

Geometric Correction and Soil Volume Estimation in Debris Flow Areas Using LiDAR data

Po-Jui Huang (1)(2), Min-Lung Cheng (1), Masashi Matsuoka (1), Hiroyuki Miura (3)

¹ Tokyo Institute of Technology, 4259-G3-2, Nagatsuta, Midori-ku, Yokohama 226-8502, Japan

² National Central University, No. 300, Zhongda Rd., Zhongli Dist., Taoyuan City 32001, Taiwan

³ Hiroshima University, 1-4-1 Kagamiyama, Higashi-Hiroshima 739-8527, Japan

Email: huang.p.ad@m.titech.ac.jp; cheng.m.ab@m.titech.ac.jp; matsuoka.m.ab@m.titech.ac.jp; hmiura@hiroshima-u.ac.jp

KEY WORDS: LiDAR, 3D nonlinear mapping, debris flow, soil volume

ABSTRACT: Debris flow prevention and post-disaster management are important in Japan because of the wide coverage of hillsides. These areas are vulnerable and might cause severe damages and casualties during heavy rainfall periods or by other natural disasters. With the aid of advancements of remote sensing technologies, to monitor the debris flow can become efficient and precise. Among them, this study exploits light detection and ranging (LiDAR) associated with its high-resolution digital elevation model (DEM) to analyze and supervise the debris flow. In order to increase the reliability of post-hazard analysis and achieve early-stage recovery soon after a disaster, this paper tries to map the debris flow areas and calculate the difference of soil volumes by pre- and post-event LiDAR-derived DEMs. However, the geometric position inconsistency might happen when mapping DEMs from varied LiDAR instruments. To solve such a problem, 2D nonlinear mapping algorithm and a 3D nonlinear mapping approach are proposed in this study. In addition, the soil volume changes caused by debris flow can be estimated by DEMs of difference (DoD). This paper takes the debris flow occurred in Hiroshima city on August 20th, 2014 as an example to validate the developed method. A non-debris flow area is selected to observe the discrepancies of DoD maps produced via 2D corrected, 3D corrected and uncorrected DEMs. By comparing the results, the 3D corrected DEM is able to calculate the variation of soil volumes more accurate.

1. INTRODUCTION

Japan is widely covered by the mountainous and hillside areas. In some of these areas, the geological conditions are fragile that surface is easily destroyed by heavy rainfall, debris flows, or others natural disasters. For example, there were debris flows caused by rainfall happening in Hiroshima city, effecting few deaths, injuries and damages of buildings in July, 2010 (Hiroshima Prefectural Government, Japan, 2010). On August 20th, 2014, Hiroshima city again suffered severe debris flow triggered by heavy rainfall, leading to 74 deaths, 44 injuries, and more than 4500 buildings were damaged (Cabinet Office, 2014). More recently in 2018, Western Japan suffered a number of debris flows and flooding by heavy rainfall with statistic data of 118 deaths, 27 injuries and more than 7500 buildings were damaged (Ministry of Land, Infrastructure, Transport and Tourism, 2018). Within a decade, many debris flows took places in western japan, making the land surfaces become more vulnerable than before. Thus, debris flow prevention and post-hazard management are becoming more and more important in Japan in order to reduce the loss of life properties.

The detection of landform change is a key component of debris flow study. The acquisition of accurate topography information is an important element in the overall geomorphic assessment process. Such information can be obtained from land survey, optical imagery, radio detection and ranging (RADAR), and light detection and ranging (LiDAR). In the past decade, the application of LiDAR has been successfully used to generate precise and comprehensive topographical information in disaster areas. Although LiDAR can provide instinct three-dimensional (3D) cloud points of the surface, to process large numbers of 3D points is a time-consuming procedure. To detect the debris flow, a digital elevation model (DEM) derived from LiDAR is one of the suitable presentations for surface change analysis. In terms of debris flow detection by using LiDAR-derived DEMs, DEMs of difference (David Williams, 2012) is one of the feasible mechanisms to recognize debris flow areas in a very short period.

