

Figure 1a. Distribution of axial orientation data on a spherical surface. a. A clustered distribution. b. A girdle distribution. In a clustered distribution, the axial orientation data have one large eigenvalue (λ_1) and two small eigenvalues (λ_2, λ_3). In contrast to this, the axial orientation data have one small eigenvalue (λ_3) and two large eigenvalues (λ_1, λ_2) in a girdle distribution.

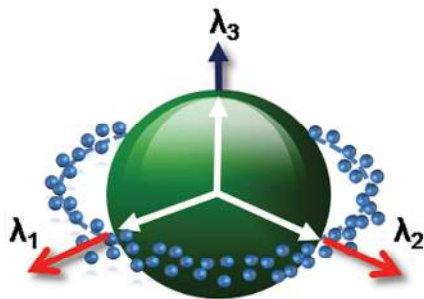


Figure 1b.

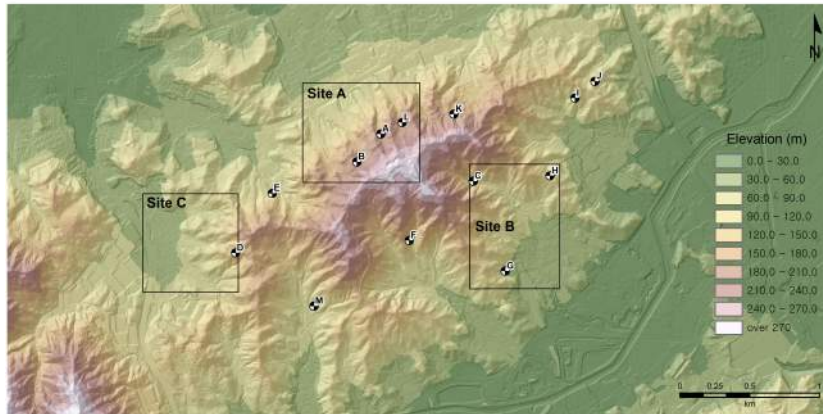


Figure 2. Location of the study area. Major landslide areas are also indicated. The position of each landslide is calculated as a mean centre for the individual landslide area: A) Raminan A.P.T.; B) Sindonga A.P.T.; C) Hyunchon-maul; D) Jeonwon-maul; E) Bodeok-sa; F) Songdong-maul; G) Umyeonsan Tunnel; H) Educational Broadcasting System buildings; I) Gwanmun-sa; J) Gangnam Church; K) Seoul Arts Centre; L) Deokwoo-am; and M) Dwit-gol. Areas outlined by black rectangles are shown in Figs. 11 to 13. The geographic coordinates of the landslide area A are 37.474013 (latitude) and 127.006552 (longitude) in decimal degrees.

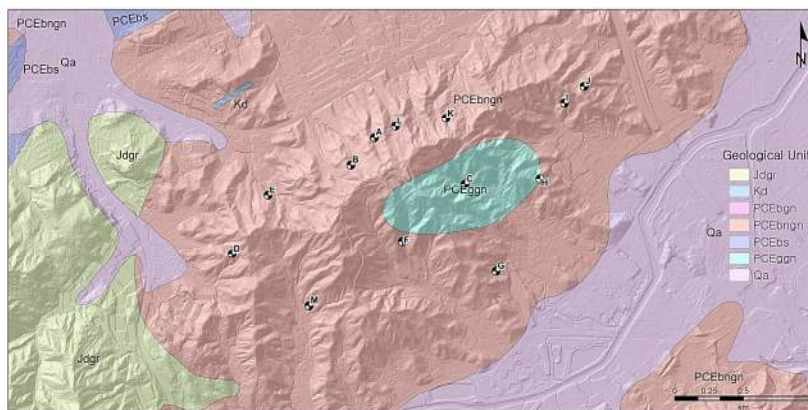


Figure 3. Geological map of the study area. Major landslide areas described in Fig. 2 are also shown. Representative geological units are: Jdgr (Jurassic daebo granite); Kd (dikes); PCEbngn (Pre-Cambrian Era banded biotite gneiss); PCEbs (Pre-Cambrian Era biotite schist); PCEggn (Pre-Cambrian Era granitic gneiss); and Qa (Quaternary alluvium). All geological information are based on Kim and Hong (1975) and Hong and Lee (1982).



