Topographic Changes in Real-scale Debris-flow Experiment Using Terrestrial LiDAR

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ABSTRACT: Most of the debris flows are triggered by small-scale slope failures. The volume of debris flows increases up to 10 times or higher by erosion and entrainment as they move along steep creeks. In general, the volume change of debris flows caused by erosion and deposition is estimated after debris flow events by field survey which is difficult to be conducted in steep mountainous regions. In this study, real-scale debris-flow experiments were performed in a natural gully. Countermeasures were installed where large erosion occurred in the first experiment. Terrestrial LiDAR surveys were performed before and after the experiments to confirm the topographic change in the gully upstream due to the debris flow experiment. Based on a 10 cm DEM constructed by the LiDAR survey, topographic changes by debris flows and the effectiveness of countermeasures against gully erosion were analyzed. As a result, it was confirmed that the installation of countermeasures could effectively prevent the gully erosion and induce deposition.

Keywords: Real-scale debris flow; LiDAR survey; Countermeasures; Erosion; Deposition

1. Introduction

Most of debris flows are triggered by small-scale slope failures. This type of debris flow moves along the steep stream, the volume is increased for 10 times or more due to the erosion and entrainment. Based on a field survey of 32 debris flows in Korea, Korea Forest Research Institute (2009) reported that the erosion amount of debris flows in the transportation zone was about 10 times larger than the initiation volume. Thus, the amount of erosion in the transportation zone greatly affects the amount of deposition and the damage scale in downstream and, accordingly, it is important to identify and predict erosion behavior in the transportation zone.

In the past, most of the debris flow experiments were carried out in a laboratory or field using artificial channels to understand the behavior of debris flows (Chae et al., 2006; Takahashi et al. 2007; Kim et al., 2008; Iverson, 2014). These artificial channels, however, were a mostly straight channel with a constant cross section, and it was difficult to confirm the topographic change due to the erosion of the transportation zone. Therefore, it is necessary to identify the topographic changes due to debris flow in the natural gully with complex shapes.

Rickenmann et al. (2003) analyzed erosion by debris flow in field and laboratory experiments. In general, topographic changes due to debris flows are estimated through field investigation. If there is any movement trace of debris flow in field investigation, the range of topographic change can be identified. However, in most cases, the amount of change cannot be confirmed because of the topographic information before the occurrence is unknown. However, field investigation can only confirm the rough topographic changes for the entire section.

Recently, research has been conducted to confirm detailed topographic changes through high-resolution topographic maps surveyed using measuring equipment such as airborne or terrestrial LiDAR (Jun et al. 2010; Saez et al. 2011; Kim et al. 2014; Miura et al. 2019). The airborne LiDAR survey has the advantage of easy data collection. However, it is difficult to accurately capture the gully shape obscured by vegetation. The terrestrial LiDAR survey is superior to determine gully shape, but difficult to collect data in steep mountainous regions. Therefore, airborne LiDAR surveys have been mostly conducted to confirm topographic changes and terrestrial LiDAR surveys were used only in special cases.

In this study, real-scale debris-flow experiments were performed in a natural gully and the topographic changes before and after the experiment were investigated using terrestrial LiDAR. The terrestrial LiDAR surveys were carried out from the debris-flow initiation facility up to 330m. A total of twice the real-scale debris-flow experiments was performed. The second experiment was performed after construction of countermeasures in the course of tranportation zone where the large erosion occurred during the first experiment. Based on a 10 cm DEM constructed by the LiDAR survey, topographic changes by debris flows and the effectiveness of countermeasures against the gully erosion by debris flow were analyzed.

2. Real-scale debris flow experiment

2.1. Study area

Fig. 1 presents the study area of the real-scale debris flow experiments which is located at Jinbu, South Korea. As shown in Fig. 1, 12 gabions in small size along the channel and one check dam at the end of the channel were installed by the Korea Forest Service (KFS). The terrestrial LiDAR surveys were administered only on the gully of upper stream, and the GPS reference points for this purpose were installed in two nearby areas of the debris-flow initiation facility and two places around the check dam installed on the gully of lower stream. The total length of the flow path for the real-scale debris flow experiments is 824 m and the width of the natural channel of stream is in a range between 5 and 20 m. The average slope angle of the initiation zone and the downstream area was 39° and 8°, respectively (Fig. 2). Fig. 2 displays the slope and width of the gully for each location of the field investigations. The field investigations were carried out at the point of changing the slope and width of the gully and the points of changing the slope direction. These field investigation points were facilitated as the points to analyze the topographic changes.

