure matches the direction of the slope.

-Check the colluvium (the area where the river channel is blocked)

The sediment of a landslide dam fills the valley immediately below the dammed lake and forms a tongue-shaped mound. Confirm the existence of the colluvium from which a landslide dam is identified and its reach. In some cases, the existence of fallen trees on the colluvium may be confirmed.

-Check the scale of landslide

Confirm whether the scale of landslide is large enough to create a landslide dam.

-Check the texture of the image

The surface inside the area of landslide scar, the colluvium, and so forth often have more even texture than forests because of differences in the state of the ground cover in forests, and these areas can, in some cases, be identified on the image.

4) When checking relative location

-Check the relation between upstream and downstream areas, etc.

Check whether there is any discrepancy among the locations of identified geographic features, such as upstream and downstream areas, dammed lakes, landslide scar, and the colluvium that blocks the river channel, and also check the coherence between the reach of the colluvium and geographic features, etc.

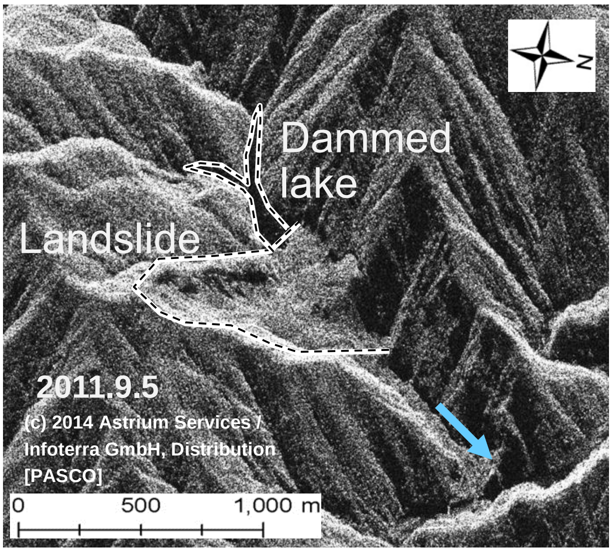
-Check the structures around the site

Check whether there are any split road networks, buried buildings, or other disturbed structures.

5) Other points to note

The interpretation checklist of **Table 2** was created while bearing in mind its utilization in practical operations, as outlined below.

- -Prepare per potential location of landslide dam
- -Check all the items from the top and evaluate in each of the three levels (○, △, ×). During interpretation, when rapid work is required, we may often waver in our judgment. Therefore, we decided to evaluate using ○ when the reliability is considered high, △ when it is considered low, and × when it is impossible to interpret.
- -Judge by referring to the result of the evaluation for each item. The evaluation result may not necessarily be ○ or △ for all items, thus we decided to apply the three evaluation levels for judgment every time. If there is any fear of a landslide dam, the location is judged to be a subject of investigation (△).
- -Save the checklist as the reason of judgment



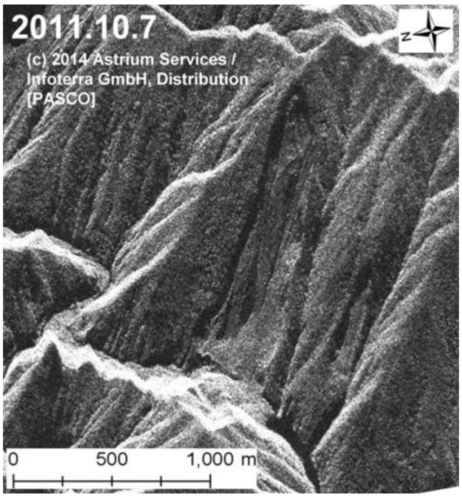
Range of confirmation	Check item	Evaluation
River channel	Dammed lake	○
Geographic features of the surrounding area	Gradient of slopes	○
Landslide	Sliding cliff	○
	Interior of the landslide scar	○
	Colluvium	○
	Scale of landslide	○
	Texture of the image	○
Relative location	Relation between the upstream and downstream regions, etc.	○
	Structures around the site	×
Judgment		○

Fig. 4 An example of interpretation (Akadani area)

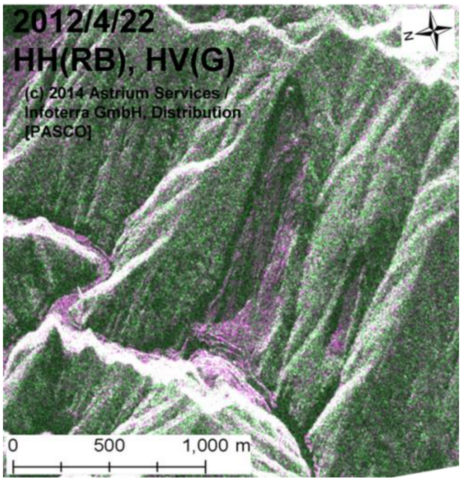
The interpretation checklist of **Table 2** is a list of qualitative judgment criteria, but it is considered that such standardization contributes to significantly decreasing the differences that exist among the results of interpretation performed by different persons. An example of interpretation using the checklist is shown in **Fig. 4**.

