Landslides detection and volume estimation in Jinbu area of Korea

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ABSTRACT
Shallow landslides triggered by heavy rainfall are common phenomena in mountainous areas of temperate monsoon regions. On July 2006 intensive shallow landslides occurred in Jinbu area, Korea triggered by heavy rainfall. An inventory of 1412 shallow landslides was constructed from intensive field works and interpretation of web-based aerial photographs, and all landslides detected were mapped across the study area. The measurements were geometrical properties (landslide length, landslide width, landslide depth) of individual landslides to establish the relationship linking landslide area to landslide volume. The relationship linking landslide area to landslide volume was obtained from the inventory of 930 landslides and is a power law function with a scaling exponent $\gamma = 1.02$, covers four orders of magnitude of landslide area and landslide volume, and is in reasonable agreement with existing relationships obtained from small scale shallow landslide events. The relationship can be used to estimate the volume of individual landslides with shallow soil depth when the area of landslide is known. However, geological and geomorphological setting should be considered to calculate accurate landslide volume with respect to disaster prevention.

Introduction
Landslides are complex natural phenomena in temperate monsoon climate regions, and often occur in mountain areas during high magnitude storms (Chen et al. 2011; Kim et al. 2012). These landslides are major natural soil disasters resulting in substantial economic, social, and geomorphologic impacts in many countries (Guthrie 2002; Schwarz et al. 2010). The high magnitude storms cause frequent shallow landslides and debris flows triggered by heavy rainfall during summer monsoon rainy season in Korea (Park et al. 2017).

Landslides are caused by various triggers including intensive rainfall, snowmelt, and earthquakes (Guzzetti et al. 2009; Broothaerts et al. 2012) and are common for most of the landslide prone areas affected by multiple factors such as topography, soil and rock type, and antecedent moisture condition. Quantifying the number, area, and volume of landslides is critical to determine landslide susceptibility and hazard (Guzzetti et al. 1999; Malamud et al. 2004) to evaluate soil mobilization dominated by mass-wasting processes (Malamud et al. 2004; Korup 2005; Imazumi and Sidle 2007; Guzzetti et al. 2008). The number of landslides in an area can be obtained where reasonably accurate landslide inventories are mapped (Galli et al. 2008; Park et al. 2017). Where landslide maps are available in digital form, the number of landslides, the area of individual landslides, and the total landslide area can be calculated. However, quantifying the volume of individual landslides is more difficult, requiring information on the surface and sub-surface geometry of the slope failure (Guzzetti et al. 2009). Estimating the volume of slope failures for a large number of landslides in an area is an even more challenging task (Malamud et al. 2004).

In July 2006 intensive rainstorms hit the eastern part of Gangwon, affecting Jinbu area in particular. These territories experience substantial rainfall because the Taebaek mountainous area interrupts the routes of seasonal fronts or typhoons coming from the southwest. Specifically, the 2006 storms produced > 440 mm rainfall (against a national average of 340 mm) during 3 days in Jinbu area resulting in thousands of shallow landslides or debris flows, and flooding of agriculture land.

Preliminary studies investigated landslide susceptibility and causal factors affecting landslide distribution (Park et al. 2017) in Jinbu area. This current study describes an inventory of 1412 shallow landslides with respect to geometrical properties (landslide length, landslide width, landslide depth) of individual landslides. We use a subset of this inventory listing 930 shallow soil slides to determine the relationship linking landslide area to landslide volume, and then we compare the relationship to existing relationships available in the literature.

Materials and methods
Study area
The study area located in Jinbu occupies approximately 127 km$^2$ and 73% of the study area is forested. The study area has altitudes ranging between 475 m and 1390 m and mean slope gradient is 23'. Thirty year average annual rainfall is 1350 mm. During the rainy season, from June to July 2006, heavy rainfall caused many shallow landslides over the study area. Those rainstorms released about 440 mm more rainfall in Jinbu area than the national average (340 mm) during the rainy season. Single intense rainfall was concentrated over the Jinbu area for 72 hours (430 mm) prior to the
landslide events (14–15 July, 2006). In the study area, rainfall-triggered shallow landslides were the most common types of slope failures: 68% of landslides occurred on forestland mainly from natural causes, 21% originated from forest roads in steep terrain, and 11% occurred in hillslope agriculture lands at lower elevations (Park et al. 2017).