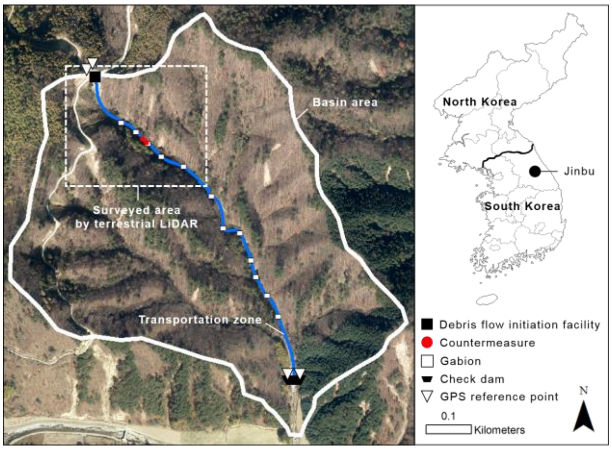


Figure 1. Overview of the study area.

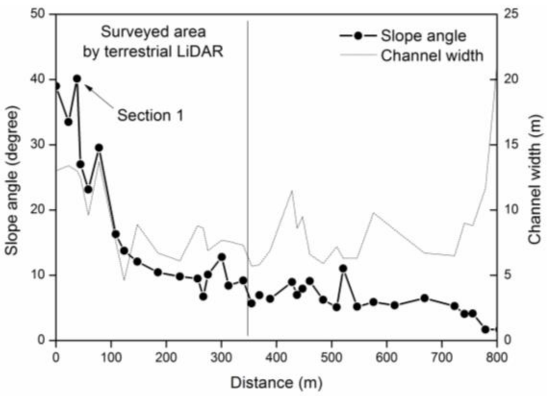


Figure 2. The slope angle and width of the channel by field investigation location.

2.2. Facility and experiment conditions

As shown in Fig. 1, the study area had the additional installation of the debris flow initiation facility and countermeasure for experiments.

Debris flow initiation facility of 12 m in width, 12.6 m in length, and 6.8 m in height (front) and 5 m in height (back) was constructed at the top of upstream channel as shown in Fig. 3. The maximum volume of soil and water container was 346 m^3 and 268 m^3, respectively.

In addition, the existing countermeasures in general are installed on the deposition part of the steep stream. However, the developed countermeasures in this present study can be installed in any part of debris-flow path because they are light, easy to construct, maintain or replace. Steel is the material for the developed countermeasure, and it is installed on the gully of the upper stream where the moving velocity of the debris flow was fast, and by disconnecting large particles, the velocity and impact of the debris flow were intended to decrease. Through this effort, it reduces the erosion that may occur while the debris flow is moving down to the lower stream is reduced by developing it to control the increase of the volume for debris flow consequently, and it was directly installed in places where significant erosion occurred in the upper stream of the first experiment. The developed countermeasures for debris flow, i.e. four hollow cylinders with holes and three rectangular boxes with grid were installed which allow the water and small sediments pass through (Fig. 4). In this study, both countermeasures were installed at locations of 188 and 200 m from the debris flow initiation facility with the intervals of 12 m. The countermeasure was worked with the rock-bolt method after drilling the hole on the exposed areas on the rocks, and then the foundation was laid down on it with the concrete to install the countermeasure. By using the leg drill, approximately 1.5 m of holes were drilled to insert the steel of 4 units (3 in the direction to face the debris flow and 1 to the opposite direction) for each countermeasure on to the rock for securing them on the countermeasure.

The real-scale debris flow experiment was conducted twice, once with and once without countermeasures. Countermeasures were installed where large erosion occurred in the first experiment. The volume of soil used in the first and second experiments were 255 m^3 (357 ton) and 214 m^3 (300 ton), respectively. The soil used in the experiment was used by bringing the soil in the Jinbu area. The soil particles used in the first experiment had a gravel of 58.9 %, sand of 39.7 % and mud of 1.4 %, and the earth particles used in the second experiment had a gravel of 62.1 %, sand of 37.9 %, and mud of 0.0 %.