2.3 Dual-polarization SAR images of the Kii Peninsula landslide dam

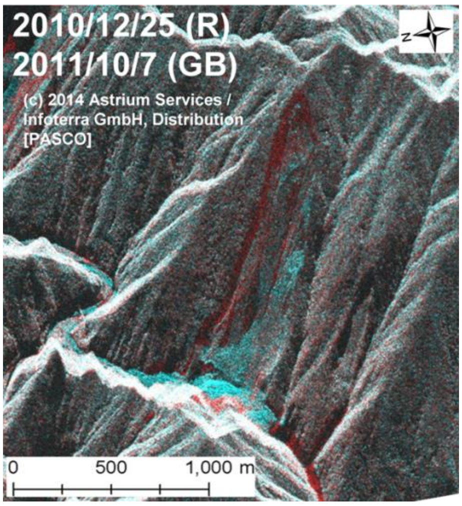
A problem with single-polarization SAR images is that it is difficult to interpret the state of ground cover, and landslide dams may thus be overlooked easily. As a trial to improve future interpretation technique and visibility, we are considering utilizing dual-polarization SAR images or SAR images from the two periods before and after the occurrence of the disaster [*Mizuno et al*., 2013].



Single-polarization SAR image



Dual-polarization SAR image (HH+HV)



SAR images of the two periods

(Red: Image before landslide, December 25, 2010;
Green, blue: Image after landslide, October 7, 2011)

Fig. 5 Dual-polarization SAR image and SAR images from before and after the disaster（Akadani area）

As for HH or VV, backscattering intensity is large in the landslide scar and denuded land, small in the forest. As for HV or VH, backscattering intensity is large in the forest, small in the landslide scar and denuded land. Therefore we can extract the place that changed into the denuded lands from the forest as the landslide scars when we use a (HH+HV) dual-polarization SAR image. A dual-polarization SAR image and SAR images from before and after the occurrence of a disaster are shown in **Fig. 5**.

In the dual-polarization SAR image, red and blue are used for the HH-polarized waves, and green is used for the HV-polarized wave, shown by superimposing them. In the SAR images of the two periods, which are superimposed, red is used for the image before landslide, and green and blue are used for the image after landslide. After landslide, the backscattering intensity of the dammed lake is indicated small and in red. Other features also make it easy to interpret.

Thus, by using different colors for different polarized waves or different periods, it is expected that locations of landslide will be expressed clearly, and it becomes easy to search for landslide dams.

3. RESPONSE TO THE COLLAPSE OF A LANDSLIDE DAM IN AMBON IN JULY 2013

A deep-seated landslide occurred on the east bank of the Way Ela River on Ambon Island, Maluku Province, Indonesia, and a large landslide dam was formed from the sediment of the landslide. The water level at the landslide dam increased gradually, and overtopping began after heavy rain on July 24, 2013. The dam failed at about 10:30 JST on the following day (July 25).

According to an announcement from the Indonesian National Board for Disaster Management and local news reports, a mudflow with a depth of 6 or 7 m struck a village, causing damage to at least 470 houses and major facilities such as schools and mosques and the evacuation of at least 5,200 residents. Three people perished in the disaster.

Because the disaster was a large-scale collapse of a landslide dam, as described above, the National Institute for Land and Infrastructure Management (NILIM) in Japan requested SAR shooting just after the collapse for the purpose of emergency monitoring of the disaster and discerned the situation by using high-resolution X-band SAR TerraSAR-X images for three periods: before formation of the landslide dam (December 23, 2011); after formation of the dam (December 9, 2012); and after the collapse (July 28, 2013). The range of the shooting is shown in **Fig. 6**, and the details of the shooting data are listed in **Table 3**. The shooting data are illustrated in **Fig. 7**.

The results of the interpretation and analysis of the satellite images, and other information, as described above, were immediately provided to the Indonesian government by the Ministry of Land, Infrastructure, and Transport (MLIT) of Japan.