Data collection and analysis

To detect landslide locations we utilized field survey data conducted by local government 2 months after the landslide occurrences. All landslides in the study area were mapped by interpreting web-based aerial photographs, and some of the landslides were confirmed in the additional field survey. Landslide maps related to landslide occurrence were constructed in the spatial database using the ArcGIS software package (Park et al. 2017) (Figure 1). These maps included a soil map (1:25,000 scale), topographic map (1:5000 scale), forest type map (1:5000 scale), and road map (1:5000 scale). From the available database of landslides, the number of landslides occurring in the study area during 14–15 July 2006 was 1412. Not all the information was available for all the landslides. The geometrical properties such as landslide length and width were inferred from web-based aerial photographs, and landslide area was calculated as the product of landslide length and width (Larsen and Torres Sanchez 1998). Landslide depths were surveyed mainly through intensive field work. Landslide volume was obtained as the product of landslide area and the average landslide depth (Larsen and Torres Sanchez 1998; Martin et al. 2002). To examine the relationship between landslide area and landslide volume, a relative volume-area scaling for the landslides in the study area was assessed based on following equation (Larsen et al. 2010):

$$V = \alpha A^{\gamma}$$

where $V$ is the volume of a landslide, $A$ is the area of a landslide, $\gamma$ is the scaling exponent, and $\alpha$ is the intercept. Also, the relationship linking landslide area and landslide volume was compared with existing relationships available in the literatures (Martin et al. 2002; Guthrie and Evans 2004; Korup 2005; Imaizumi and Sidle 2007; Guzzetti et al. 2008; Imaizumi et al. 2008; Guzzetti et al. 2009).

Results and discussion

Geometrical properties

Heavy rainfall on 15 July 2006 in Jinbu area caused at least 1412 landslides, mainly referable to earth and debris flow according to the classification of Varnes (1978). These landslides were mapped and characterized in the study area of 127 km² (Figure 1). The frequency distributions show geometrical properties such as length, width, depth, and area for all landslides occurring in the study area (Figure 2). Mean length (N = 1412) of all landslides was around 32 m and mean width was 17 m (N = 1412). The most common types of landslides were shallow soil slides with depth < 1 m (N = 930). The mean area of all landslides was around 393 m², with a standard deviation of 327 m². In total, the mapped landslides occupied 1.7 km² which is almost 1.5% of

Figure 1. Spatial distribution of landslides occurring in the study area.
the entire study area (127 km²). Because not all landslides occurring in the study area were identified, this calculation is an underestimation of the total landslide area.

**Landslide volume**

The individual landslide volume occurring in the study area varies widely and is summarized in Figure 3. The smallest landslide volume was 2.5 m³ and the largest was 1165 m³. The mean was 220 m³, with a standard deviation of 186 m³. Not all information on landslide depths was available for calculating all landslide volumes (Figure 2). Thus, the 930 landslides in the study area theoretically produced about 200,844 m³ of slope material; however, these underestimated the volume of slope material produced from all 1412 landslides occurring in the study area.

The 930 landslides for which information on landslide area and landslide volume was available are plotted in Figure 3. Landslide area (A) covers four orders of magnitude (6 × 10⁰ m² ≤ A ≤ 2.1 × 10³ m²) and landslide volume (V) spans four orders of magnitude (2.5 × 10⁰ m³ ≤ V ≤ 1.2 × 10³ m³), and the accuracy of each landslide measurement depends on the size of the landslide. Based on Equation (1), the relative volume-area scaling for the landslides in the study area resulted in V = 0.596A⁰.⁰² (R² = 0.89; N = 930) (Figure 3). The relationship compared well with the exponent
between 1.0 and 1.3 found by Larsen et al. (2010) for the shallow soil-based landslides. Indeed, all mapped landslides were soil-based landslides (Park et al. 2017) according to the subdivision of Larsen et al. (2010). This power law relationship can be used to estimate the volume of individual landslides with shallow soil depth when the area of landslide is known.