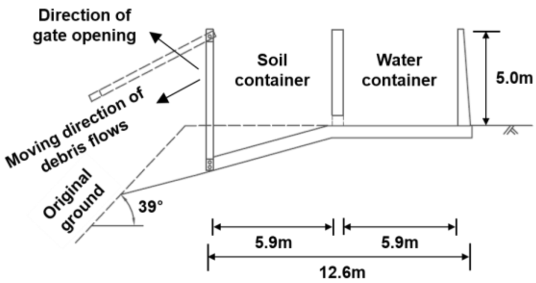


Figure 3. Diagram of debris-flow initiation facility.

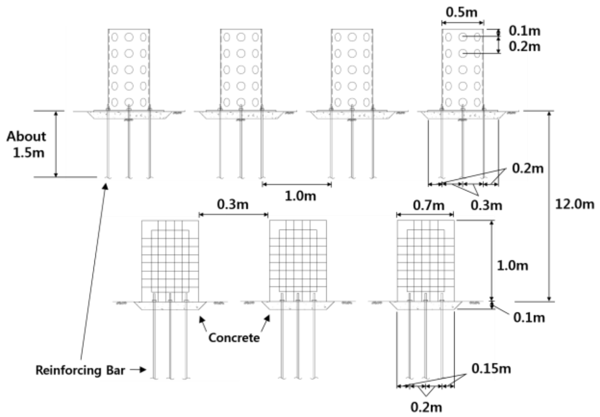


Figure 4. Diagram of countermeasures.

3. Data processing and analysis

Fig. 5 shows the flow chart to analyze the topographic changes for the two real-scale experiments. Terrestrial LiDAR survey was conducted to obtain a high-resolution topographic map before and after the experiment. Based on a 10 cm DEM constructed by the LiDAR survey, topographic changes (erosion and deposition) were estimated. To start with the reference points in global positioning system (GPS), two reference points were set in the upper and lower channel by using total station. The collected data used the point-scape program of Trimble to remove the noise and plant, and the DEM was generated by using approximately 1,000,000 units of point data. Fig. 6 presents the LiDAR data processing for the removal of dense and distorted contour lines to extract the DEM representing the flow path only. After that, The cross-sectional analysis was performed for the analysis of topography changes. The DEM was generated with the cell with the size of 0.1 m × 0.1 m. The erosion depth was estimated at intervals of about 1 m in each cross-section.

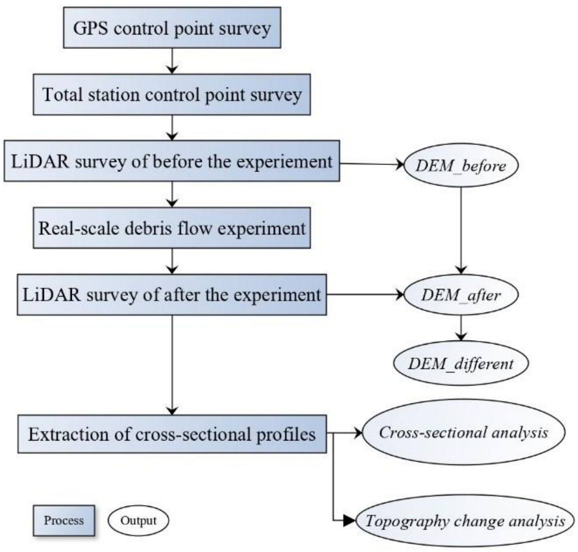


Figure 5. Flowchart of the topographic change analysis.

