Study of Automatic Forest Road Design Model Considering Shallow Landslides with LiDAR Data of Funyu Experimental Forest

Masashi Saito, Msahiro Goshima, Kazuhiro Aruga, Keigo Matsue, Yasuhiro Shuin, Toshiaki Tasaka

Abstract – Nacrtak

In this study, a model to automatically design a forest road considering shallow landslides using LiDAR data was examined. First, in order to develop a shallow landslide risk map of the Funyu Experimental Forest, a slope stability analysis was carried out using the infinite slope stability analysis formula. The soil depth was surveyed at 167 points using simple penetration tests, and the frequency distributions of the soil depth were estimated as logarithmic normal distributions. A soil depth map of the experimental forest was made using the mode values of the lognormal distributions. Then, shallow landslide risk maps were also made for the experimental forest by a slope stability analysis using these soil depth distributions. Finally, an automatic forest road design model was developed with a LiDAR based highly accurate Digital Terrain Model (DTM) and shallow landslide risk map using cubic spline interpolation and dynamic programming. The program has capability of minimizing the earthwork costs while avoiding shallow landslide risk areas. The program can be effectively used to design an environmentally sound low volume road automatically.

Keywords: LiDAR, automatic forest road design, shallow landslide, spline interpolation, dynamic programming

1. Introduction – *Uvod*

To enable more efficient and stable timber extraction from forest resources, as well as sustainable forest management, considering the perspective of public functions such as land and watershed conservation and climate change mitigation, it is necessary to develop forest road networks in Japan. Extensive field investigations, including a preliminary survey, route survey, and cross-section survey, are necessary to design a forest road. This entails considerable time and cost. Work experience is also necessary to select the best route for a forest road from many alternatives. It is not easy even for an advanced engineer to examine both an earthwork and slope failure on site. If a design model could be developed to examine both an earthwork and slope failure and select the best route from many alternatives, it would help forest engineers design forest roads.

A variety of forest road design supporting models to reduce the necessary workload have been developed using DTMs (Digital Terrain Models). Reutebuch (1988) developed a computer program for the preliminary route location, ROUTES, which estimated grades and distances along a possible road route using DTM. Liu and Sessions (1993) developed a preliminary planning model for road systems that designed the route while estimating the establishment cost, maintenance expense, and transportation cost using DTM. Douglas and Henderson (1988) optimized a forest road route location using a dynamic programming approach, and Suzuki et al. (1998) optimized a forest road route location using a hybrid model that combined the Dijkstra method and genetic algorithms. These models considered only the optimization of horizontal arrangements.

It is necessary to examine not only the horizontal arrangement but also the vertical arrangement to design the best route. Dynamic programming has been widely used in the literature and in practice to optimize the vertical arrangement (Kanzaki 1973). Heuristic combinatorial optimization models, simulated annealing, genetic algorithms, and tabu search have been studied to minimize the construction and maintenance costs by optimizing the vertical arrangement (Akay 2006; Ichihara at al. 1996; Aruga et al. 2005) using DTM. However, most of these models have demonstrated a lack of accuracy because of the low reproducibility of geographical features. Therefore, it has been difficult to adjust the design to the site.

In order to improve the geographical features, Aruga et al. (2006) developed a forest road design model using LiDAR (Light Detection and Ranging) data, which demonstrated a significant improvement in representing relatively accurate geographical features. However, no comparison with field investigations was given in that paper. Therefore, we developed a forest road design model using LiDAR data for the Funyu Experimental Forest and conducted a comparison with field investigations (Saito et al. 2007). As a result, it was found that the ground surfaces produced by the LiDAR data represented the ground surfaces well and the forest road design results using the LiDAR data were similar to the established forest road.

Slope failure, which is an important constraining factor in forest road design and establishment in the mountainous areas of Japan, was not considered in the study (Saito et al. 2007). Umeda et al. (2007) and Suzuki et al. (2007) carried out numerous field surveys of spur road networks and clarified the terrain conditions required for constructing spur road networks. Umeda et al. (2007) implied that a detailed DTM generated from airborne laser measurements could extract the terrain conditions required for constructing spur road networks. Yoshimura (1997) predicted the collapse risk places from the results of field investigations using fuzzy integration and planned forest road networks considering the environmental impact of failure and soil erosion using the Dijkstra method. However, his study did not focus on forest road design.

In this research, shallow landslide risks were determined using an infinite slope stability analysis. Then, an automatic forest road design model was developed considering shallow landslide risks while accurately calculating the earthwork volumes and costs using the detailed topographical information of a high resolution DTM generated from LiDAR.

2. Study site and method – *Mjesto i metoda istraživanja*

2.1 Study site – *Mjesto istraživanja*

The study site was around the terminal point of the main forest road at the Funyu Experimental Forest of Utsunomiya University in Japan (Fig. 1 and 2). The vegetation around the study site was a mixed forest composed of cedar, cypress, pine, oak, azalea, and maple. A high resolution (1 m grid) DTM was made by processing the LiDAR data using the intersection angle method, which was a new technique developed by Saito et al. (2008) to create ground surfaces from the raw LiDAR data. This method reproduces geographical features more clearly than the 1 m grid DEM, which an aerial survey company generated using the roller method and manual filtering in the Utsunomiya University Forest.

At the study site, the operation system included falling with a chainsaw, processing with a processor, yarding with a tower yarder, and transporting using a truck with a 4 t loading capacity. On terrain where it

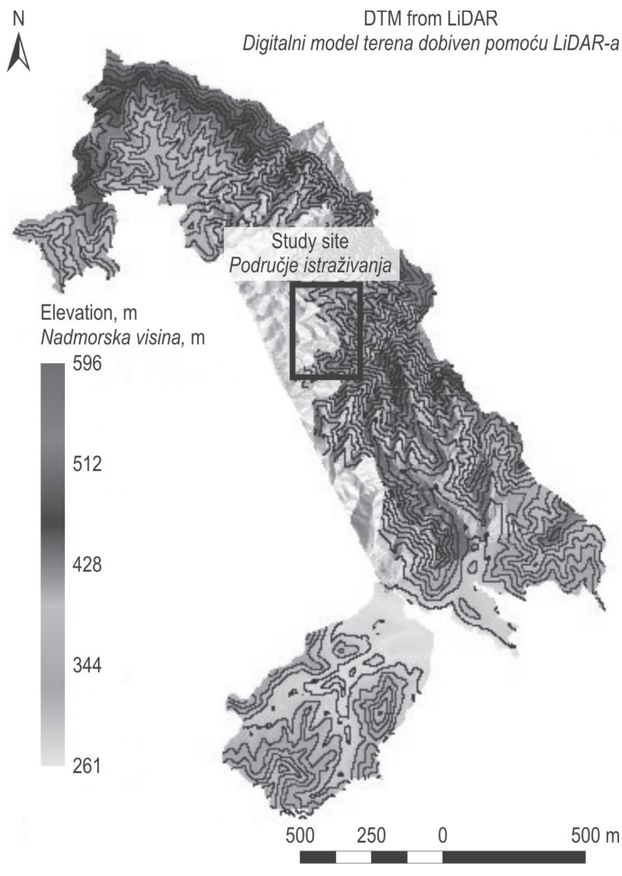

Fig. 1 Funyu Experimental Forest of Utsunomiya University
Slika 1. *Pokusni šumski object Funyu, Utsunomiya sveučilišta*

Fig. 2 Study site with high resolution DTM
Slika 2. *Područje istraživanja prikazano digitalnim modelom reljefa visoke rezolucije*

was difficult to construct forest roads, spur roads were constructed from landings to forest roads and a forwarder was used for forwarding. The starting point of the planned forest road was set as the terminal of the main forest road established in 2003, while the terminal point was the terminal of the main forest road established in 2005 (Fig. 2). The length and width of the planned forest road were about 850 m and 4 m, respectively. This forest road was a main road with full bench construction and planned to be used permanently.

