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Original Article

Development of a Method of Forest Road Network Planning Using GIS that Discriminates and Avoids Dip Slopes

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1. Introduction

Efficient and reasonable layout of the forest road network based on construction and maintenance cost and efficient timber production is important in forest management. At the same time, places prone to collapse must be avoided and geographical and geological stability must be secured for long term use of the road especially when road density increases.

Japan islands are fundamentally composed of accretionary wedges (SAKAI, 2009). Except for igneous rock areas and colluvial slope, terrains are classified into either dip or opposite slope especially in accretionary wedges. A dip slope is a slope in the same direction of the inclined stratum, which generally makes filling difficult. Indeed the dip slope on a mountain side is generally gentle having long and smooth river systems (SUZUKI, 2000), and it is not difficult to construct roads. However, landslides and collapse of the cutting slope frequently occur, so that roads on a dip slope require higher construction and maintenance costs (SAKAI, 2012). Road planning must consider not only efficiency and construction cost but also safety factors and maintenance cost. A dip slope is often covered with thick colluvial soil, and such accumulated soil is prone to slide after a heavy rain. On the contrary, a road planned on the opposite slope which is steep, with a short and parallel waterfall and, winding in short sections (SUZUKI, 2000), takes much time to construct, but is stable once constructed (SAKAI, 2012). Therefore, it is important to distinguish a dip slope from the opposite slope to locate a stout and stable road network in advance to road network planning.

It is impossible to distinguish a dip slope on a contour map alone, but it is possible to distinguish a dip slope with the help of published digital geological maps. If the method of distinguishing a dip slope from such digital data could be established, it will save much manpower for reconnaissance and risky areas can be avoided in road construction. We tried to distinguish the dip slope using both contour map and digital geological map.

We also conducted a study to develop an efficient road network design applying geographical information system (GIS). For example, Yoshimura and Kanzaki predicted zones with a high risk of collapsing by using the fuzzy theory and considered the influence of soil erosion (YOSHIMURA

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and Kanzaki 1998). Saito used a high resolution digital terrain model (DTM) by light detection and ranging (LiDAR) for topographical information, and calculated the earth-volume and cost, and judged the risk of collapsing by a dynamic model of slope stability (Saito, 2012). He also developed an automatic method for designing a forest road avoiding dangerous areas. However, they did not consider geological factors. We developed a method of route location using GIS considering the geological structure, dip or opposite slope. GIS helps to simulate the route location, and stout roads considering the dip slope will help decrease road maintenance cost on the long term.

2. Methods

2-1 Study site

We applied the method at The University of Tokyo Chiba Forest (UTCBF) located in the southeastern part of the Boso Peninsula. It lies from 140º 5 ′ 33 ″ to 10 ′ 10 ″E and from 35º 8 ′ 25 ″ to 12 ′ 51 ″N. Most of the forest exists at altitudes of 50 – 370 m. The geographical structure