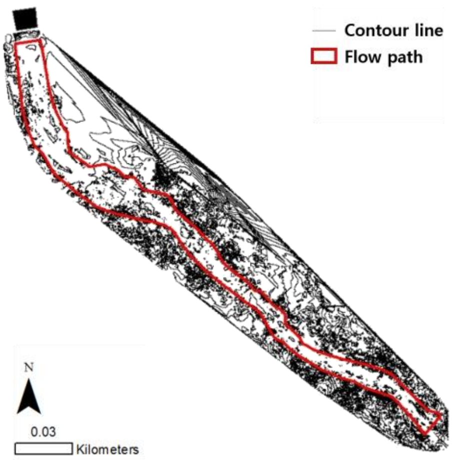
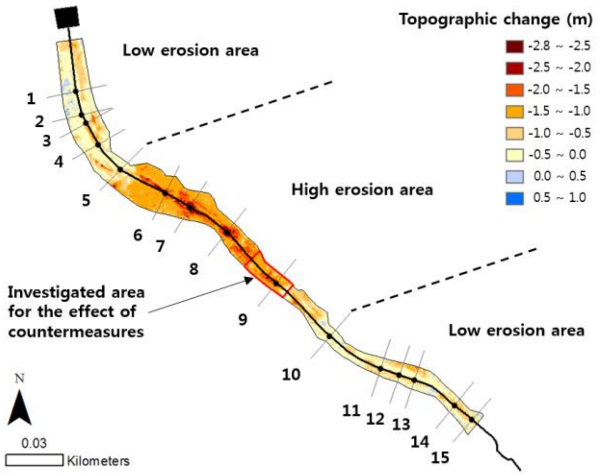


Figure 6. Flow path selection using contour map.

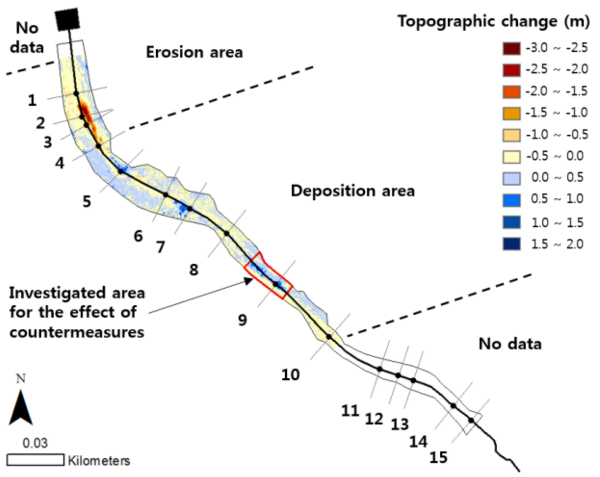
4. Analysis results

4.1. Topographic change

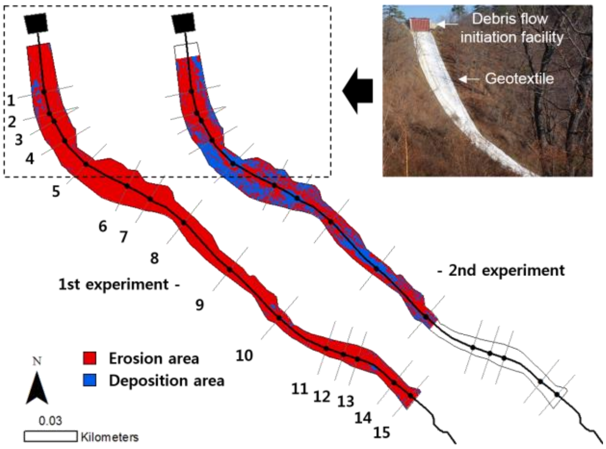
Through the real-scaled debris flow experiment, the DEM was used to analyze the debris flow with the topographic change (erosion and deposition) generated while moving along the flow path. As a result, in the first experiment, the erosion has mainly occurred, and the average erosion depth was used to distinguish the low and high erosion area. From the debris flow initiation facility, the average erosion depth was 0.39 m from Section 5, and between Section 10 and 15, it is shown to generate 0.38 m of low erosion. However, between Section 5 to 10, a relatively high erosion of 1.23 m was shown (Fig. 7a). In the second experiment, the deposition was shown to occur, and the average erosion depth was used to classify for erosion and deposition area. Between Sections 4 and 10, it was shown to have a shallow erosion and deposition of 0.5 m in its entirety. In particular, in the zone where the countermeasure is installed, it showed the fact that up to 2.0 m of deposition occurred (Fig. 7b). In the second experiment, it showed the erosion still occurred from the debris flow initiation facility to Section 4. It was clearly demonstrated in Fig. 7c that is displayed only for the erosion and deposition area. Consequently, prior to Section 4, all experiments had the erosion generated. In this zone, Geotextile was installed to reinfo-