**Comparison with existing relationships linking landslide area to volume**

Existing relationships between landslide area and volume are available in the literature (Guzzetti et al. 2009) (Table 1). Guthrie and Evans (2004) examined 124 debris flows in the west coast of British Columbia and found $V = 0.155A^{1.09}$ for $7 \times 10^2 \text{ m}^2 \leq A \leq 1.2 \times 10^3 \text{ m}^2$. Korup (2005) studied 23 landslides with $A > 1.2 \times 10^6 \text{ m}^2$ in western New Zealand and obtained the relationship $V = 0.02A^{1.95}$. Imaizumi and Sidle (2007) measured the volume of 51 shallow landslides in central Japan and found $V = 0.39A^{1.31}$ for $1 \times 10^1 \text{ m}^2 \leq A \leq 3 \times 10^3 \text{ m}^2$. Also, Imaizumi et al. (2008), working in Japan, examined 11 small landslides and found $V = 0.19A^{1.19}$ for $5 \times 10^3 \text{ m}^2 \leq A \leq 4 \times 10^5 \text{ m}^2$. Guzzetti et al. (2008) studied 539 landslides worldwide and obtained the relationship $V = 0.084A^{1.43}$ for $1 \times 10^1 \text{ m}^2 \leq A \leq 1 \times 10^9 \text{ m}^2$. Guzzetti et al. (2009), working in central Italy, estimated the area and volume of 677 landslides and found the relationship $V = 0.074A^{1.45}$ for $6 \times 10^1 \text{ m}^2 \leq A \leq 2 \times 10^6 \text{ m}^2$. Martin et al. (2002), in a study of landslides in British Columbia, measured the area and volume of 45 shallow landslides and obtained the relationship $V = 1.036 \times A^{0.88}$ for $2 \times 10^2 \text{ m}^2 \leq A \leq 5.2 \times 10^4 \text{ m}^2$.

Although most of the existing relationships present a similar trend, the results can be attributed to different types of

![Figure 3. Relationships between landslide area (A) and landslide volume (B) in the study area. Circles represent the landslide area (A) (x-axis, m²) and the landslide volume (V) (y-axis, m³) of 930 landslide data. Dashed line is best fit obtained by linear fitting technique.](image)

| ID | Equation | Min A (m²) | Max A (m³) | N | Source |
|----|----------|------------|------------|---|--------|
| 1  | $V = 0.596A^{1.02}$ | $0.6 \times 10^1$ | $2.1 \times 10^3$ | 930 | This work |
| 2  | $V = 0.074A^{1.45}$ | $2 \times 10^5$ | $1 \times 10^6$ | 677 | Guthrie and Evans (2004) |
| 3  | $V = 0.155A^{1.09}$ | $7 \times 10^2$ | $1.2 \times 10^2$ | 124 | Korup (2005) |
| 4  | $V = 0.02A^{1.95}$ | $1 \times 10^1$ | $3 \times 10^1$ | 23 | Imaizumi et al. (2008) |
| 5  | $V = 0.39A^{1.31}$ | $1 \times 10^1$ | $3 \times 10^1$ | 51 | Guzzetti et al. (2007) |
| 6  | $V = 0.084A^{1.43}$ | $1 \times 10^1$ | $1 \times 10^2$ | 539 | Guzzetti et al. (2008) |
| 7  | $V = 0.19A^{1.19}$ | $5 \times 10^1$ | $4 \times 10^2$ | 11 | Imaizumi et al. (2008) |
| 8  | $V = 1.036A^{0.88}$ | $2 \times 10^2$ | $5.2 \times 10^4$ | 615 | Martin et al. (2002) |

Column 1 lists the equation number. Column 2 presents the equation (landslide area [A] and landslide volume [V]). Columns 3 and 4 show the minimum and maximum values for landslide area (A). Column 5 presents the number of landslide data (N). Column 6 gives the sources of landslide data.
slope failures, different criteria in calculating landslide area and volume, and different geological and physiographic settings (Guzzetti et al. 2009). Where landslide area was calculated as the product of landslide width and length (Larsen and Torres Sanchez 1998), or landslide volume was obtained as the product of landslide area and the average landslide depth (Larsen and Torres Sanchez 1998; Martin et al. 2002), the volume of the landslides was probably overestimated (Guzzetti et al. 2009). Where the size of the landslide scar was measured (Imaizumi and Sidle 2007; Imaizumi et al. 2008), the volume of the landslide was underestimated. The relationship obtained in the current study is in reasonably good agreement with existing relationships for relatively small landslides including our result (Martin et al. 2002; Imaizumi et al. 2008) have a smaller scaling exponent than the relationships obtained for large landslides (Korup 2005). This may be attributed to different methods adopted to measure landslide volume or a change in the scaling of the dependency of landslide volume from landslide area with increasing landslide size (Guzzetti et al. 2009).

Conclusions

This study area of 127 km² in Jinbu, Korea was intensively affected by rainfall-triggered shallow landslides, of which 1412 landslides were mapped and their geometrical properties were characterized. The relationship linking landslide area to landslide volume was obtained from the inventory of 930 landslides and is a power law function with a scaling exponent $\gamma = 1.02$, and is in reasonable agreement with relationships obtained from small scale shallow landslides. This power law relationship can be used to estimate the volume of individual landslides with shallow soil depth when the area of landslide is known; however, geological and geomorphological settings should be considered to estimate exact landslide volume with respect to disaster prevention. We expect our results to contribute to regional studies of soil disaster caused by landslide events.

Disclosure statement

No potential conflict of interest was reported by the authors.

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