2.2 Slope stability analysis – *Analiza stabilnosti pokosa*

A slope stability analysis was used to determine the slope failure potential distributions. The infinite slope stability analysis formula with the 10 m grid DTM was used instead of the 1 m grid DTM because the 1 m grid DTM was too detailed for a slope stability analysis. The area where the safety rate (F) shown in the following equation became one or less was judged to be the area of slope failure potential.

$$F = \frac{c + \left(\gamma s \times h \text{-} \gamma w \times hw\right) \times \cos^2\theta \tan\varphi}{\gamma s \times h \times \cos\theta \sin\theta} \tag{1}$$

Where:

- c soil cohesion, N/m^2
- γs soil density, kg/m^3
- h soil depth, m
- γw water density, kg/m^3
- hw groundwater level, m
- θ slope angle, °
- φ soil internal frictional angle, °

In this study c, φ, and γs were assumed to be 1 730 N/m^2, 30°, and 2 000 kg/m^3, respectively, from the classification of the surface soil in the Funyu Experimental Forest as sandy soil (Goshima et al. 2008). γw is 1 000 kg/m^3. θ was calculated from the 10 m grid DTM. hw was calculated using the probable rainfall intensity for 1 h calculated by the fair formula from the Automated Meteorological Data Acquisition System's probable rainfall intensity calculation program for every return period (Public Work Research Institute 2010). The return periods used covered a range of 10 to 100 years, with 10 year increments (Table 1).

h was estimated from the values found in a previous study where 167 points were evaluated using simple penetration tests (Goshima et al. 2008). This test can explain a vertical change in the resistance of the soil layer based on the number of times a 5 kg hammer has to fall from a 50 cm height (*Nc* value) to penetrate the cone 10 cm into the soil. The soil layer depth was determined from an *Nc* value of 20 or less because the basement geology of the Funyu Experimental Forest belongs to the Neogene Tertiary Formation and the Kanto loam soil layer (Ohsaka et al. 1987). The spatial distribution of the soil depths was estimated using the method by Iida et al. (2005). They paid attention to the inclination and average depth of the water catchment area, and estimated soil depths as logarithmic normal distributions with five classes of slope angles and four classes of average depths for a water catchment area.

2.3 Process for automatic determination of route *Postupak automatskog projektiranja šumske ceste*

The route determination method using the cubic spline interpolation proposed by Tasaka et al. (1996) balanced cut and fill materials and reduced the earth-

Table 1 Rainfall intensities and slope failure areas
Tablica 1. *Intenzitet padalina i područja pojave klizanja kosina*

Rainfall duration, h *Trajanje oborina*, h	Return period, year *Vrijeme promatranja, godina*	Rainfall intensity, mm/h *Intenzitet oborina,* mm/h	Shallow landslide risk areas, ha *Rizična područja s obzirom na mogućnost pojave klizišta*, ha	
			Lognormal distributions *Logaritamska normalna distibucija*	Survey data *Terenski podaci*
1	10	50.28	51.18	68.42
1	20	59.21	53.34	70.58
1	30	65.16	59.26	76.51
1	40	69.74	57.11	78.66
1	50	73.51	64.65	80.82
1	60	76.77	68.96	85.66
1	70	79.59	51.18	89.44
1	80	82.13	71.66	93.21
1	90	84.45	73.81	95.90
1	100	86.58	75.43	96.98

work volumes. Therefore, we introduced this method to the program for the automatic forest road design model using the DTM generated from LiDAR data (Saito et al. 2009). In addition, this method has preferred because its process time was very short, even on a personal computer.

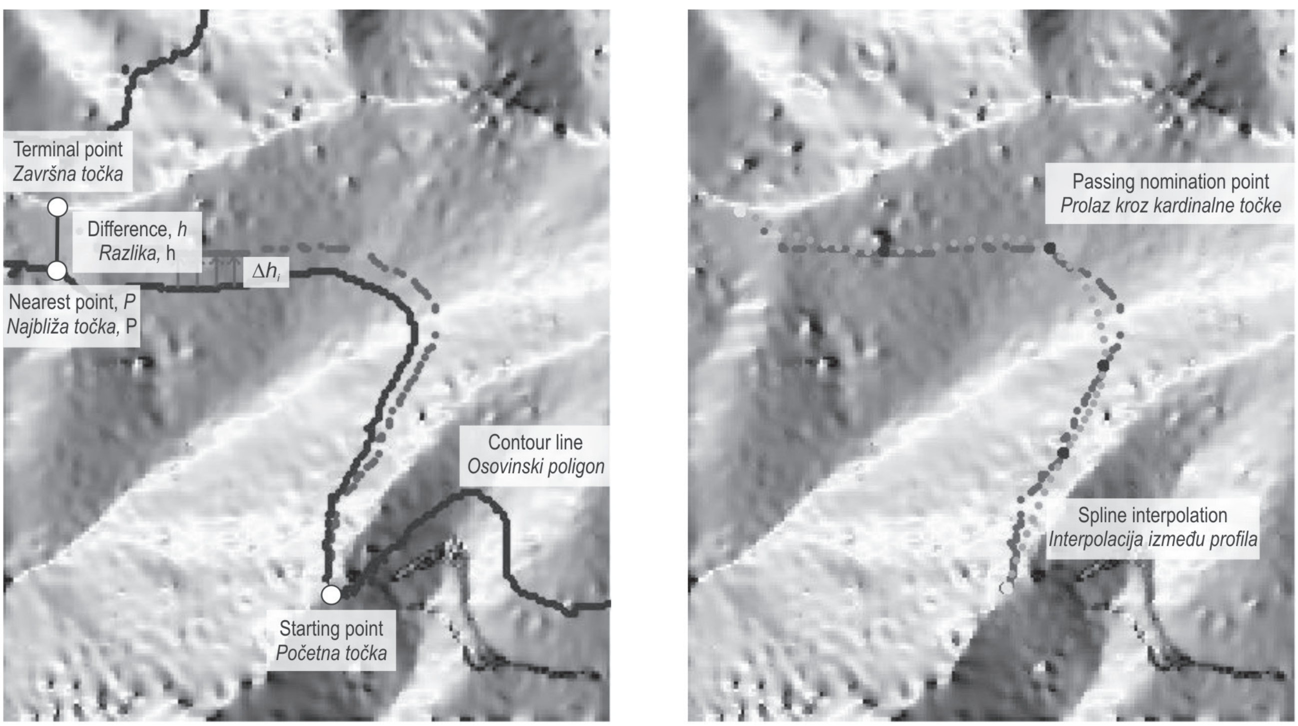

Fig. 3 Forest road design process
Slika 3. *Postupak projektiranja šumske ceste*

Table 2 Unit costs (Nihon Rindo Kyokai 2004)