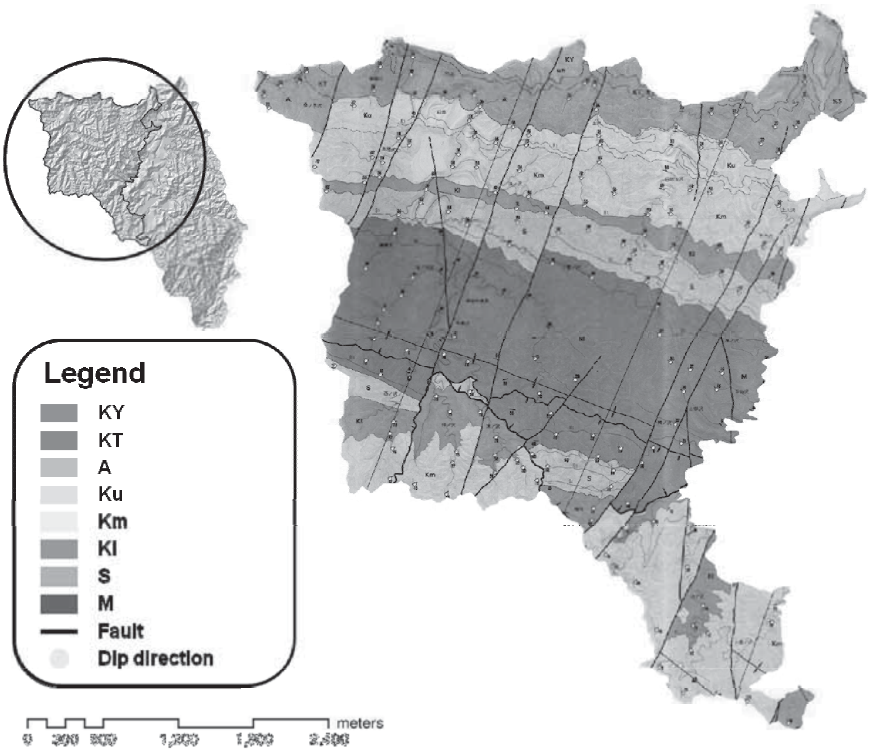


Figure 1. Study area and information of dip direction of stratum by 1/10,000 geological map from UTCBF

Note : KY: Massive mudstone interbedded with tuffs and sandstones, KT: Andesitic breccias, sandstone, tuff and calcarenite, A: Mudstone with interbeds of sandstone, KU: Sandstone interbedded with tuffs and mudstones, KM: Sandstone with interbeds of mudstone, KI: Sandstone and granule conglomerate, S: Mudstone with interbeds of tuff, M: Mudstone with interbeds of tuff and sandstone consists of marine deposits from the Neogene period, partly covered with n-onmarine deposits from the Quaternary period; slopes are generally very steep, about 26degrees, and the contour lines are complicated (University Forest In Chiba, 2007). The planned area was 2,226ha consisting of 1~23 compartments among 47 compartments (Figure 1).

2-2 Theory of distinguishing dip slope area

The procedure for planning the forest road network consisted mainly of three parts; 1) identifying the dip slope area from geological data and terrain data, 2) finding in advance the area for forest road network from forest resource data and terrain data, and 3) connecting these areas with a forest road considering the dip slope (Figure 2).

The dip slope has been mainly studied in the field of land-slide as a risky area. Suzuki classified the patterns of combination between slope (θ) and relative dip, that is, apparent dip (β) explained later into six types (horizontal dip, daylighting dip, parallel dip, hangnail dip, vertical dip, and infacing dip) and evaluated each stability (Suzuki, 2000), although horizontal, vertical and infacing dips were not quite dip slope, and his daylighting and hangnail dips were problem slopes in this study (Figure 3). Iwahashi *et al*. also classified dip slope and opposite slope of the area, and examined the number of collapse (Iwahashi *et al*., 2001). In this study, Suzuki's classification was summarized into three patterns for the practical purpose of distinguishing dip slope from the view point of road construction as shown in Figure 3.

First, the 10m digital elevation model (DEM) data was utilized as terrain data to calculate slope and aspect. Geological data was analyzed using the digital geological maps of Japan 1:200,000,