(a) First experiment



(b) Second experiment

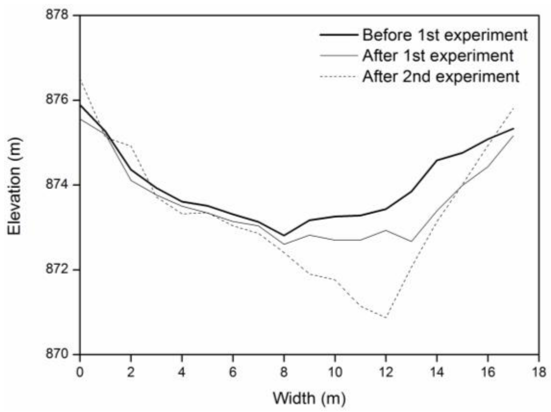


(c) Comparison of erosion and deposition areas

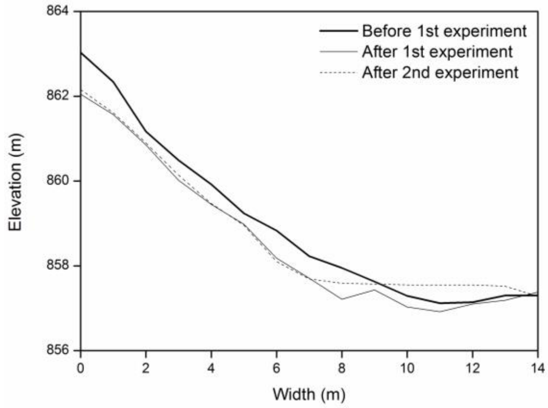
Figure 7. Analysis of topographic change through DEM.

rce prior to the experiment, but during the experiment, Geotextile was lost to have significant erosion. This type of result displays the power of generating artificial debris flow.

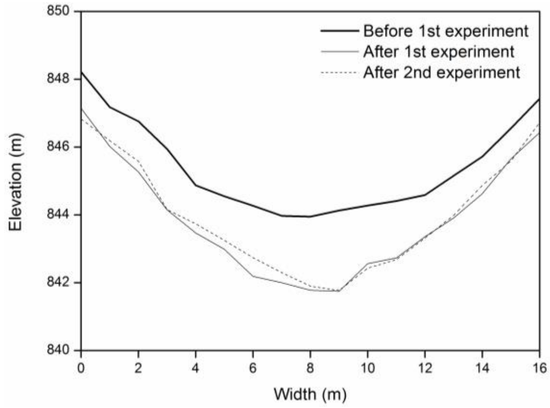
Fig. 8 demonstrates the result of the cross-section analysis. By extracting 15 sections to the gully and vertical direction at the points where the field investigations were implemented, the topographic change before and after the experiment was confirmed. Among them, 4 specific sections were selected to demonstrate Fig. 8a, Fig. 8b, Fig. 8c, and Fig. 8d. The left and right sides on this graph are applicable for the left and right sides. In Section 3 that is applicable for the initiation zone, the soil layer was reinforced with the Geotextile, but the erosion was intensely generated in the right bank. In particular, the second experiment has the erosion to increase for approximately 3 times than the first experiment. (Fig. 8a). In the bend part, Section 5, the superelevation occurred on great scale. In the first experiment, in the left bank, the parallel erosion was generated with the sloped area, but in the second experiment, there was no erosion, and the deposition occurred in the gully floor (Fig. 8b). Section 7 and 9 are the zones with significant topographic change in the first experiment. In the first experiment for both sections, the erosion was significantly generated while the second experiment had the deposition. Furthermore, in the two cross-section applicable for the straight-line zone, the symmetric topographic change has been generated based on the central part (Fig. 8c, Fig. 8d).