Tablica 2. *Troškovi (Nihon Rindo Kyokai 2004)*

Item – *Radni zahvat*	Machine – *Stroj*	Unit cost, soil *Jedinični trošak, materijal C kategorije*	Unit cost, rock *Jedinični trošak, materijal A kategorije*
Cutting – *Iskop*	Bucket excavator – *Bager*	235 yen/m^3	339 yen/m^3
Smoothing – *Profiliranje planuma*	Bulldozer – *Buldozer*	140 yen/m^3	140 yen/m^3
Compacting – *Sabijanje*	Bulldozer – *Buldozer*	108 yen/m^3	108 yen/m^3
Transporting – *Transport*	Dump truck – *Kamion kiper*	435 yen/m^3	552 yen/m^3
Fill slope greening – *Stabiliziranje pokosa iskopa*	–	1 083 yen/m^2	1 083 yen/m^2
Cut slope greening – *Stabiliziranje pokosa nasipa*	–	1 860 yen/m^2	0 yen/m^2
Retaining wall – *Potporni zid*	–	16 000 yen/m^2	16 000 yen/m^2

The procedure is as follows (Fig. 3):

⇒ The starting and terminal points are determined;

⇒ A contour line is generated from the starting point;

⇒ The nearest point, P, on the contour line from the terminal is determined;

⇒ The difference in elevation, h, between the terminal point and P is calculated;

⇒ The length, l, along the contour line is calculated from the starting point to P;

⇒ The difference, h, is distributed proportionally in the distance Δhi for each point i, where these points are located at 20 m intervals along the contour line;

⇒ Each point moves to a point in the steepest slope direction so that the elevation of the new point becomes the same as the elevation of each point added by the elevation difference on each point, Δhi. The new point is considered to be the passing nomination point;

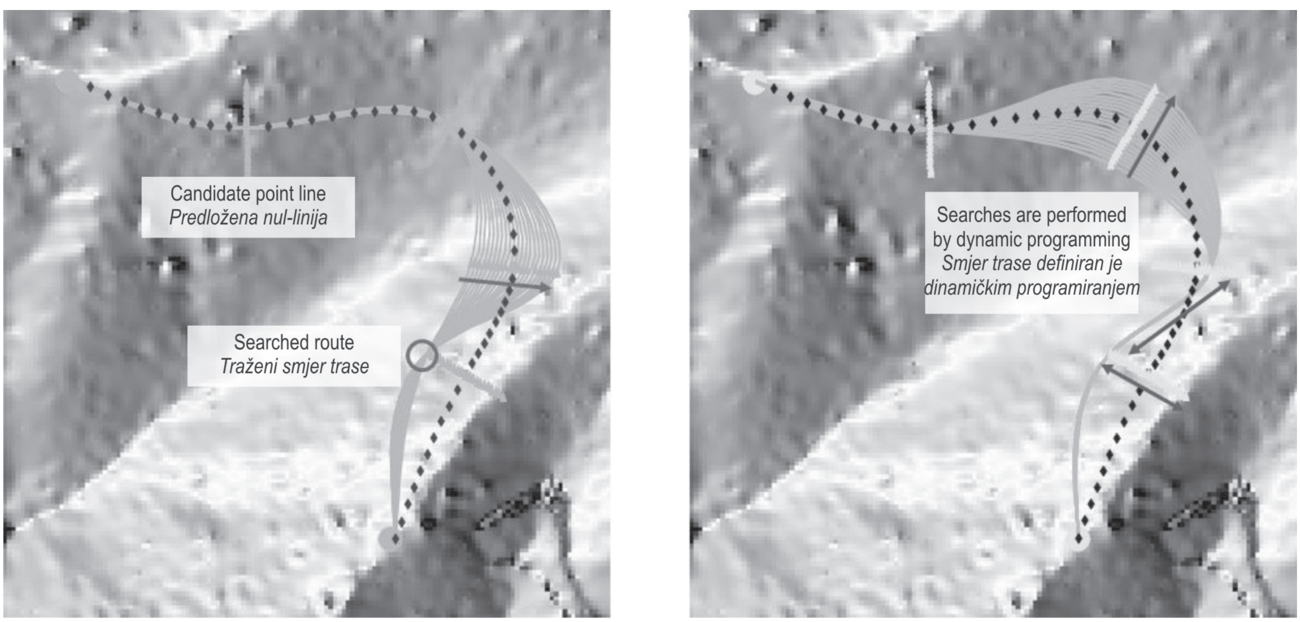

Fig. 4 Minimum earthwork cost route search process

Slika 4. *Postupak pronalaženja trase šumske ceste s najmanjim troškovima zemljanih radova*

The cubic spline interpolates between the nomination points at 20 m intervals, and a temporary route is determined.

Then, the program searches for the minimum earthwork cost route based on the temporary route using dynamic programming as follows (Fig. 4):

⇒ The curvature radius of each nomination point on the internal solution route is determined;

⇒ Nomination points that have local minimum curvature radius values are determined to be the base points for searching for the minimum earthwork cost route using dynamic programming (Kanzaki 1973);

⇒ Candidate points are generated on both sides of the base points on the normal line ranging from 1 m to 10 m at 1 m intervals;

⇒ The minimum earthwork cost route is determined using dynamic programming by selecting from the combinations of these candidate points connected with the cubic spline interpolation.

2.4 Earthwork cost estimation – *Procijenjene vrijednosti zemljanih radova*

In order to calculate the earthwork costs, the unit costs listed in Table 2 were used.

The soil type influenced the work efficiency of the forest road establishment. The road width was 4.0 m, the fill slope was 1:1 (45°), and the cut slope was 1:0.8 (51°) for soil and 1:0.3 (73°) for rock. When the slope length became 3 m or more, the slope was assumed to be made by a retaining wall with a slope of 1:0.2 (Fig. 5). The earthwork volumes were estimated using the average end section method. Cut and fill areas were estimated from the differences between the forest road cross sections designed by the program and the ground surfaces of DTM while dividing each section between adjacent candidate points into 10 individual sections. It was assumed that a soil pit or waste site was 2 km away from the construction site.

In a previous study designed section length was 200 m and its earthwork volume was about 3 600 m^3 (18 m^3 per meter) (Saito et al. 2007). In this study, the designed section was extended to 850 m. The extended 650 m section was measured by LiDAR in 2003 before the forest road establishment and again after the forest road establishment in 2005. Therefore, the earthwork volumes of the established forest road were estimated from the difference between the LiDAR data measured before and after the forest road establishment. The forest road was constructed with a full bench. Therefore, it was assumed that the differences in the DTM between 2003 and 2005 were cutting volumes.

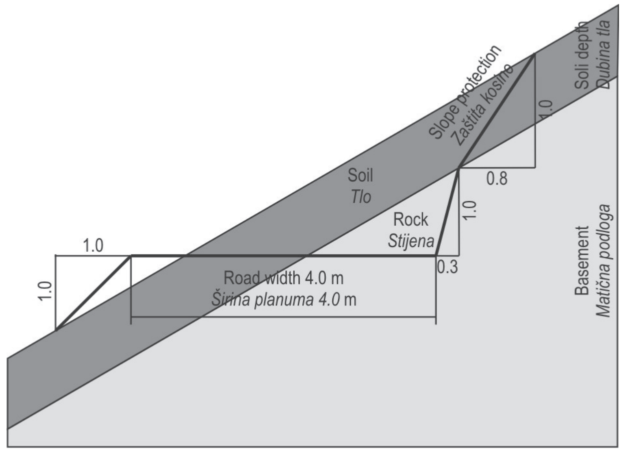

Fig. 5 Cross-section considering soil depth

Slika 5. *Poprečni presjek s obizrom na dubinu tla*

2.5 Shallow landslide risk consideration *Rizična područja s obzirom na mogućnost pojave klizišta*

In this research, the shallow landslide risk map was overlapped on the road map to search for the route while avoiding a forest road failure. A failure was assumed to occur when the forest road passed over shallow landslide risk areas. In this case and the forest road was then assumed to be established again. It was also assumed that the restoration costs would be the same to 10 times as much when passing over shallow landslide risk areas based on the probable rainfall intensities for 100 to 10 years, with 10 year steps.