In order to manage the early-stage recovery planning soon after a disaster, LiDAR-derived DMEs of pre- and post-disaster are utilized to estimate the land surface change. This study tries to investigate the variations of soil volumes before and after a disaster via DEM of difference (DoD) as an indicator for land surface change. However, geometric information between two DEMs might be inconsistent due to different instruments used. The geometric errors show up in unaffected areas caused by geometric inconsistency which would create a distorted DoD map and misestimate soil volumes. In order to solve this problem, a two dimensional (2D) nonlinear mapping method is to detect and modify the deformation of DEM

by finding shifting vectors in x and y directions (Kosugi, 2004). Also, such a method can be used to correct the two DEMs and create a DoD map to estimate soil volumes (Miura, 2015). However, the 2D nonlinear mapping method, which consider planar information acquiring from DEMs only, is slightly inadequate to detect practical land surface changes without the inclusion of elevation data. In order to improve the reliability of the soil volume estimation by DoD maps, a three dimensional (3D) nonlinear mapping method, including correction of geometric errors of elevation, is proposed in this paper. The method improves the process for modify the geometric inconsistency and generate a more reliable DoD map by considering completed 3D spatial information. Experimental results show that the proposed method can estimate the soil volume differences more accurate than using 2D information only. As a consequence, the 3D nonlinear mapping method is more reliable when utilizing LiDAR-based DEMs for change detection of land surface.

2. STUDY AREA AND DATA USED

The study area locates in Hiroshima prefecture, the western part of Japan. The target areas include a part of Asaminami-ward (Yagi-Midorii area) and Asakita-ward (Kabe area) where debris flows triggered by a heavy rainfall on August 20, 2014. The area of Yagi-Midorii region is about 9 km² and the area of Kabe is around 36 km². A major reason to select these two study sites is that they are widely covered by mountainous and hillside landforms, where are suitable for post-disaster investigation and analysis by the proposed method.

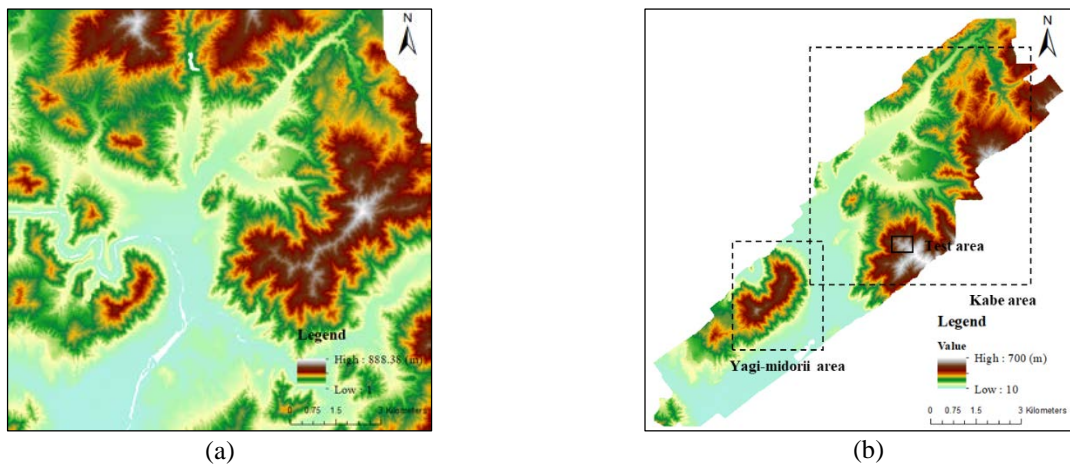


Figure 1. Pre- and post-event DEMs of the study sites (a) pre-event DEM generated in 2013. (b) post-event DEM measured on 27th, August, 2014.

The pre-event DEM derived from LiDAR data is accessed from the Geospatial Information Authority of Japan in 2013 with spatial resolution of 5 meters in Figure 1(a). For the post-event DEM acquisition, LiDAR data measured on August 27th, 2014, one week after the disaster is manipulated to generate the DEM with spatial resolution of 1 meter, showing as Figure 1(b). In order to utilize the pre-and post-event DEMs for debris flow detection, the pre-event DEM is resampled to spatial resolution of 1 meter by bilinear interpolation so that resolution of the pre- and post-event data are consistent for further usages. To examine the feasibility of the proposed method, which uses nonlinear mapping to detect the differences between two DEMs, the test sites are focused on the regions without debris flow in Figure 1(b).