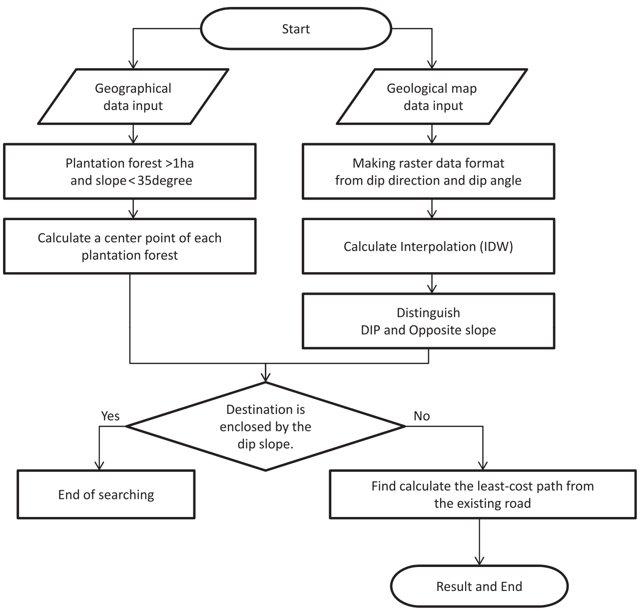


Figure 2. Flowchart of procedure for planning the road network

Kanto-Koshin ′ etsu and Izu-Ogasawara Islands published by National Institute of Advanced Industrial Science and Technology and the 1:10,000 geological map provided by the investigated site, UTCBF. We definitely need to obtain the data of slope (θ) and apparent dip of stratum (β) to classify the slopes, and this geological information of stratum has not been digitized in the 1:200,000 digital geological map. Most of the existing studies obtained and analyzed the data by utilizing the 1:50,000 geological map. As the 1:50,000 geological map has not been prepared by UTCBF, the above 1:10,000 geological map was arranged to analyze at GIS through creating the point data that had dip direction of stratum by scanning and rasterization. The information of dip direction of each point was digitized by reading in clockwise 360 degrees. This point data was interpolated to a 10 m grid using the IDW (Inverse Distance Weighted) technique.

Here Figure 4 explains the relationship between steepest angle of stratum direction (α), that is, true dip and apparent dip (β) of stratum, where Point A in Figure 4 is the point in calculation whether dip or opposite slope. The apparent dip here is the same as the relative dip which Suzuki used (Suzuki, 2000). The following formula can be derived,

$$\tan\beta = \tan\alpha \ \cos\eta , \quad (1)$$

where η is the direction from the dip direction.

Then, the slope could be distinguished as dip slope if η is $0 - 90°$, and opposite slope if η is $90 - 180°$.

In order to validate the results of calculation, some sample points which were in extracted area as dip slope were picked up, and the actual geological layer was investigated by the naked eye at these points, and the correctness of this method was analyzed.

2-3 Applying GIS to forest road planning

Esri ArcInfo GIS 9.3 software was used for route planning. Inclination and direction of slopes were analyzed by using 10 m x 10 m DEM, which was prepared from the data of UTCBF as mentioned above.

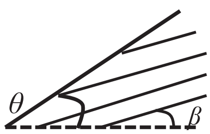
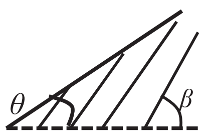
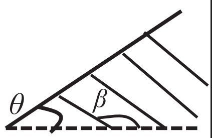
Structure			
Type of slope	Dip slope	Dip slope	Opposite slope
Define	$0^o \leq \beta < \theta$	$\theta < \beta \leq 90^o$	$90^o < \beta < 180^o$
Stability of Road construction	Not stable	Not stable	Stable
			Modify from the Suzuki(2000)[10]

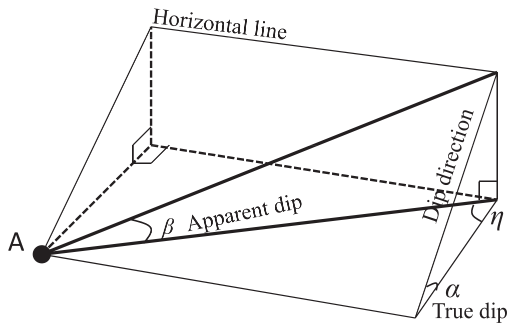
Figure 3. Classification of slope by combination of slope (θ) and apparent dip (β)

In this study, forest areas which had priority for harvesting were picked up first. The forest areas which had high priority were defined as covered by plantation forest larger than 1 ha on a non-dip slope less than 35 degrees, When the slope exceeds 35 degrees, it is difficult to construct road without walls, and the cost increases drastically, so that it is said that high density road networks cannot be realized on such steep terrain (Sakai, 2009). The areas with a slope less than 35 degrees were extracted using the DEM data. Indeed harvesting should be carried out in a plantation forest, but was inappropriate in a forest smaller than 1 ha taking into consideration the cost-benefit balance of constructing or efficient maintenance of forest road. This factor lead the qualification; plantation forests larger than 1 ha. The area of plantation forests was selected from the forest resource map and data of UTCBF. When some plantation forests were adjoined with each other, the area was added up. Road network could be located at the preferential area, which satisfied these factors.