Figure 4a. Landslides in Site A. a. Overall trace of the landslide at Ramian A.P.T. area. Components of debris flows which VanDine (1996) proposed are identified. Looking southeast. b. Eroded colluvial layers observed at 320 m from the initiation zone.



Figure 4b.



Figure 5a. Landslides in Site B. a. A closer look of the landslide Initiation zone. A small volume of soil slid down along the smooth clayey surface which acts as a slickensided shear plane. b. Upstream valley where debris flows were traced. Looking northwest.



Figure 5b.



Figure 6a. Landslides in Site C. a. Landslide initiation zones. An area outlined by a black solid line presents a closer look of one of the initiation zones in slopes (Fig. 6b). Looking northeast. b. A closer look of the landslide initiation zone indicated in Fig. 6a.



Figure 6b.

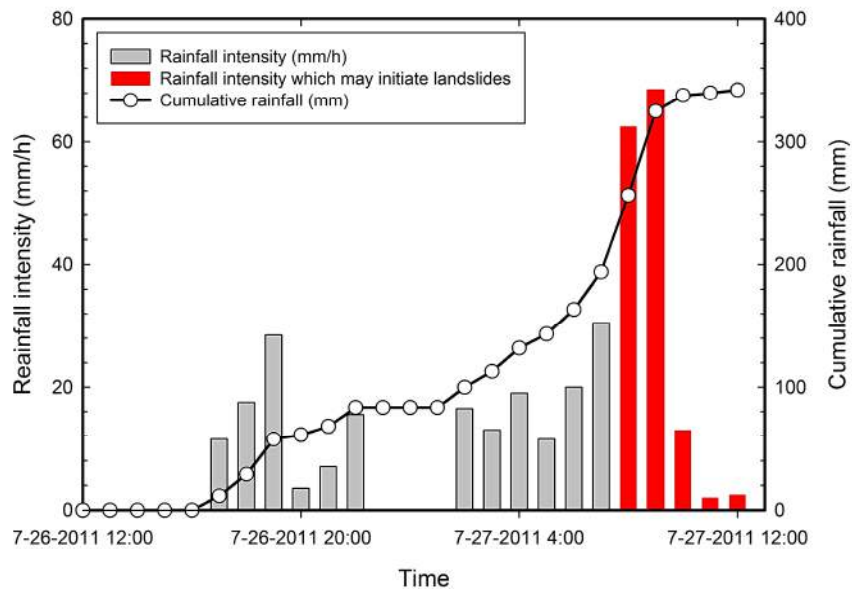


Figure 7. Temporal variation of precipitation from July 26 to 27, 2011. Vertical bars indicate the rainfall intensity and cumulative rainfall is shown by a single line with circles. Some vertical bars in red represent the rainfall intensity which might cause landslides in the study area.

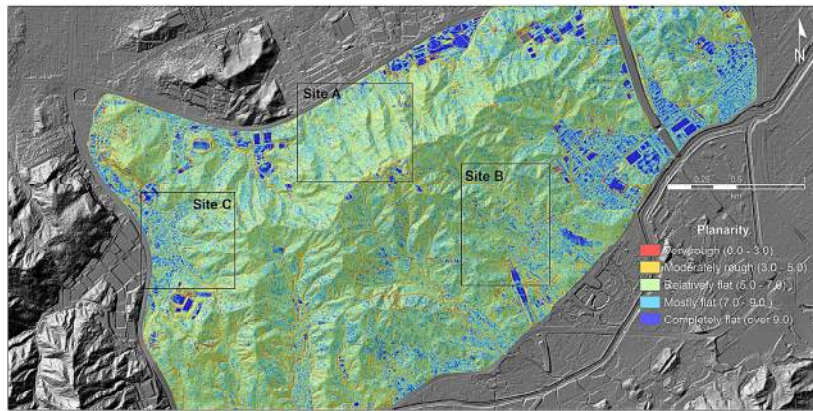


Figure 8. Spatial distribution of the Planarity over the effective study area. Areas outlined by black rectangles are shown in Figs. 11 to 13.