3. METHOD

Two approaches of 2D nonlinear mapping and a proposed 3D nonlinear mapping are utilized to perform the geometric corrections of the LiDAR-based DEMs before and after a disaster. Figure 2 presents a designed work flow of nonlinear mapping in order to correct the geometric inconsistency between two DEMs. The purpose of nonlinear mapping is to move pixels in the pre-event DEM to their most probable positions by shifting vectors. For this reason, the shifting vectors play the role in enhancing the searches of more exact correspondences between the pre-event and post-event DEMs for detecting the land surface changes.

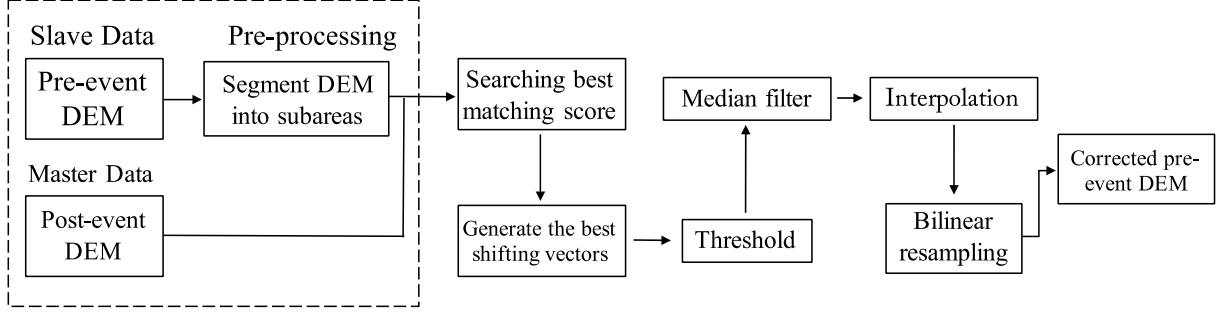


Figure 2. A proposed diagram of nonlinear mapping for LiDAR-based DEM on geometric correction

3.1 2D Nonlinear Mapping

In the data pre-processing stage of 2D nonlinear mapping technology, pre- and post-event DEMs are set as slave and master data, respectively. The pre-event DEM is divided into many sub-patches with same dimension of N by N pixels as moving windows. Although both of the DEMs have been processed that the planar information of x and y is roughly consistent, a geometric inconsistency might be remained during resampling the pre-event DEM. In order to correct this geometric error, a searching window by extending 10 pixels based on the moving windows is utilized in Figure 3(a). The moving window slides in the searching window from its center to directions of left, right, upward, and downward for matching scores computation, demonstrating as Figure 3(b). The amount of each movement of the moving window is defined as a shifting vector (dx, dy) in this study. Therefore, the matching score (s_{2D}) can be acquired via Equation (1).

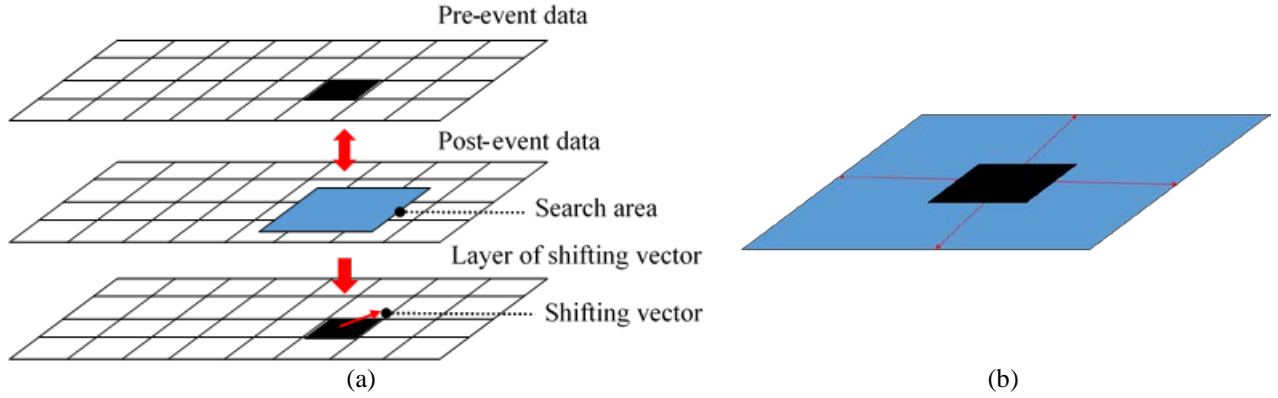


Figure 3. (a) Search best matching score in searching area and generating shifting vector. (b) The shifting vectors generated by sliding the moving window within searching window.