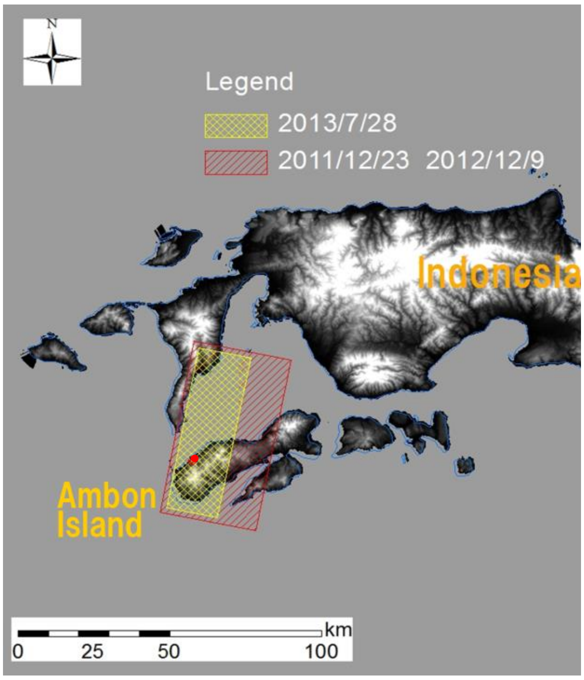


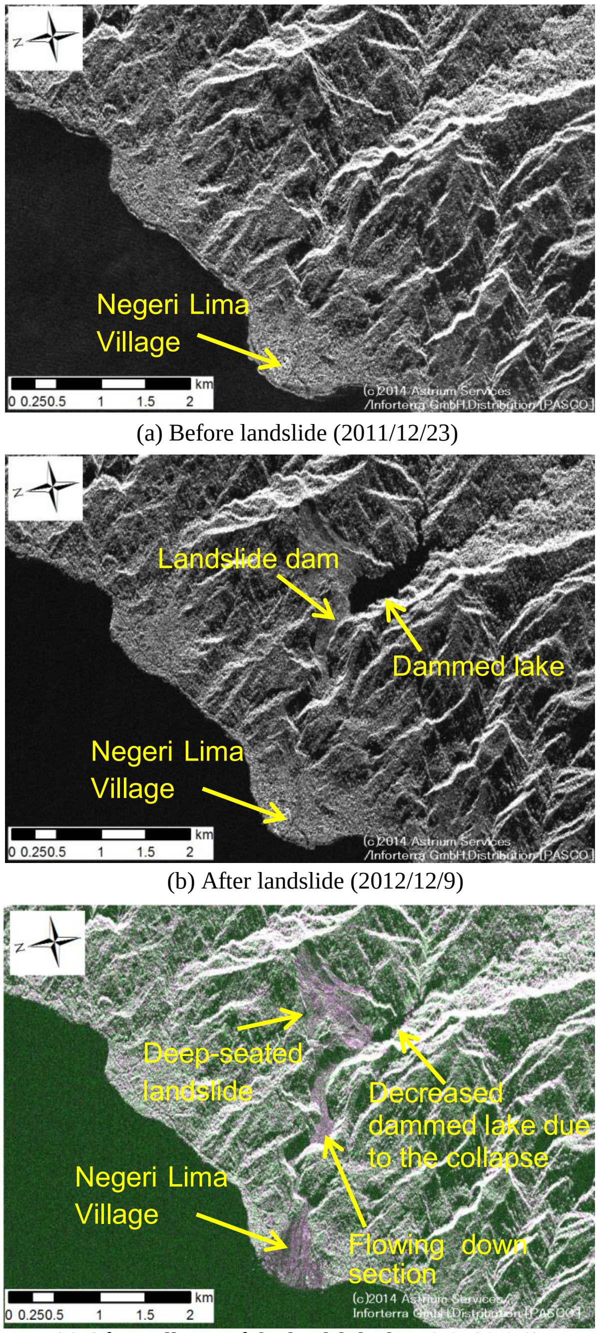
Fig. 6 The area captured by TerraSAR-X

Table 3 TerraSAR-X data specifications

Date	Acq. mode	Inc. angle	Resolution	Pol.
2011/12/23	Strip map	41°	3 m	HH
2012/12/9	Strip map	41°	3 m	HH
2013/7/28	Strip map	41°	6 m	HH+HV

3.1 Urgently discerning the state of collapse using superimposed single-polarization SAR images

Superimposed images from before and after the formation of the landslide dam (RGB images) are shown in **Fig. 8**, with RGB allocated as R to December 9, 2012, and G and B to December 23, 2011 (intensity images). The range indicated as "dammed lake" is assumed to be the range where the backscattering intensity decreased compared to its value before the formation of the landslide dam because of reflections from the water surface affected by the water level, which became higher due to formation of the landslide dam after the deep-seated landslide occurred on the east-bank slope and blocked the river channel. The range