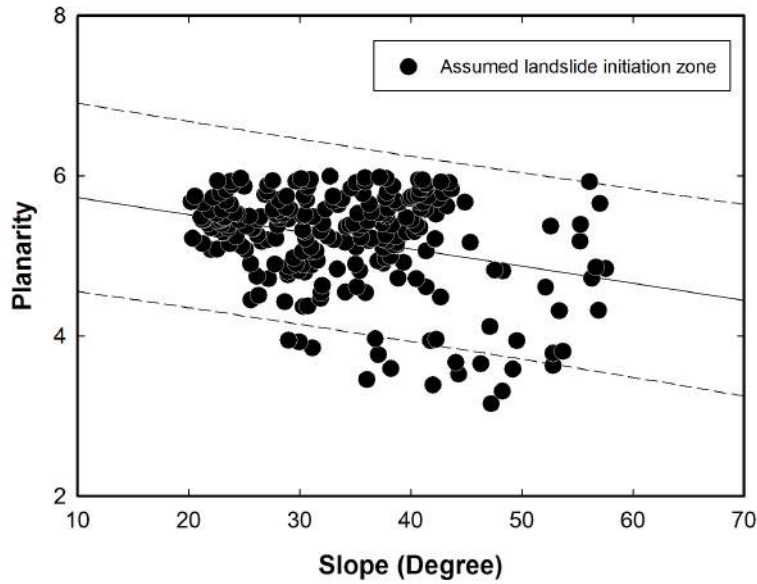


Figure 9a. Relationships between Planarity and slopes in the study area. Values for slope and Planarity are shown on the abscissa and ordinate, respectively. The linear regression is indicated by a black line and 95 percent of prediction intervals are also presented as dotted lines. a. Site A. b. Site B. c. Site C.

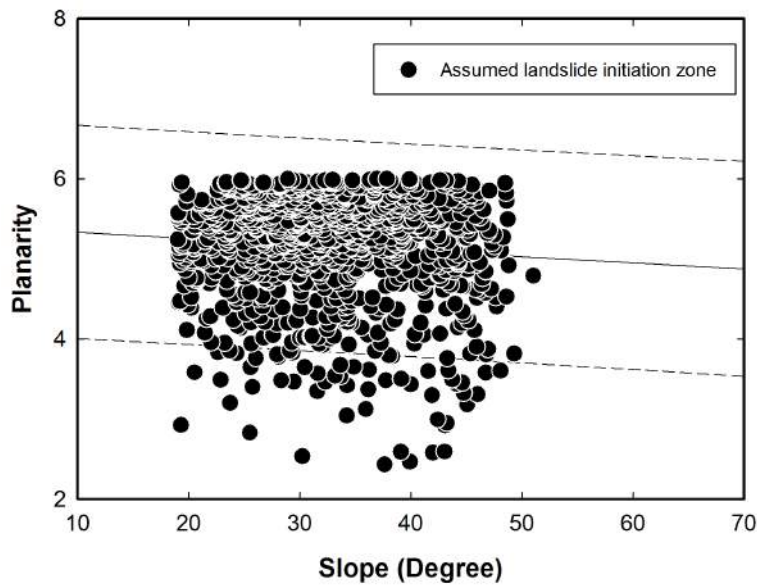


Figure 9b.

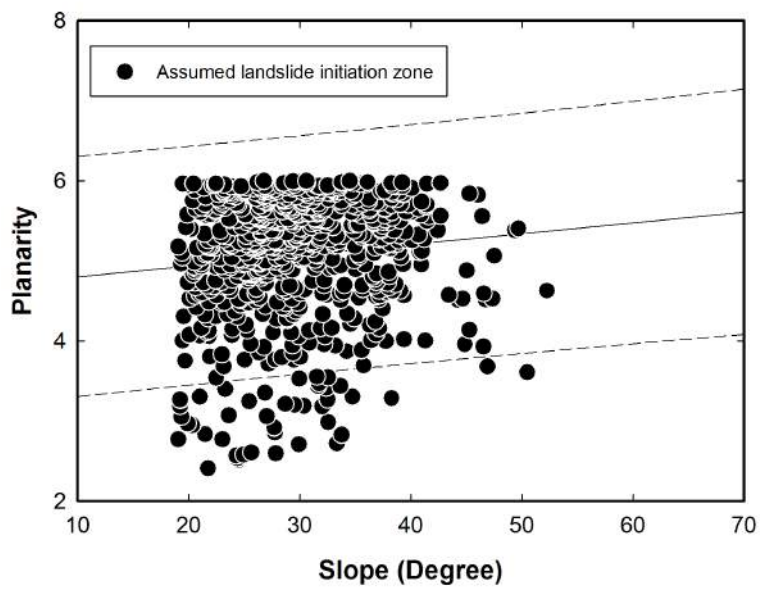


Figure 9c.