$$s_{2D} = \frac{1}{N^2} \sqrt{\sum_{j=-(N-1)/2}^{(N-1)/2} \sum_{i=-(N-1)/2}^{(N-1)/2} \{d1(i_c + i, j_c + j) - d2(i_c + i + dx, j_c + j + dy)\}^2} \quad (1)$$

In this equation, s_{2D} is the matching score when comparing the similarity of the moving window and the searching window. N is the size of the moving window, and $d1(i_c, j_c)$ and $d2(i_c, j_c)$ stand for the elevations of the central pixel in each sub-patch of the post-event and the pre-event DEMs. In the area without debris flow, a best corresponding position between two DEMs can be evaluated by a lowest matching score. In the area without debris flow, the best corresponding positions between two DEMs can be evaluated by a lowest matching score. A best shifting vector can be obtained according to the smallest matching score afterwards.

3.2 3D Nonlinear Mapping

A 3D nonlinear mapping, which involves the elevation within the searching window, is developed to improve the limitation of 2D nonlinear mapping. The searching window is thus embedded with elevation information by a given range so that the searching window expands from 2D to 3D. The range of the elevation for the searching window from -0.5m to 0.5m is utilized in this paper. A matching score based on three-dimensional information (s_{3D}) derived from DEMs can be determined by Equation (2).

$$s_{3D} = \frac{1}{N^2} \sqrt{\sum_{j=-(N-1)/2}^{(N-1)/2} \sum_{i=-(N-1)/2}^{(N-1)/2} \{d1(i_c + i, j_c + j) - d2(i_c + i + dx, j_c + j + dy) + dz\}^2} \quad (2)$$

In this Equation, dz is the shifting vector of elevation. Similar to 2D nonlinear mapping, a group of 3D shifting vectors can be collected when comparing the similarity between the moving window and the searching window. A most probable 3D shifting vector is obtained by the lowest matching score in area without debris flow. In debris flow areas, however, some of the shifting vectors might be misestimated due to the variations of landforms. Such shifting vectors should be stripped or modified to acquire suitable solutions. This study exploits a threshold and a median filter to solve this problem. A given threshold is to find inappropriate 3D shifting vectors in the layer of shifting vector in Figure 3(a) and remove them. For those lost data of 3D shifting vectors, the median filter of Equation (3) is used to interpolate the missing values so that a complete layer of 3D shifting vectors can be achieved. In this formula, $M(d_{xc}, d_{yc})$ is the central pixel and (d_{xs}, d_{ys}) can be derived from surrounding pixels.

$$M(d_{xc}, d_{yc}) = \text{med}(d_{xs}, d_{ys}) \quad (3)$$

But the previous 3D shifting vector only represent the information of the central pixel within a N by N moving window, detailed shifting vectors for the remaining pixels surrounding the center are unavailable. In order to fill up every pixel with its suitable 3D shifting vector, a bilinear interpolation is applied by the acquired values. According to the shifting vectors, these pixels are further adjusted to their correct positions and to generate new values corresponding to the origin pre-event data by the bilinear resampling. Consequently, the corrected pre-event DEM can be obtained to compute the DoD map for the analysis of debris flow areas and the estimations of soil volumes. In this paper, the DoD map is simply subtracting the new pre-event DEM from the post-event DEM. And thus pixel-based soil volume is calculated from the pixel size (1m^2) multiplying the erosion and deposition depths of the pixels in the DoD map.

4. EXPERIMENTAL RESULTS AND ANALYSES

4.1 Comparisons Between 2D and 3D Nonlinear Mapping

The conventional 2D and the proposed 3D nonlinear mapping approaches are applied to investigate their effects on the geometric corrections of DoD maps. Figure 4 presents a DoD map in the non-debris flow area by the original DEMs from LiDAR 3D point cloud. In the area of non-debris flow, the difference of elevation should be close to zero. However, it is apparent in this figure that the geometric errors are widely produced because of the horizontal positional errors between two data. Figure 5 shows the DoD maps corrected by 2D nonlinear mapping and two examples of 3D nonlinear mapping methods with different dimensions of the moving windows (i.e., $N = 21$ and 31 in this study) in the non-debris flow area. By using shifting vectors to minimize the geometric errors between two DEMs, the geometric errors in Figure 5 become smaller than in Figure 4. Although the 2D nonlinear mapping can amend the most positional errors, some of them in the aspect of elevation cannot be modified. To solve this problem, the 3D nonlinear mapping which can correct the errors in terms of elevation is applied to improve the result.