In order to examine the effect of the usage period on forest road design, some limited usage periods were considered in the analyses, although permanent use was assumed for this main forest road. The usage period for the spur roads was assumed to be 10 years. In this case, the reconstruction costs for shallow landslide risk areas based on each probable rainfall intensity, excluding 10 years, were set to zero because it was assumed that the spur roads were not to be used for more than 10 years. Furthermore, in order to examine the effect of the strength of the forest road structure on the forest road design, it was assumed that no slope failure occurred by some years probable rainfall intensity. It was difficult to assess the strength of the forest road structure in relation to failure because natural conditions and construction techniques affected it. Therefore, the 10 year probable rainfall intensity was assumed as the probable rainfall intensity by which no slope failure occurred in just a test case of this study although the effect of the strength of the forest road structure on forest road design should be examined in

Table 3 Results of soil depth survey, cm
Tablica 3. *Rezultati istraživanja dubine tla, cm*

Catchment depth – *Vodonosni sloj*		Inclination – *Nagib*				
		0–15 °	15–25 °	25–35 °	35–45 °	45–55 °
0–20 m	Number of samples – *Broj uzoraka*	16	51	79	14	0
	Survey average, (SD) – *Srednja vrijednost (Sd)*	266 (95.5)	151.2 (89.8)	130.8 (94.4)	86.1 (52.8)	–
	Theoretical lognormal distribution *Teoretska logaritamski normalna distibucija*	311	171	101	58	32
	Difference – *Razlika*	–45	–19.8	29.8	28.1	–
20–200 m	Number of samples – *Broj uzoraka*	3	6	9	3	0
	Survey average, (SD) – *Srednja vrijednost (Sd)*	182.9 (134.5)	79.8 (25.4)	62.1 (121.6)	67.1 (29.7)	–
	Theoretical lognormal distribution *Teoretska logaritamski normalna distibucija*	217	117	68	38	21
	Difference – *Razlika*	–34.1	–37.2	94.1	29.1	–
200–2 000 m	Number of samples – *Broj uzoraka*	2	7	6	0	0
	Survey average, (SD) – *Srednja vrijednost (Sd)*	83.1 (1.9)	48.3 (111.3)	159.6 (81.7)	–	–
	Theoretical lognormal distribution *Teoretska logaritamski normalna distibucija*	152	81	46	26	14
	Difference – *Razlika*	–68.9	67.3	113.6	–	–
2 000–20 000 m	Number of samples – *Broj uzoraka*	0	1	0	0	0
	Survey average, (SD) – *Srednja vrijednost (Sd)*	–	116	–	–	–
	Theoretical lognormal distribution *Teoretska logaritamski normalna distibucija*	106	55	31	17	9
	Difference – *Razlika*	–	61	–	–	–

a future study. In this case, the reconstruction cost for slope failure caused by the 10 year probable rainfall intensity was set to zero.

3. Results and discussion – *Rezultati s raspravom*

3.1 Soil depth – *Dubina tla*

With regard to the soil depth, large influences were expected from terrain factors such as the elevation, inclination, water catchment area, etc. Negative correlations were found between the soil depth and slope angles for the average depth of the water catchment area (Table 3). Although the survey points were not evenly distributed on the geographical features, the results were similar to our expectations.

In order to determine the spatial distribution of soil depths, the method by Iida et al. (2005) was applied to the Funyu Experimental Forest.

Fig. 6 shows a comparison of the measured values of soil depth and the theoretical lognormal distribution at an inclination of 25–35° and an average depth for the water catchment area of 0–20 m. Table 3 lists the averages of the survey results, the mode values of the lognormal distributions, and the differences for each category. The soil depth comparisons were relatively consistent, and this method could approximate the soil depth by a lognormal distribution, although the maximum and average errors were 152.0 cm and 15.0 cm, respectively (Table 3). Then, a soil depth map for the experimental forest was made using the mode values of the lognormal distributions as the estimated values of soil depth (Fig. 7).

3.2 Slope failure – *Klizanje kosina*

Shallow landslide risk area distributions were estimated using the estimated soil depths and the different probable rainfall intensities (Table 1). As an example, the shallow landslide risk areas predicted

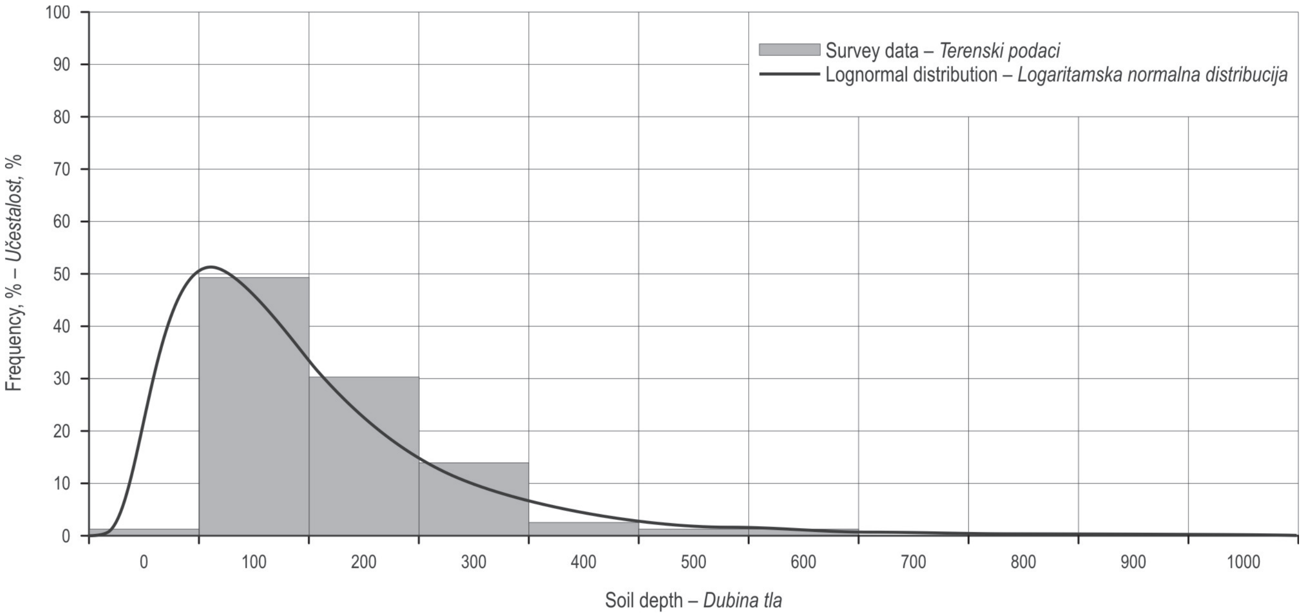

Fig. 6 Example of lognormal distribution and soil depth frequency distribution of survey results
Slika 6. *Primjer logaritamske normalne distibucije i distribucije dubina tla na istraživanom području*