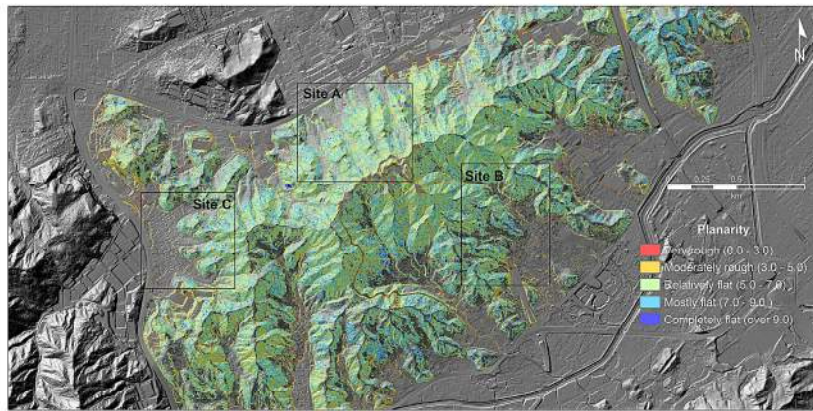


Figure 10. Spatial distribution of the Planarity where the mean slope value of above 19 degrees over the effective study area. Areas outlined by black rectangles are shown in Figs. 11 to 13.

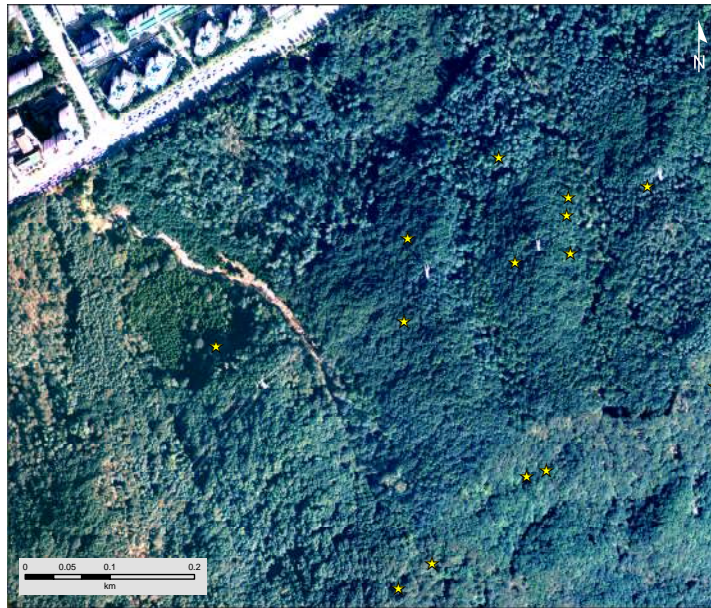


Figure 11a. Landslides characteristics in Site A. a. Aerial photograph, before the landslide. Yellow stars represent landslide initiation zones. b. Modified Planarity. Areas outlined by yellow circles with a diameter of 5 m are supposed to be the source areas. c. Aerial photograph, after the landslide. Orange lines indicate observed routes from the landslide initiation zones.