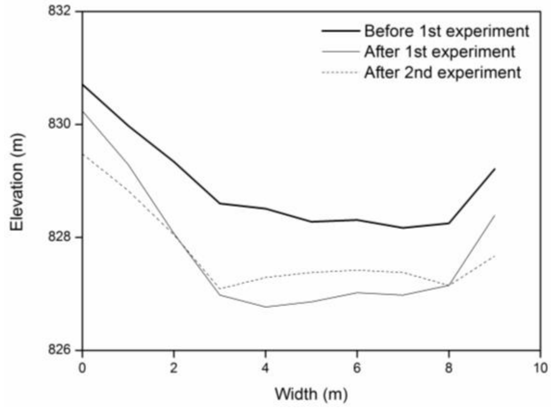
(a) Section 3
(Cross-section at 65 m, Initiation zone)



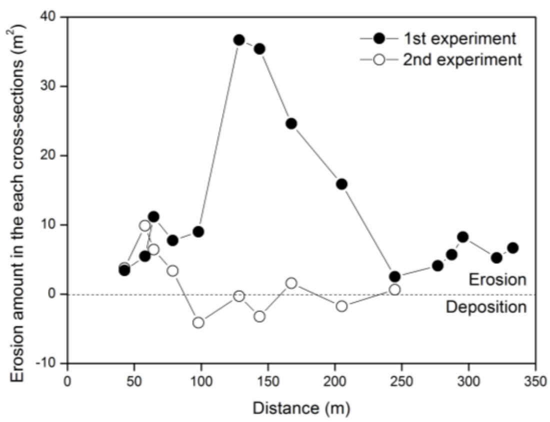
(b) Section 5
(Cross-section at 98 m, Bend part)



(c) Section 7
(Cross-section at 144m, Zone with large topographic changes)



(d) Section 9
(Cross-section at 205m, Countermeasure installed zone)



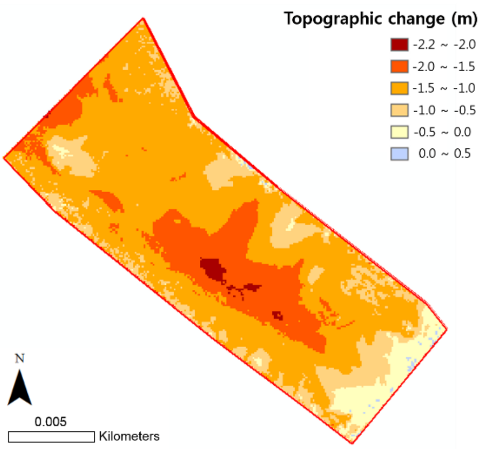
(e) Estimation result of erosion amount by cross-sections

Figure 8. Cross-sectional analysis.

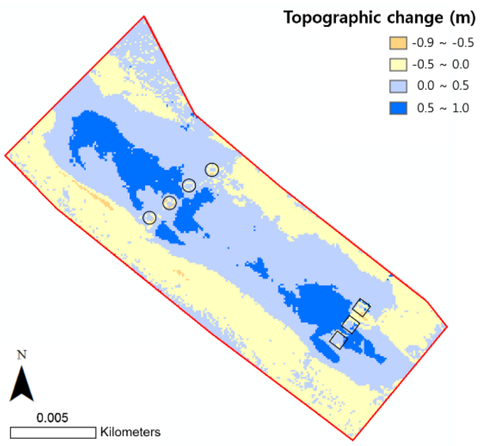
Through such cross-section analysis, the volume of erosion before and after the experiment for each section was calculated to demonstrate in Fig. 8e. As a result, in the first experiment, a significant erosion was generated between approximately 100 ~ 200 m with a maximum of 36.7 m^2 and an average of 28.2 m^2. However, in the second experiment, an average of 0.9 m^2 on the average deposition was generated in the same zone.

4.2. Effect of countermeasures

In order to estimate the effect of countermeasures on topographic changes, the amount of volume changes before and after the first and second experiments were investigated around Section 9 where countermeasures were installed (Fig. 9). As shown in Fig. 9, it can be clearly seen that the effect of countermeasures on the erosion and deposition of debris flows. The observation area is about 233 m2 for the gully which is about 25 m long and 9 m wide. From Fig. 10a, the estimated erosion and deposition derived from the LiDAR analysis show that there was no deposition in the first experiment (without countermeasure). Only erosion with maximum depth of 2.2 m and an average of 1.2 m were observed in the first experiment. On the other hand, in the second experiment (with countermeasure), it can be clearly seen that the deposition was dominated with maximum and average depth of 1 m and 0.15 m, respectively; only a small amount of erosion at each side with the depth around 0.5 m was observed.