Next, the forest road network that connected each prior area was calculated. For calculation, the grid of DEM was used as the base unit, as reported by Kobayashi (1983) and Sakurai *et al*. (2004). Furthermore, in this study, a dip slope was considered.

The gravity center of each extracted priority area was determined as the destination of road network, and its position was expressed by the coordinate of the DEM. When the destination was on a dip slope, it was not considered in road planning. Then the constructing costs for each destination and between destinations and existing roads were calculated.

The Dijkstra method (Dijkstra, 1959) was used to form the forest road network. When calculating cost for each section, the DEM grids were treated as nodes in the Dijkstra method, and edge path costs between each node were given as road construction cost per unit length. When the dip slope was considered, the algorithm was arranged to avoid the dip slope area.



β = apparent dip
α = true dip
η = Deviation angle between dip direction and direction of apparent slope

Apparent dip: $\tan\beta=(\tan\alpha)*(\cos\eta)$

Figure 4. Relationship between true dip and apparent dip of stratum
Note : The slope expressed by the stratum. Point A is the investigating point whether dip or opposite slope

After this process of calculating every road section, the minimum network was computed by Prim's algorithm (Prim, 1957). In the algorithm, the initial node was existing road. This algorithm gave the cost-minimum forest road network from the cost table prepared in advance.

We estimated the road construction cost on slopes below 35 degrees without walls based on standard unit price for civil engineering works (Construction Research Institute, 2006) assuming that the construction by $0.28m^3$ class excavator and 3 m in road width, and obtained the regression line of unit price of construction as follows (Figure 5),

$$y = 205.9 \exp(0.068x), \qquad (2)$$

Where y is unit price of road construction (JPY / m), and x is degrees of slope.

3. Results and discussion

The assumed dip slope area from the apparent dip (β) and surface slope (θ) are shown in Figure 6. The extracted dip slope area was accounted for 8 percent of the total area with an area of 201ha. The dip slope was found in a bundle on the slope in the north direction and more than 76 percent was distributed on gentle slope areas with a slope angle of less than 35 degrees (Figure 7). To validate this assumption, 11 points in the extracted dip slopes were investigated by the naked eye. As a result, all points were actually on the dip slop.

Figure 8 shows the extracted priority areas for harvesting area and numbered destination and the results of outline of forest road network not considering dip slopes. Roads were divided into sections between destinations and existing roads. Road density reached 14.0 m/ha. This network and result will be called ‘ Not considering dip slope (ND)', hereafter. On the other hand, a road network covering the planning area considering dip slopes was allocated as shown in Figure 9.