(a) Before landslide (2011/12/23)

(b) After landslide (2012/12/9)

(c) After collapse of the landslide dam (2013/7/28)

Fig.7 SAR image of Ambon

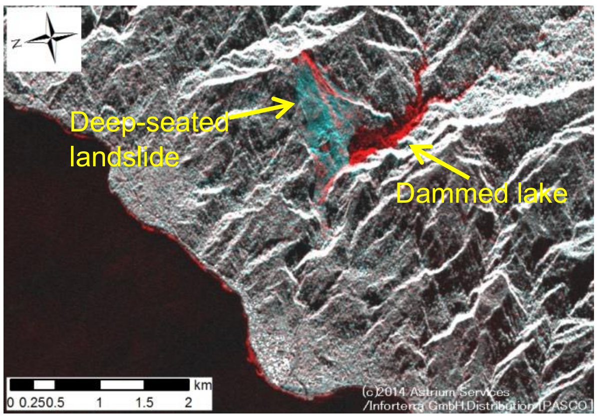


Fig. 8 Stacking of SAR images of Ambon (before and after landslide)

indicated as "deep-seated landslide" is assumed to be the location where the backscattering intensity increased compared to the time period before formation because of an increase in the degree of roughness of the land surface caused by the deep-seated landslide. Clear geographic features of a ridge are visible at the location where the landslide occurred in the before- landslide image.

Based on the interpretation result of the superimposed before and after landslide dam images, it was assumed that deep-seated landslide occurred from the top of the slope and extended a width of ~260 m at the top of the slope and ~900 m at the bottom. The sediment of the landslide flowed partially downstream, but most of it stopped directly beneath the landslide site. The total length of the landslide dam was as long as ~900 m, and the dammed lake, with a maximum estimated width of at least 300 m, extended ~1,700 m upstream.

Fig. 9 Optical image of Ambon (before collapse of the landslide dam) (Photograph by the public works ministry of Indonesia)

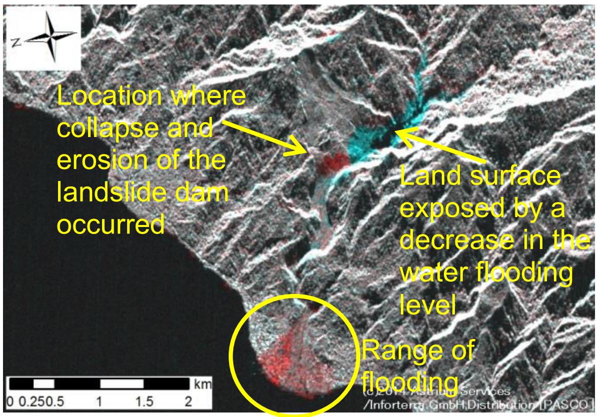


Fig.10 Stacked SAR images of Ambon (before and after collapse of the landslide dam)

A photograph of the region after formation of the landslide dam taken from a plane by the Indonesian government is shown in **Fig. 9**. The landslide dam formed in the downstream area of the Way Ela River, and the valley exit is at ~1 km downstream from the landslide dam. At the valley exit, an alluvial fan has formed along the seashore, and many buildings can be observed on the surface of the fan.

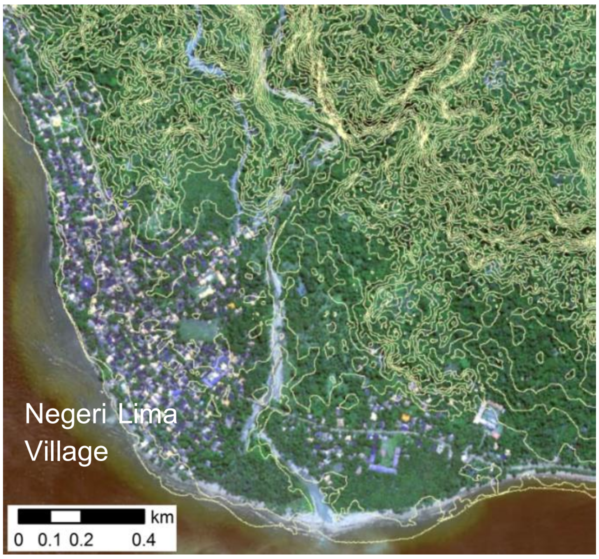
Superimposed images from before and after collapse of the landslide dam are shown in **Fig. 10**, with RGB allocated and expressed as R to July 28, 2013, and G and B to December 9, 2012. In the image, the collapsed part of the landslide dam and the range of flooding are indicated in red, which indicates the range where the backscattering intensity decreased compared to its value before the collapse. The range where the water level decreased and the land surface was exposed because of water behind the landslide dam flowing out is indicated in blue, and this area represents the area where the degree of roughness and backscattering intensity increased compared to the pre-collapse condition.