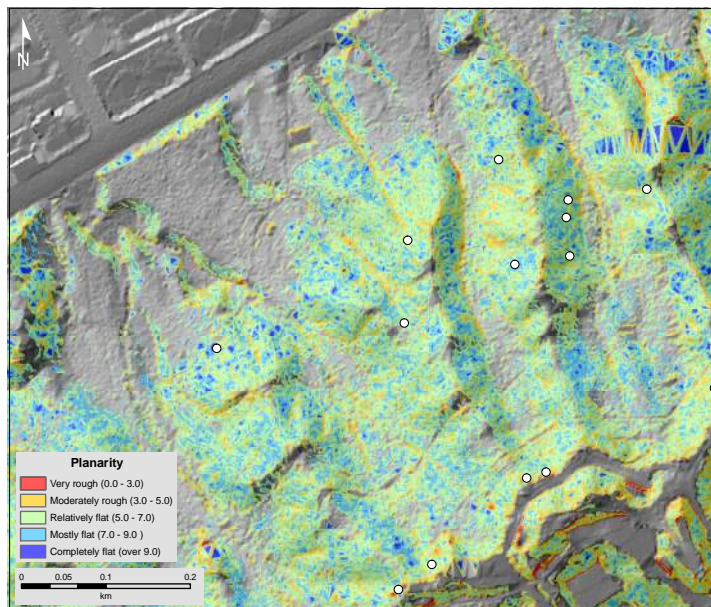


Figure 11b.



Figure 11c.



Figure 12a. Landslides characteristics in Site B. a. Aerial photograph, before the landslide. Yellow stars represent landslide initiation zones. b. Modified Planarity. Areas outlined by yellow circles with a diameter of 5 m are supposed to the source areas. c. Aerial photograph, after the landslide. Orange lines indicate observed routes from the landslide initiation zones.

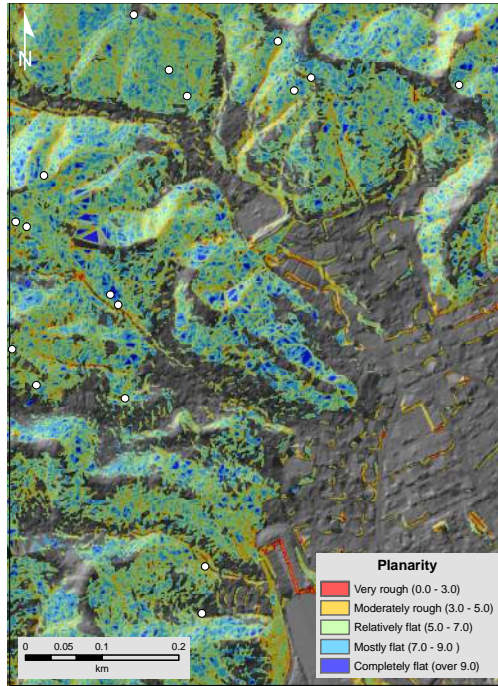


Figure 12b.



Figure 12c.



Figure 13a. Landslides characteristics in Site C. a. Aerial photograph, before the landslide. Yellow stars represent landslide initiation zones. b. Modified Planarity. Areas outlined by yellow circles with a diameter of 5 m are supposed to the source areas. c. Aerial photograph, after the landslide. Orange lines indicate observed routes from the landslide initiation zones.

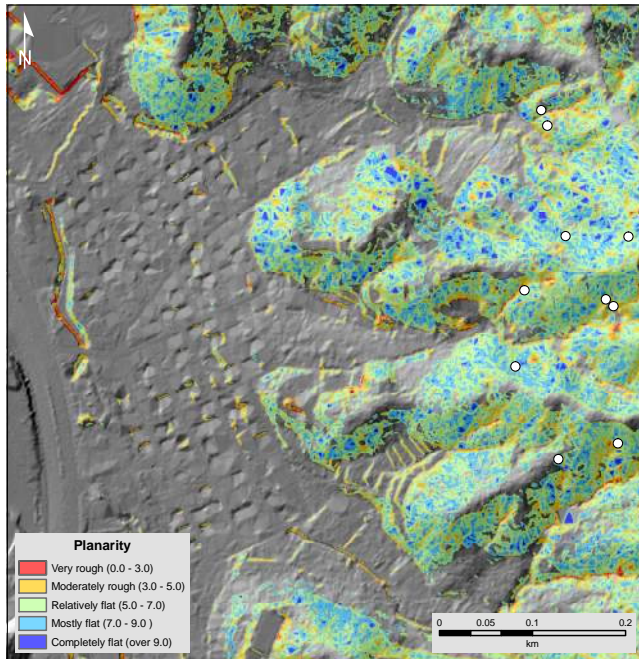


Figure 13b.



Figure 13c.