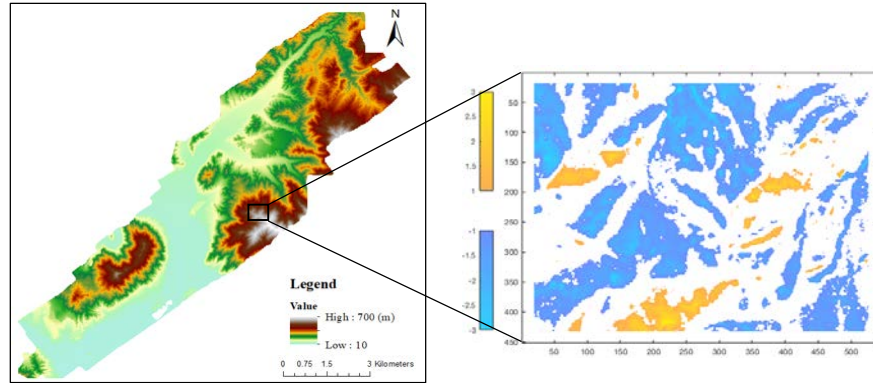


Figure 4. Geometric inconsistency in non-debris flow area

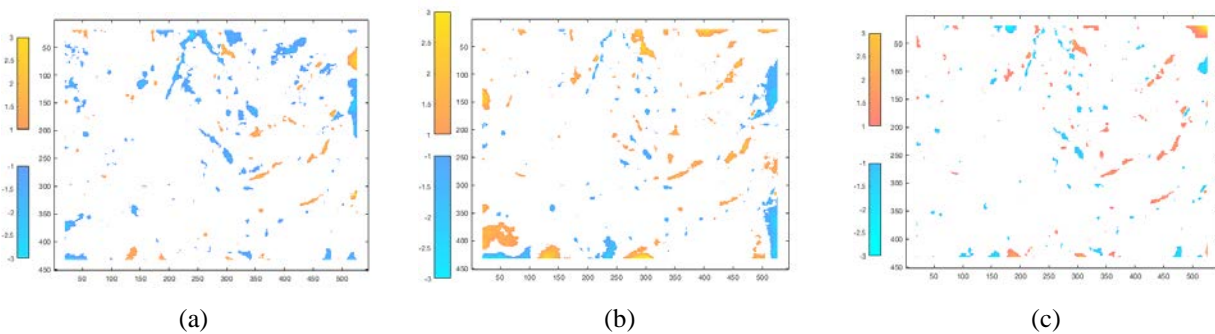


Figure 5. DoD map corrected by different methods and segment size. (a) DoD map corrected by 2D nonlinear mapping with $N = 21$. (b) DoD map corrected by 3D nonlinear mapping with $N = 31$. (c) DoD map corrected by 3D nonlinear mapping with $N = 21$.

To evaluate the reliability of the improved DoD maps by the proposed method, Figure 6 displays the value distribution of pixels of DoD maps corrected by the 3D method with different sizes of N , the 2D method as well as the original uncorrected DEMs. The comparison shows that the positional errors in the uncorrected DEM cause abnormal negative in non-debris flow area, while, the distributions of 2D and 3D corrected DoD maps are more normal than uncorrected one. Table 1 presents the mean values and standard deviations derived from different methods. The mean of the DoD map corrected by 3D method with $N = 21$ is much closer to zero and its' standard deviation is the smallest in this experiment. It implies the locational errors are almost divested by the proposed 3D nonlinear mapping with the moving window size of $N = 21$.