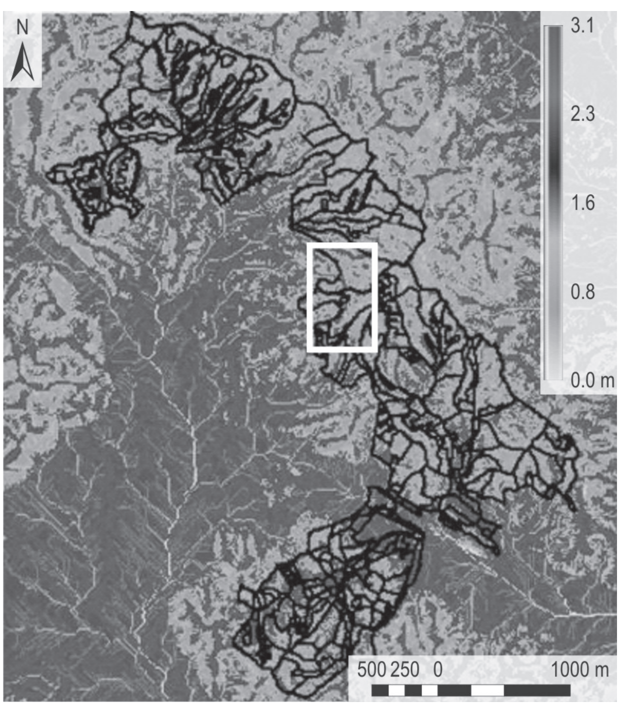

Fig. 7 Estimated soil depth map, white frame: study site
Slika 7. *Karta procjenjenih dubina tla, bijeli okvir: područje istraživanja*

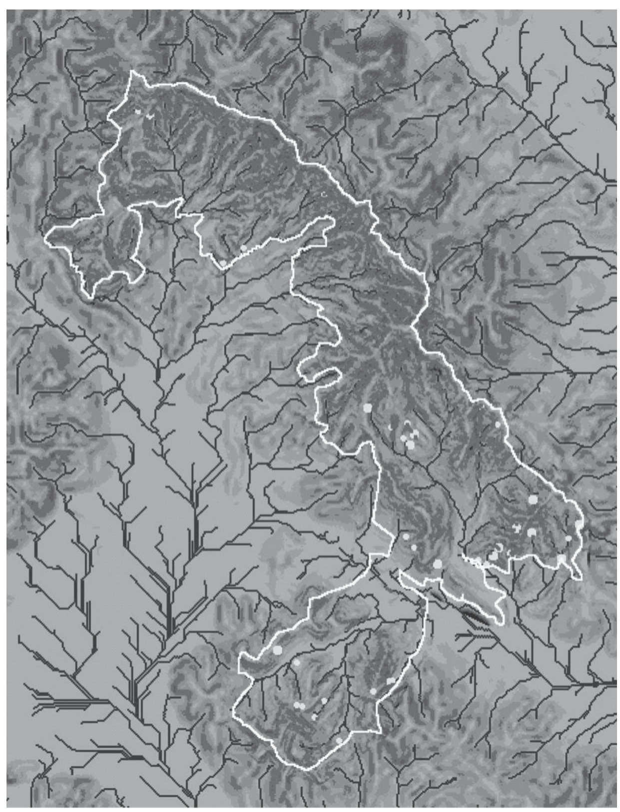

Fig. 8 Shallow landslide risk map based on 50 year probable rainfall intensity
Slika 8. *Karta pojavnosti klizišta na temelju predviđenog 50 godišnjeg intenziteta padalina*

using the 50 year probable rainfall intensity are shown in Fig. 8. The shallow landslide risk areas estimated using the mode values of the lognormal distributions

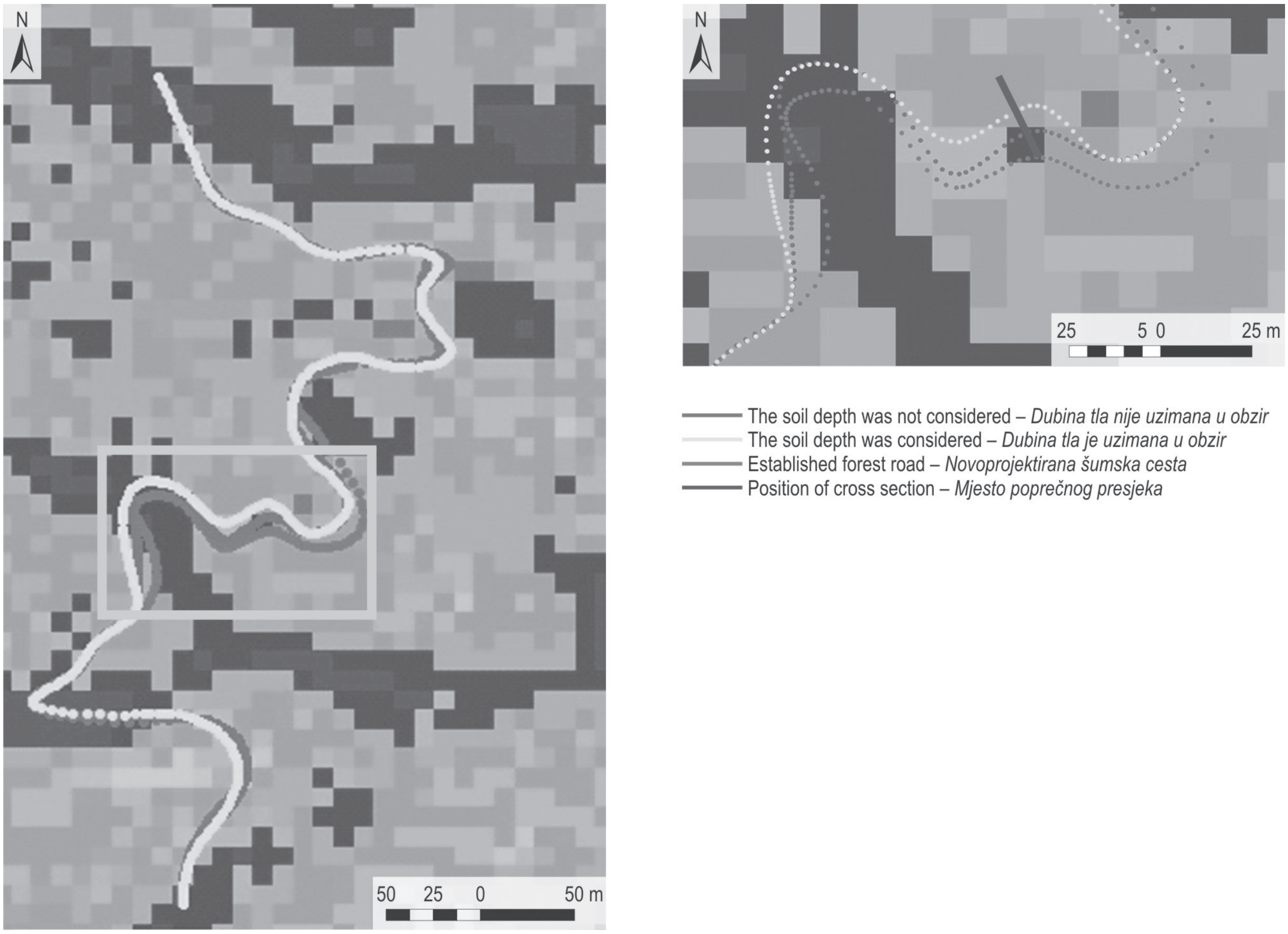

Fig. 9 Forest road design considering soil depth, right: close-up of frame in the figure on the left
Slika 9. *Projektiranje šumske ceste na temelju dubine tla, desno: uvećani prikaz iz okvira s lijeve strane*

as soil depths were 12% of the Funyu Experimental Forest, 538.77 ha, while those estimated using the average soil depth of the survey results were 15%. 16% of the shallow landslides that occurred in 1998 were predicted using the mode values of the lognormal distributions as soil depths (Fig. 8), while 11% were predicted using the average soil depth of the survey results. Thus, using the mode values of the lognormal distributions as soil depths improved the shallow landslide risk prediction.