Table 4 High-resolution optical satellite images used for creation of the DEM

	Satellite name	Resolution	Date of shooting	Shooting angle
Before collapse	WorldView-2	0.5m	2012/10/08	28.0°
	QuickBird	0.6m	2012/12/29	25.9°
	WorldView-2	0.5m	2013/02/02	5.1°
	WorldView-1	0.5m	2013/02/05	32.2°
	WorldView-1	0.5m	2013/02/08	40.7°
	WorldView-1	0.5m	2013/02/08	41.8°
	WorldView-2	0.5m	2013/02/10	18.5°

3.2 Evaluation of the risks associated with the landslide dam remaining after collapse

To discern the form of the landslide dam and the geographic features of the river basin, which include the flooding area, after formation but before collapse of the landslide dam, we prepared a 2-m mesh DEM (after formation and before collapse) of the landslide dam in the Way Ela River basin by stereo-image analysis of high-resolution optical satellite images. Specifically, because the frequency of cloud cover is high at the Way Ela River basin because of its climate, the DEM was created by combining multiple stereo-pair images using the optical images shown in **Table 4** (seven pre-collapse scenes). Additionally, ASTER-GDEM Ver.2 (30-m mesh, accuracy in the vertical direction of ~10 m) was used supplementally for locations that were in areas not affected by changes in geographic features caused by the landslide dam and covered with clouds that prevented creation of a DEM. A correction for the height of trees (average height of bushes: 10 m; average height of tall trees: 15 m) was implemented based on the result of an on-site investigation of the height of trees in the area around the village in the downstream reaches that would become the flooding area when the dam collapsed (DEM before collapse). The created DEM is shown in **Fig.11**.



Contour interval: 5 m
Background image: February 2, 2013, WorldView-2

Fig. 11 2-m mesh DEM (downstream area) after formation but before collapse of the landslide dam

Subsequent to the landslide dam collapse and flooding, NILIM and the Public Works Research Institute (PWRI) determined the state of collapse of the landslide dam and evaluated the risks associated of the landslide dam remaining after the collapse using the after-formation and before-collapse DEM of the landslide dam, the result of a sounding of the dammed lake before collapse by the Indonesian government, and the before-collapse and after-collapse SAR images shown in **Fig.10**.

As a result, the state of the site was assumed to be as follows.

-The flooding area of the range limited to the land where there was a clear change, such as collapsed houses and overturning of living trees, between the before and after collapse condition is ~370,000 m^2. Note that the entire range of flooding is larger than this. And the outflow flood quantity was ~13,000,000 m3.

- To discern the form change of the dammed lake before and after collapse of the landslide dam, we overlaid 3 types of images as described above, and compared those. From these results, we assumed to the form of the landslide dam after collapse. Consequently, the water depth of the remaining dammed lake is around 30 m, the altitude of the crown of the levee of the landslide dam decreased by ~55 m because of erosion (it actually was ~65 m), collapsed to ~140 m above sea level (it actually was ~130 m), and the height of the landslide dam was halved from ~110 to ~55 m (it actually was ~45 m). Thus, the length of the crown of the levee (the length in the direction of vertical section of the mountain stream) became longer, to 400 m or more, because the top part of the levee was eroded. Based on the reasons above, it is expected that the existing landslide dam will not collapse again.

-Adequate caution must be exercised in the event of an enlarged collapse from the side of the deep-seated landslide where the bottom is washed out by erosion.

From the above-mentioned information, the collapse situation of the landslide dam was reported to the Indonesian government and announced publicly by MLIT on August 5, 2013.

4. CONCLUSIONS

We interpreted SAR satellite images urgently to utilize these as data for preliminary investigations in landslide-dam disasters in the Kii Peninsula, Japan and Ambon, Indonesia. From these results, our conclusions are as follows:

-If the disaster-hit area is in a mountainous region, if the disaster occurs at night or in bad weather conditions, or if it occurs over a wide area or in a foreign country, monitoring the disaster using high-resolution SAR satellite images, which can be acquired even at night or during bad weather, is very effective.

-By using different colors in SAR images for different polarized waves or different periods, locations of landslide scar will be expressed clearly, and it becomes easy to search for landslide dams.

Currently, data from the SAR satellite operated by Germany, Italy, and Canada are generally available. Additionally, the operations of the domestically produced ALOS-2 launched in May 2014 will start. It is expected that those data will be utilized greatly in the disaster prevention area.

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