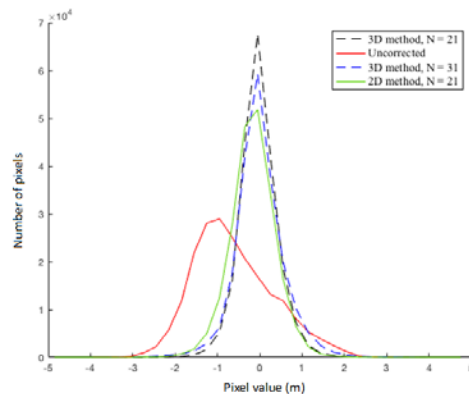


Figure 6. Distribution of DoD map corrected by non-corrected DEMs as well as DEMs of 2D and 3D nonlinear mapping correction.

Table 1. Mean value and standard deviation of DoD map by each method.

	Mean value	Standard Deviation
3D method N = 31	0.0460	0.4315
2D method, N =21	-0.0083	0.3476
3D method, N =21	-0.0027	0.3281
Uncorrected	-0.5632	0.9013

4.2 Soil Volume Estimation Based on DoD Map

Since the 3D nonlinear mapping method is available for geometric correction, this method with a moving window size of $N = 21$ is applied to calculate the DoD map of the entire target area, as shown in Figure 7. These two figures demonstrate the overlays of aerial photography and the DoD map in Yagi-Midorii area and Kabe area, respectively. The test areas in this paper are also marked by polygons in Figure 7 to indicate their actual locations where the hazard took place in 2014, Hiroshima City.

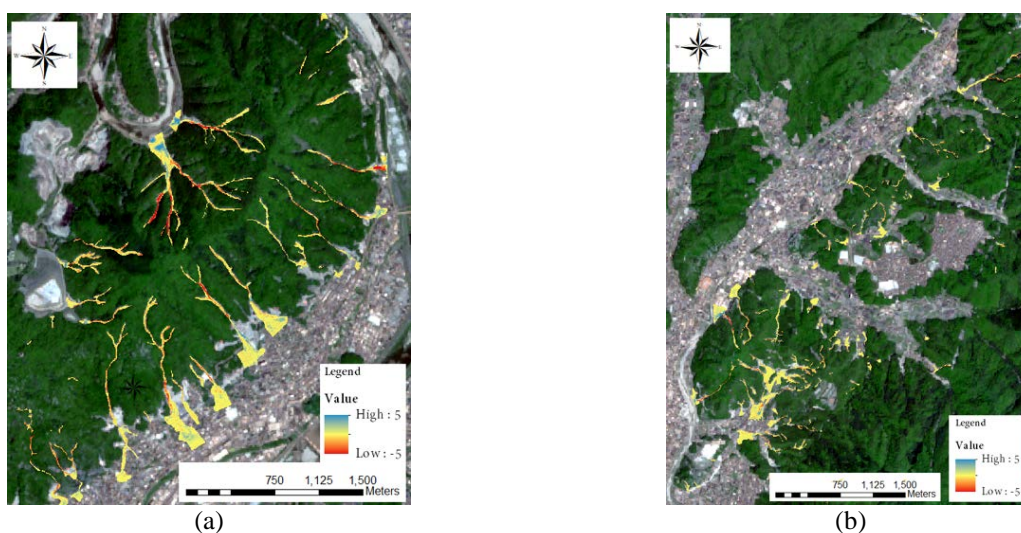


Figure 7. (a) DoD map in Yagi-Midorii area corrected by 3D nonlinear method. (b) DoD map in Kabe area corrected by 3D nonlinear mapping method.

To analyze the changes of soil volume in the disaster areas, Figure 8(a) illustrates the erosion depths in upstream and deposition depths in downstream of each debris flow. The average erosion depth is 0.5m and deposition depth is 1m approximately. This figure also shows that the absolute depths in upstream are greater than the downstream area by twice. Such a phenomenon might happen because some of the debris are rushed into the buildings in the flat downstream areas and most of debris are dealt with immediately by the governmental rescue operations. Also, the erosion and deposition soil volumes for each upstream and downstream areas are evaluated by aggregating all the pixels' calculation. Figure 8(b) shows the relationship between the erosion and deposition soil volumes in the upstream and downstream of each debris flow. The total erosion and deposition soil volumes in upstream and downstream regions are summarized in Table 2 with total erosion around 700,000(m³) and total deposition about 320,000(m³). Table 3 interprets the total distribution of erosion and deposition volumes estimated by the uncorrected, in order to compare the estimations of soil volume by the uncorrected and the 3D-based corrected DoD maps. The total erosion volume estimated by the uncorrected DoD map is about 900,000(m³), reaching 200,000(m³) more than DoD map improved by the 3D correction. However, there is almost no discrepancy in deposition volumes based on Figure 8(b). The difference of soil volumes between the two DoD maps is more significant in the erosion volumes of upstream. It's because the 3D nonlinear mapping method can eliminate locational errors between two DEMs more efficacious in mountainous and hilly areas than flat areas. These results indicate that the erosion volumes derived from uncorrected DoD map are probably overestimated, and the DEMs corrected by the 3D method is conducive to create precise DoD map and then to estimate soil volumes accurately.