3.3 Forest road design considering soil depth *Projektiranje šumske ceste s obzirom na dubinu tla*

The estimated earthwork volume for the established forest road was 13 487 m^3, while that estimated by the program was 14 162 m^3, which was 21.8 m^3 per meter. Thus, the program estimated the earthwork volume accurately. Although the forest road was constructed with a full bench, the planned forest road after this section was designed by the program with a balance of cut and fill materials in order to reduce the earthwork volumes and costs (Saito et al. 2007).

The horizontal alignments designed by the program considering the soil depth did not change significantly compared to those for the established forest road. In Fig. 9, »The soil depth was not considered« means that the soil depth was not considered in the route determination, but costs were estimated with considering soil depth.

However, some sections shown in Fig. 9 were changed so that the forest road avoided the thick soil depth areas where the earthwork volumes, and thus earthwork costs, were relatively high, even though the unit costs were lower. Although the gradients of the forest road considering soil depth became large in areas to avoid these thick soil depths, these were within forest road regulations. The maximum gradi-

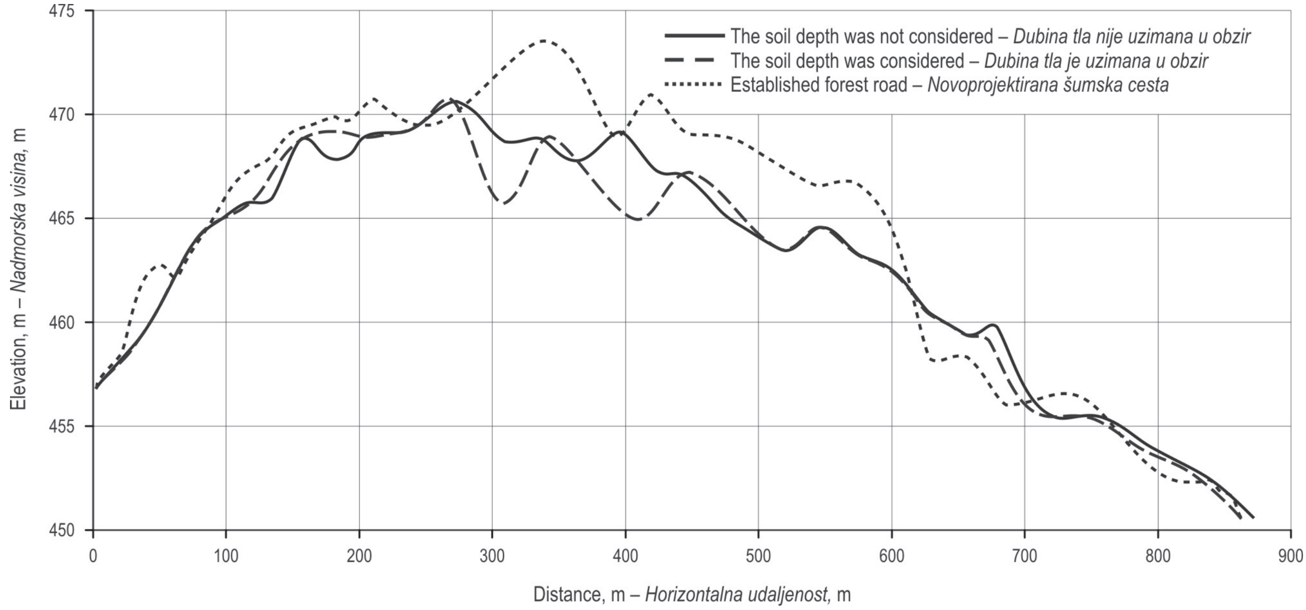

Fig. 10 Profile considering soil depth

Slika 10. *Uzdužni profil šumske ceste s obzirom na dubinu tla*

ent was 12.2% on the section from 268 m to 308 m (Fig. 10).

In a comparison of cross-sections, the forest road considering soil depth passed over areas of thin soil depth, where the amount of soil to be cut was small. Moreover, because the majority of the cutting slopes consisted of rocks, little slope protection was necessary (Fig. 11).

In a comparison of the earthwork volumes, the amount of rock increased, and the amount to be transported increased (Table 4).

Therefore, the earthwork costs increased (Table 5). However, the slope protection cost was reduced, and the total cost was also reduced. The program could find the minimum cost route by searching for areas with thin soil depths.

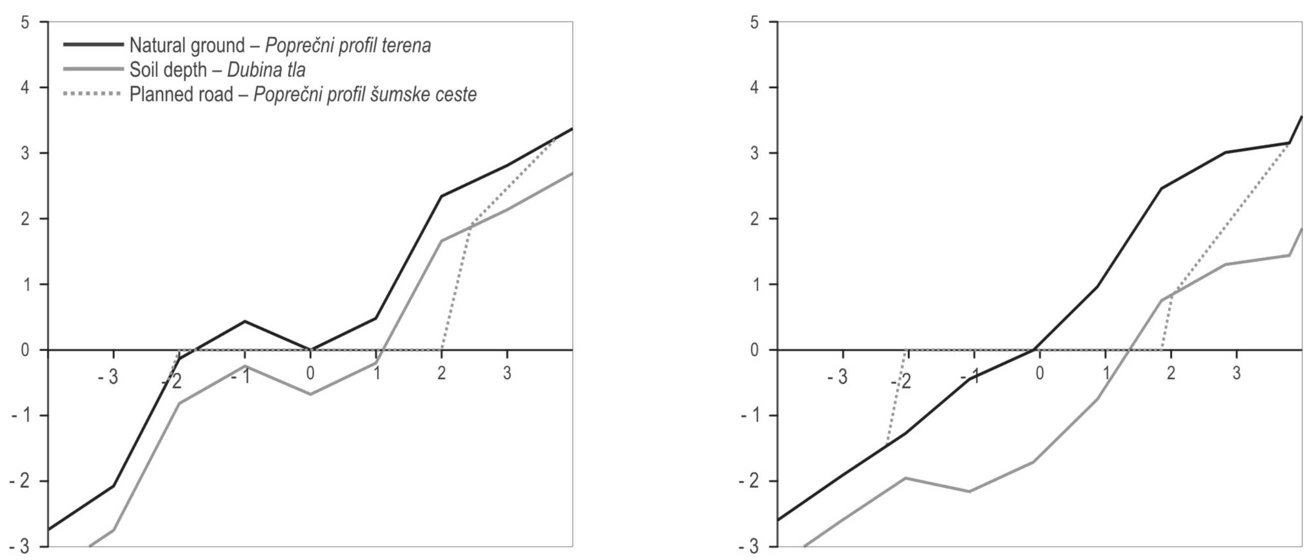

Fig. 11 Cross section, left: soil depth was considered; right: soil depth was not considered