Table 1. Types of the spherical distributions based on eigenvalues and eigenvectors of the orientation matrix M . The order of eigenvalues is $\lambda_1 > \lambda_2 > \lambda_3$. R is the length of the resultant vector. Modified from Mardia (1972).

Eigenvalue distribution	Spherical distribution	Eigenvector distribution
$\lambda_1 \simeq \lambda_2 \simeq \lambda_3$	Random	No preferred orientation
$\lambda_1 > \lambda_2, \lambda_3$	$\lambda_2 \neq \lambda_3$ Unimodal if R is large	Concentrated at one end of v_1
	Bimodal otherwise	Concentrated at both ends of v_1
	$\lambda_2 \simeq \lambda_3$ Unipolar if R is large	Rotational symmetry about v_1
$\lambda_1, \lambda_2 > \lambda_3$	Bipolar otherwise	
	$\lambda_1 \neq \lambda_2$ Girdle	Girdle plane containing v_1 and v_2
	$\lambda_1 \simeq \lambda_2$ Symmetric girdle	Rotational symmetry about v_3

Table 2. Landslides occurred in Mt. Umyeon, 2011. Each landslide area denoted by capital alphabet is also described in Fig. 2. Data are modified from Yoo et al. (2014). Cases being considered in this study (Sites A to C) are indicated in the column of the representative area name.

ID	Representative area name	No. of landslide	Individual initiation zone		
			Type of landslide ¹	Ave. slope (Deg.)	Ave. volume (m ³)
A	Ramian, Imgwang A.P.Ts. (Site A)	6	OD	36.5	936.4
B	Sindonga A.P.T. (Site A)	3	OD	26	105.0
C	Hyungchon-maul (Site B)	30	CD	34	75.4
D	Jeonwon-maul (Site C)	22	CD	27	62.9
E	Bodeok-sa	14	OD	26	86.7
F	Songdong-maul	18	CD	36	182.0
G	Umyeonsan Tunnel	2	CD	29	129.3
H	Educational Broadcasting System buildings	3	CD	29	70.2
I	Gwanmun-sa	5	CD	31.5	90.9
J	Gangnam Church	11	CD	37	94.9
K	Seoul Arts Center	15	OD	37.3	207.3
L	Deokwoo-am	5	OD	35	98.7
M	Dwit-gol	16	CD	30.5	64.2
	Total	150			

¹Evans (1982). OD: Open slope Debris flow; CD: Channelized Debris flow

Table 3. Distribution of Planarity and corresponding slope values in the study area.

ID	No. of landslide	Area (m ²)	Planarity ¹ (%)					Slope (%)				
			0-3	3-5	5-7	7-9	over 9	10-20°	20-30°	30-40°	40-50°	over 50°
A	6	117.6	0.0	14.1	63.4	21.6	0.9	0.4	31.4	50.4	14.5	3.3
B	3	58.8	0.9	17.6	56.7	14.1	10.7	0.9	33.0	57.9	6.0	2.2
C	30	588	0.5	13.7	62.9	21.3	1.6	2.2	39.4	44.4	14.0	0.0
D	22	431.2	1.2	16.0	60.0	22.0	0.8	1.9	50.6	42.8	4.5	0.2
E	14	274.4	0.1	22.3	62.0	14.5	1.1	2.2	45.8	36.5	15.5	0.0
F	18	352.8	0.7	20.9	54.8	21.7	1.9	3.0	42.5	46.1	7.7	0.7
G	2	39.2	0.0	46.7	49.3	4.0	0.0	4.0	22.7	73.3	0.0	0.0
H	3	58.8	0.0	5.6	79.5	14.1	0.9	0.9	50.4	48.7	0.0	0.0
I	5	98	0.4	35.4	53.3	9.8	1.1	7.4	61.8	16.8	10.9	3.1
J	11	215.6	0.0	19.9	52.1	25.7	2.3	4.1	48.4	44.7	2.8	0.0
K	15	294	0.0	18.0	57.2	23.9	0.9	2.0	26.6	53.7	17.7	0.0
L	5	98	0.0	24.7	67.2	8.1	0.0	0.5	27.3	47.0	15.7	9.5
M	16	313.6	1.2	29.6	60.0	8.4	0.6	1.9	25.3	42.7	24.1	6.0
Total	150											

¹Min: 2.41, Max: 13.26, Average: 5.92