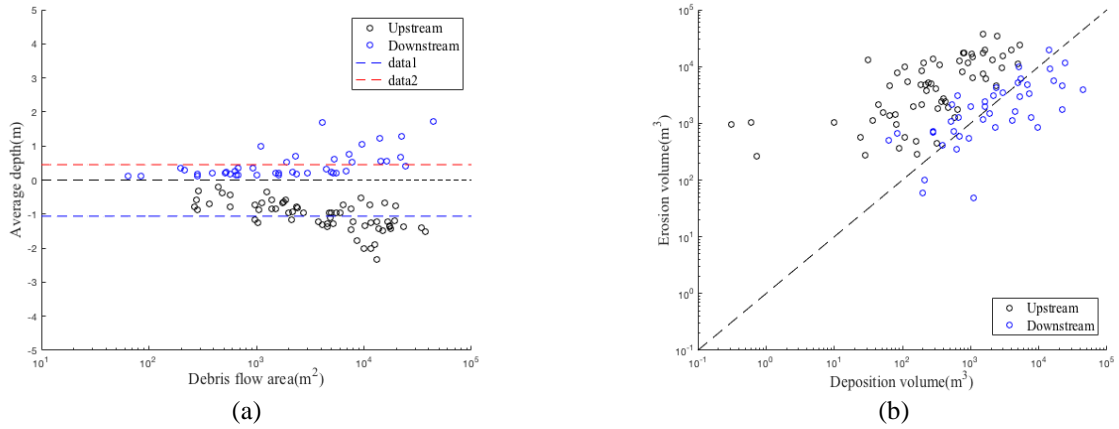


Figure 8. (a) Average depths of erosion and deposition in upstream and downstream. (b) Deposition and erosion volumes of each debris flow.

Table 2. Total erosion and deposition volumes (using 3D nonlinear mapping corrected DEMs in this study).

3D	Erosion (m ³)	Deposition (m ³)
Upstream	-561120	76449
Downstream	-130798	238000
Total	-691909	314449

Table 3. Total erosion and deposition volumes (using uncorrected DEMs).

Uncorrected	Erosion (m ³)	Deposition (m ³)
Upstream	-768010	77895
Downstream	-150996	250239
Total	-919006	328134

The soil volumes of each debris flow area in this study are compared to the result calculated by Chugoku Regional Development Bureau, Japan who used the LiDAR-derived DEM in 2009 for pre-event data with spatial resolution of 1 (m). Figure 9 shows the comparison of erosion volume and deposition volume of the study areas in this paper. The correlation coefficient of erosion volumes is 0.9815, which is better than the correlation coefficient of deposition volumes of 0.9106. This proves that the 3D nonlinear mapping method is more effective to deal with geometric errors in mountainous and hillside areas than flat areas.