Slika 11. *Poprečni presjek šumske ceste, lijevo: u obzir je uzimana dubina tla; desno: dubina tla nije uzimana u obzir*

Table 4 Earthwork volumes, m^3

Tablica 4. *Količina zemljanih radova,* m^3

	Soil only *Materijal C kategorije*	Soil and rock *Materijal B kategorije*
Cutting volume, soil *Volumen iskopa C kategorije*	2 366.44	1 977.86
Cutting volume, rock *Volumen iskopa A kategorije*	2 256.56	2 745.22
Cutting volume, total *Ukupni volumen iskopa*	4 623.00	4 723.08
Filling volume *Volumen nasipa*	4 681.63	4 481.99
Transporting volume *Volumen transportiranog materijala*	58.64	241.09

Table 5 Costs considering soil depth

Tablica 5. *Troškovi s obzirom na dubinu tla*

	Soil only *Materijal C kategorije*	Soil and rock *Materijal B kategorije*
Earthwork cost *Troškovi zemljanih radova*	¥ 2 339 098	¥ 2 450 479
Slope protection cost *Troškovi zaštite pokosa*	¥ 19 570 977	¥ 16 309 148
Cost per meter *Troškovi po dužnom metru*	¥ 25 626	¥ 21 839

3.4 Forest road design considering slope failure *Projektiranje šumske ceste s obzirom na klizanje kosina*

Fig. 12 shows the results for a forest road design with a shallow landslide risk map. The establishment costs of a forest road design without avoiding shallow landslide risk areas was about 5 000 yen per meter cheaper than when trying to avoid the shallow landslide risk areas (Table 6).

However, the distance of forest road on the shallow landslide risk areas using the 10 year probable rainfall intensity was significantly reduced when avoiding the shallow landslide risk areas (Table 7). Therefore, the restoration costs were reduced, and the total costs were also reduced (Table 6). Because the forest road designed by the program bypassed only the shallow landslide risk areas using the 10 and 20 year probable rainfall intensities, the routes were almost the same shape and hardly any differences were observed in a comparison of the profiles and cross-sections.

In order to examine the effect of the usage period on forest road design, it was assumed that the forest road was only used for 10 years. The reconstruction costs for slope failure caused by each probable rainfall intensity, excluding 10 years, were set to zero. The forest road alignments did not change significantly because the forest road designed with a consideration of shallow landslide risk areas using just the 10 year

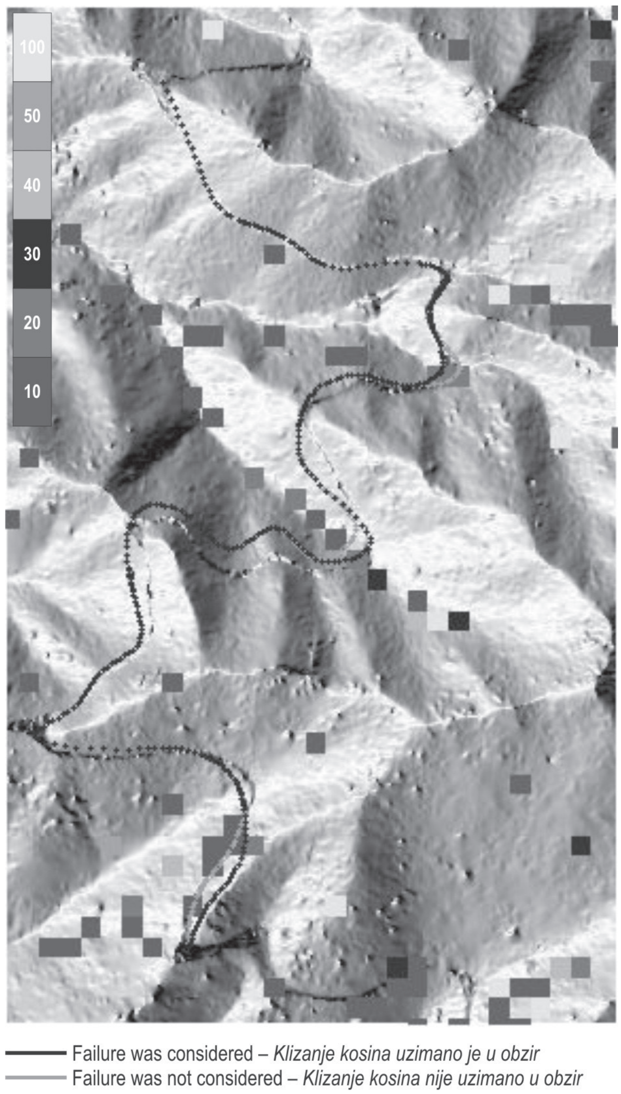

Fig. 12 Forest road design considering shallow landslide risk

Slika 12. *Projektiranje šumske ceste s obzirom na mogućnost pojave klizišta* probable rainfall intensity only bypassed the shallow landslide risk areas based on the 10 year probable rainfall intensity (Table 7). However, the establishment costs were reduced compared to a forest road that considered shallow landslide risk areas based on all of the probable rainfall intensities and were similar to those for a forest road designed without considering shallow landslide risk areas because the route did not bypass the shallow landslide risk areas based on the 20 year probable rainfall intensity (Table 6).

Furthermore, it was assumed that a slope failure did not occur by the 10 year probable rainfall intensity, in order to examine the effect of the strength of the forest road structure on the forest road design. As a result, the forest road designed by the program did not bypass shallow landslide risk areas based on the 10 year probable rainfall intensity, but only bypassed shallow landslide risk areas based on the 20 year probable rainfall intensity (Table 7). Although, when not considering the shallow landslide risk areas based on the 10 year probable rainfall intensity, the forest road alignment was similar to that when considering shallow landslide risk areas based on all of the probable rainfall intensities, the establishment costs were reduced compared to those of the forest road that considered shallow landslide risk areas using all of the probable rainfall intensities, and were similar to those for the forest road designed without considering shallow landslide risk areas (Table 6).

Thus, the effects of the usage period and strength on the forest road design were not significant at this study site. However, this method could be used to design a forest road considering shallow landslide risk areas based on the usage period and strength of the forest road. For instance, from the viewpoint of usage periods, main forest roads should avoid shallow landslide risk areas based on the probable rainfall intensities for 30 years or less, while spur roads should avoid shallow landslide risk areas based on the probable rainfall intensities for 10 years or less. From the viewpoint of structures, main forest roads should avoid shallow landslide risk areas based on the probable rainfall intensities for 50 years or more, while spur roads should avoid shallow landslide risk areas based on the probable rainfall intensities for 20 years or more.

4. Conclusions – *Zaključci*

In this study, the frequency distributions of soil depth were estimated as logarithmic normal distributions and a soil depth map for the experimental forest was created using the mode values of these lognormal distributions. The program developed in this study could find the minimum cost route by considering the soil depth and searching for areas with thin soil depth on the forest road. However, this study used only two classifications, that is, sandy soil and soft rock, even though there were various types of soils and rocks in various areas. In addition, the earthwork costs were different; for example, the excavating costs for hard rock increased because of the need for a breaker. Thus, it is important to clarify the soil type, but it is difficult to predict the soil type in large areas. Therefore, a technique for predicting the soil type in large areas by remote sensing should be researched.