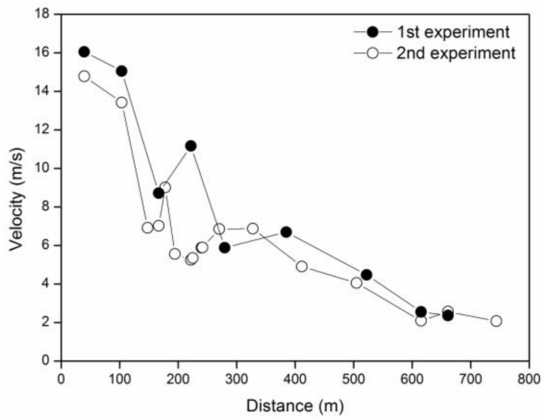
(a) Without countermeasures



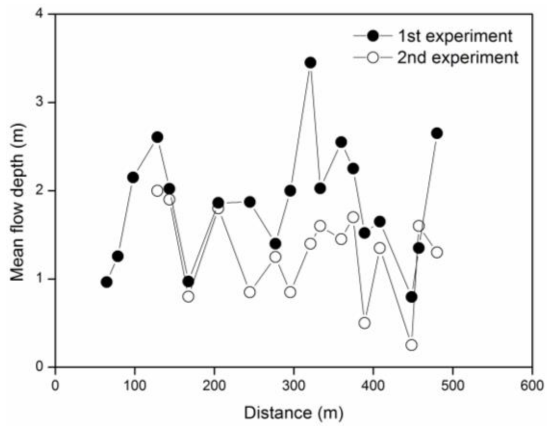
(d) With countermeasures

Figure 9. The amount of topographic change.

In order to confirm the velocity decreasing effect of the countermeasure, the velocity for each location was calculated through video filming and analysis and compared the velocity of the first and second experiments. In addition, the average flow depth calculated through the field investigation was compared (Fig. 10). The countermeasure was installed in approximately 188 ~ 200 m zone. As a result of velocity analysis in this zone, the first experiment that had not installed the countermeasure showed an increase from 8.7 m/s to 11.2 m/s for approximately 1.3 times. This is attributable to the influence of narrow width and straight-line zone. As a result of installing the countermeasure in such a zone, the velocity was decreasing from 9.0 m/s to 5.6 m/s for approximately 62 % and it increased gradually up to the designated base of approximately 76 m away. Thereafter, the velocity difference of the first experiment and the second experiment was approximately 1.5 m/s or less for similar results. In addition, the average flow depth of the same zones was shown to be relatively lower. It implies the fact that lowering of the average flow depth under the same velocity would be the decrease of impact as much. Thus, it can be concluded that the countermeasures effectively decreased the velocity and dynamic energy of the debris flow.



(a) Velocity



(b) Mean flow depth

Figure 10. Comparison between estimated velocity and measured mean flow depth by first and second experiment.

5. Conclusions

In this study, real-scale debris-flow experiments were conducted to analyze the topographic changes in a natural gully caused by debris flows at the study area located in Jinbu, Korea. The first experiment was performed in a natural gully. The second experiment was performed after construction of countermeasures in the course of transportation zone where the large erosion occurred during the first experiment. The topographic changes before and after the experiment were investigated using terrestrial LiDAR. The effect of countermeasures were confirmed using the topographic changes. Based on a 10 cm DEM constructed by the LiDAR survey, topographic changes by debris flows and the effectiveness of countermeasures against the gully erosion by debris flow were analyzed.

As a result of the analysis of the topographic changes, it was found that the large amount of soil erosion has occurred at sections 5 to 10 for the first experiment (without countermeasures); for the second experiment (with countermeasures), a large amount of soil was deposited in the same section. In particular, comparing of the topographic changes of the two experiments at the location of the countermeasure structure, no deposition occurred in the first experiment (without countermeasures). But, the deposition was dominated in the second experiment (with countermeasure). In addition, as a result of calculating the velocity for each location through the video filming and analysis, for the case of the second experiment where the countermeasure was installed, the velocity was shown to be reduced for approximately 62 % momentarily at the installation points. After the installation point of the countermeasure, it was shown to recover with a similar velocity to the first experiment, but the average flow depth was shown to be relatively lowered. Thus, it can be concluded that the countermeasures effectively decreased the velocity and dynamic energy of the debris flow.

Acknowledgement

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