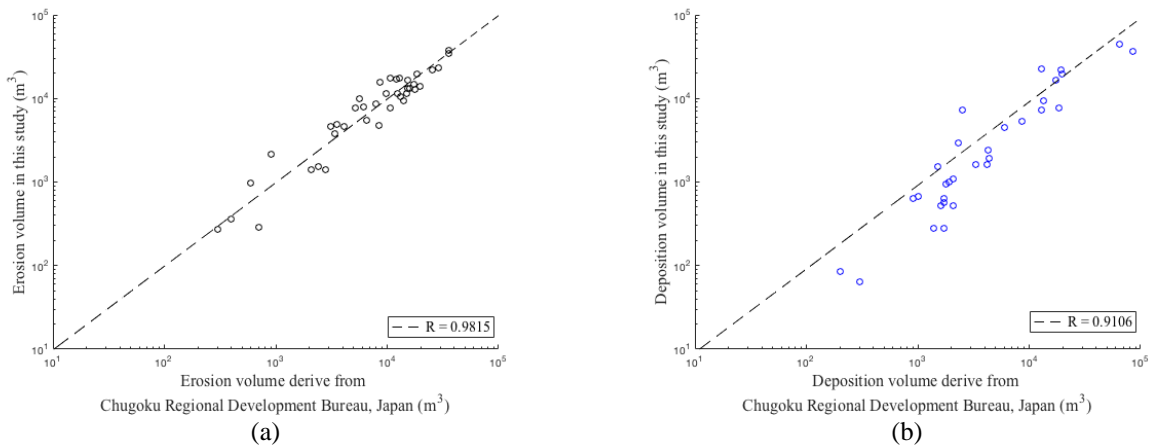


Figure 9. (a) Comparison of erosion volumes with Chugoku Regional Development Bureau, Japan. (b) Comparison of deposition volumes with Chugoku Regional Development Bureau, Japan.

5. CONCLUSIONS

In this study, the 3D nonlinear mapping is developed to modify the geometric inconsistency of two DEMs in order to increase the reliability to accurately detect land surface deformation before and after a disaster. The proposed 3D nonlinear mapping has the capacity to diminish the geometric errors for LiDAR-based DEMs. When matching two DEMs, thereby, more accurate matching results can be achieved comparing to geometric corrections by 2D nonlinear mapping. In addition, the soil volume in the debris flow areas can be estimated by the DoD maps by using the improved DEMs. The experimental outcomes express that the average depths of erosion in upstream is about 1 (m) and the average depths of deposition in downstream is about 0.5 (m). The total erosion and deposition volumes estimated by the 3D nonlinear mapping corrected DoD map are about 700,000 (m³) and 300,000 (m³), respectively. Also, the little difference of deposition volumes estimated by 2D and 3D methods illustrates that the nonlinear mapping method can decrease the geometric errors more effective in hillside areas than flat terrain. The soil volumes estimated between this study and Chugoku Regional Development Bureau (Japan) has a high consistency in debris flow areas. As a consequence, the 3D nonlinear mapping methods exploited in this study is useful to create better DoD maps and estimate the debris flow volumes accurately.

Acknowledgement

Authors are grateful to Geospatial Information Authority of Japan (GSI) and Aero Asahi Corporation, Japan for providing the pre- and post-event LiDAR-derived DEMs, respectively. This research was supported in a part by scientific research grant-in-aid KAKENHI 19H02408 (PI: Prof. Hiroyuki Miura of Hiroshima University).

References

- Cabinet Office, Government of Japan, 2014, Summary of Hiroshima City debris flow disaster that occurred on August 20, 2014. (in Japanese)
- David Williams, R., 2012. DEMs of Difference, Geomorphological Techniques, Chap.2, Sec.3.2, British Society for Geomorphology.
- Doshida, S. and Araiba, K., 2015. The geographical features of the Hiroshima landslide disaster triggered by heavy rainfall on August 20, 2014, 10th Asian Regional Conference of IAEG, 7p.
- Hiroshima Prefectural Government, Japan, 2010, Debris flow disaster in Hiroshima due to heavy rain in July 2010. (in Japanese)
- Jaboyedoff, M., Oppikofer, T., Abella ´n, A., Derron, M., Loye, A., Metzger, and R., Pedrazzini, A., 2010. Use of LIDAR in landslide investigations: a review, *Natural Hazards* 66, pp.5–28.
- Kosugi, Y., Sakamoto, M., Fukunishi, M., Lu, W., Doihara, T., and Kakumoto, S., 2004. Urban change detection related to earthquakes using an adaptive nonlinear mapping of high resolution images, *IEEE Geoscience and Remote Sensing Letters* 1 (3), pp.152–156.
- Ministry of Land, Infrastructure, Transport and Tourism, Japan, 2018, Summary of debris flow disasters caused by heavy rain in July 2018. (in Japanese)
from http://www.mlit.go.jp/river/sabo/H30_07gouu.html.
- Miura, H., 2015. Soil volume estimation in debris flow areas using LiDAR data in the 2014 Hiroshima, Japan rainstorm, *SPIE Remote Sensing*, 9p.