Shallow landslide risk maps were also made in the experimental forest by a slope stability analysis using these soil depth distributions. Using the mode values of the lognormal distributions as soil depths improved the shallow landslide risk prediction. Finally, an automatic forest road design model that considered shal-

Table 6 Costs considering shallow landslide risk
Tablica 6. *Troškovi s obzirom na mogućnost pojave klizišta*

	Failure was not considered *Klizanje kosina nije uzimano u obzir*	Failure was considered *Klizanje kosina je uzimano u obzir*	Only 10 years were considered *U obzir je uzimano 10 godišnje razdoblje*	Only 20 years were considered *U obzir je uzimano 20 godišnje razdoblje*
Establishment cost *Troškovi izgradnje*	¥ 18 759 627	¥ 19 852 451	¥ 18 956 214	¥ 18 822 390
Reconstruction cost *Troškovi obnove*	¥ 9 353 400	¥ 4 063 920	¥ 2 064 422	¥ 1 086 428
Cost per meter *Troškovi po dužnom metru*	¥ 32 880	¥ 27 972	¥ 24 586	¥ 23 309

Table 7 Length of forest road on shallow landslides risk areas, m
Tablica 7. *Duljina cesta na područijima na kojima postoji mogućnost pojave klizišta,* m

	Failure was not considered *Klizanje kosina nije uzimano u obzir*	Failure was considered *Klizanje kosina je uzimano u obzir*	Only 10 years were considered *U obzir je uzimano 10 godišnje razdoblje*	Only 20 years were considered *U obzir je uzimano 20 godišnje razdoblje*
10 year probable rainfall intensity *Predviđeni 10 godišnji intenzitet padalina*	35.2	10.2	9.2	35.2
20 year probable rainfall intensity *Predviđeni 20 godišnji intenzitet padalina*	18.8	18.7	18.8	9.6

low landslide risks was developed that accurately calculated the earthwork volumes and costs using the detailed topographical information of a high resolution DTM generated from LiDAR in this research. The program could minimize the earthwork costs while avoiding shallow landslide risk areas. The program could easily design an environmentally sound low-volume road automatically.

The effects of the usage period and risk of failure on forest road design were also examined in this study. Forest roads were designed avoiding some types of shallow landslide risk areas using different probable rainfall intensities. This simple method of weighing the probable rainfall intensity and restoration costs could be used to design a forest road while considering shallow landslide risk areas with the usage period and risk of failure of the forest road. However, it would be difficult to clarify the effects of these weights on a main forest road or spur road design. Therefore, a future study should be conducted to clarify how many years of probable rainfall intensity and how much reconstruction costs should be used for various types of roads and areas.

In addition to shallow landslide risk, collapses that occur as the result of forest road construction should be considered (Yoshimura 1997). Although collapses caused by forest road construction are important for forest design, they were not considered in this study because natural conditions and construction techniques affected them and their assessment was difficult. However, a high-resolution DTM might help to predict these collapses (Umeda et al. 2007). Thus, this study should also be extended in the future to consider collapses that occur as the result of forest road construction using a high-resolution DTM.

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Sažetak

Istraživanje automatskog projektiranja šumskih cesta s obzirom na plitka klizišta pomoću LiDAR-a na pokusnom objektu Funyu

U radu je istražen model automatskog projektiranja šumskih cesta s obzirom na plitka klizišta pomoću LiDAR-a. Istraživanje je provedeno na pokusnom objektu Funyu, Sveučilišta Utsunomiya u Japanu, za koje je napravljen, upotrebom »intersection angle method«, digitalni model terena visoke rezolucije (1 m mreža). Prvo, kako bi se napravila karta plitkih klizišta na području istraživanja, napravljena je analiza stabilnosti nagiba pomoću formule za izračuna stabilnosti (1). Dubina tla je mjerena na 167 mjesta pomoću jednostavnih penetracijskih testova, te je frekvencija dubine tla procjenjivana na osnovu logaritamske normalne distribucije. Karta dubine tla na pokusnom objektu napravljena je korištenjem vrijednosti logaritamske distribucije. Također, napravljena je karta plitkih klizišta za pokusni objekt pomoću analize stabilnosti nagiba s obzirom na dubinu tla. Nakon toga, pomoću programa za automatsko projektiranje, na osnovu digitalnog modela reljefa, postavljena je trasa ceste koristeći metodu interpolacije zemljanih radova po dužnom metru. Takva metoda je korištena zbog kratkog vremena obrade podataka na osobnom računalu, te zbog toga što omogućava smanjenje zemljanih radova, prebacivanjem materijala iz iskopa u nasip šumske ceste. Kao pomoć pri postavljanju trase šumske ceste, karta plitkih klizišta je postavljena preko digitalnog modela reljefa te se na takav način trasa ceste mogla postaviti tako da se izbjegnu mjesta na kojima bi došlo da značajnog oštećenja i propadanja šumske ceste. Nakon postavljene trase šumske ceste napravljen je izračun troškova zemljanih radova, uzimajući u obzir opasnost od klizišta. Pretpostavljeno je na temelju predviđanja intenziteta padalina u sto godišnjem razdoblju, podijeljenom na 10 perioda, da bi troškovi obnove ceste bili jednaki trošku izgradnje ili čak do deset puta veći prilikom prelaska ceste preko klizišta. Kako bi se istražio utjecaj vremena upotrebe šumske ceste na projektiranje ceste, za analizu je odabrano nekoliko ograničenih vremena upotrebe, iako je za ovu cestu predviđeno neograničeno vrijeme upotrebe. Kao rezultat, utjecaja vremena upotrebe i kvaliteta projektiranja nisu značajni za ovo područje istraživanja. U budućim istraživanjima bi se trebalo razjasniti kroz koliko godina predviđeni intenzitet padalina utječe na troškove obnove različitih vrsta cesta u različitim područjima. Međutim ova metoda se može koristit za projektiranje šumskih cesta s obzirom na opasnost od klizišta, na osnovu vremena upotrebe i nosi-

vosti šumske ceste. Tako, korišteni program ima mogućnost da prilikom projektiranja šumske ceste smanji troškove zemljanih radova izbjegavajući područja na kojima postoji mogućnost pojave klizišta. Učinkovito korištenje programa omogućuje automatsko projektiranje šumskih cesta na okolišno prihvatljiv način s minimalnim zahvatima u okoliš gdje se cesta gradi.

Ključne riječi: LiDAR, automatsko projektiranje šumskih cesta, klizišta, interpolacija između profila, dinamičko programiranje

Authors' address – *Adresa autorâ:*

Assist. Prof. Masashi Saito, PhD. *
e-mail: m_saito@shinshu-u.ac.jp
Shinshu University
Faculty of Agriculture
Department of Forest Science
8304, Minamiminowa-Village
Kamiina-County 399-4598
JAPAN

Msahiro Goshima, MSc.
Assoc Prof. Kazuhiro Aruga, PhD.
e-mail: aruga@cc.utsunomiya-u.ac.jp
Assoc Prof. Keigo Matsue, PhD.
e-mail: matsue@cc.utsunomiya-u.ac.jp
Prof. Yasuhiro Shuin, PhD.
e-mail: shuin@cc.utsunomiya-u.ac.jp
Prof. Toshiaki Tasaka, PhD.
e-mail: tasaka@cc.utsunomiya-u.ac.jp
Utsunomiya University
Faculty of Agriculture
Department of Forest Science
350 Mine
Utsunomiya 321-8505
JAPAN

* Corresponding author – *Glavni autor*

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