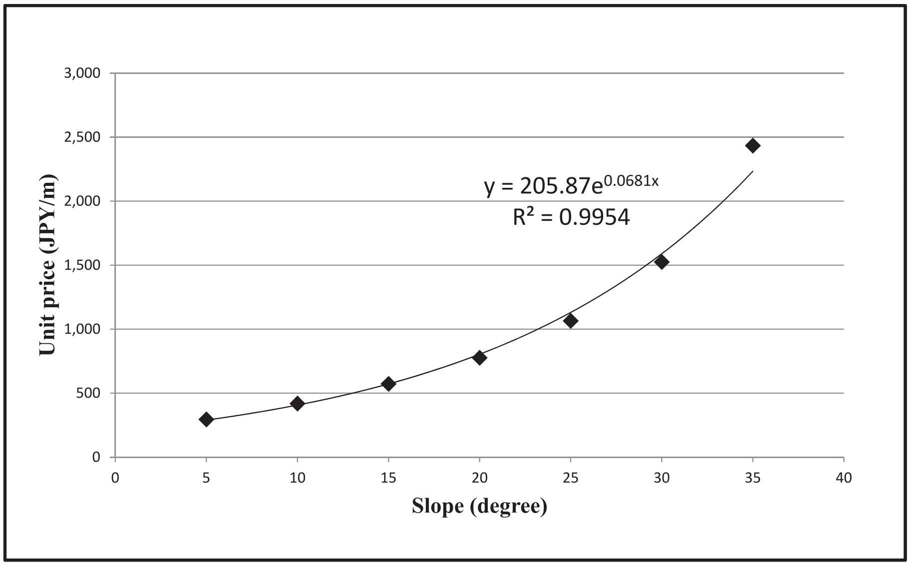


Figure 5. Unit price of road construction

This result will be called ‘ Considering dip slope (CD) ’ hereafter. The total length of the network in CD was 13,251 m which is slightly shorter than that in ND with 13,381m. The total construction cost and average construction cost of unit length in CD was 20,242,578 JPY and 1,528 JPY/m, which were higher than those of ND, that was 16,228,603 JPY and 1,213 JPY/m, respectively. The average degrees of mountain slope where roads were located could be estimated as 29 degrees at CD and 26 degrees at ND from Figure 5. The route locations of both situations

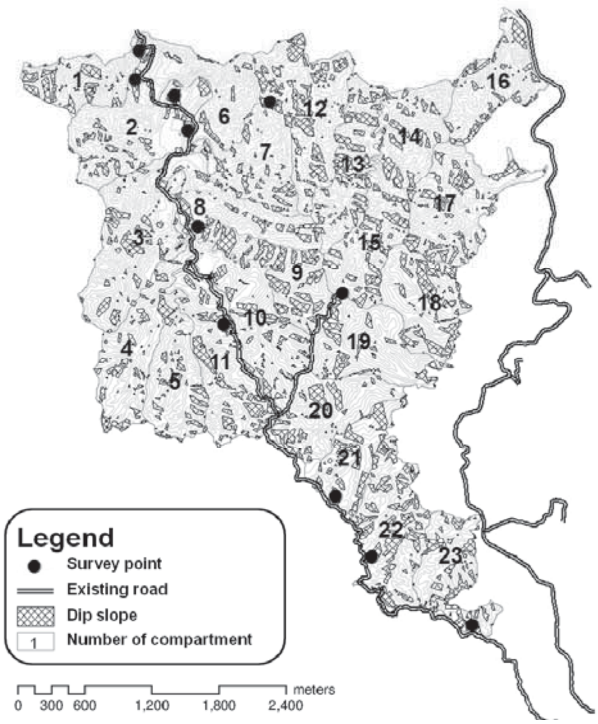


Figure 6. Extracted dip slope area and confirmation survey area

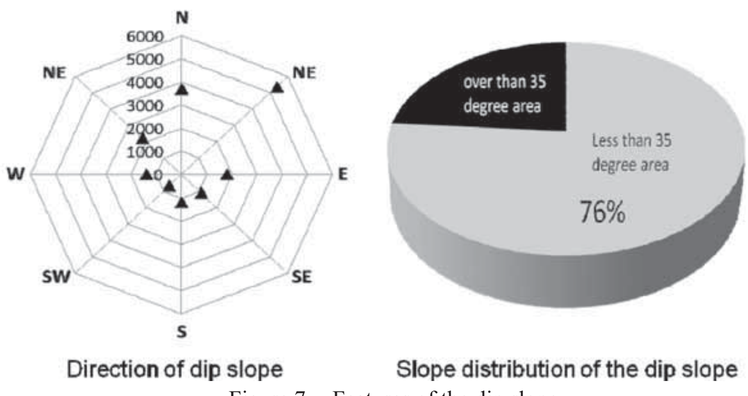


Figure 7. Features of the dip slope

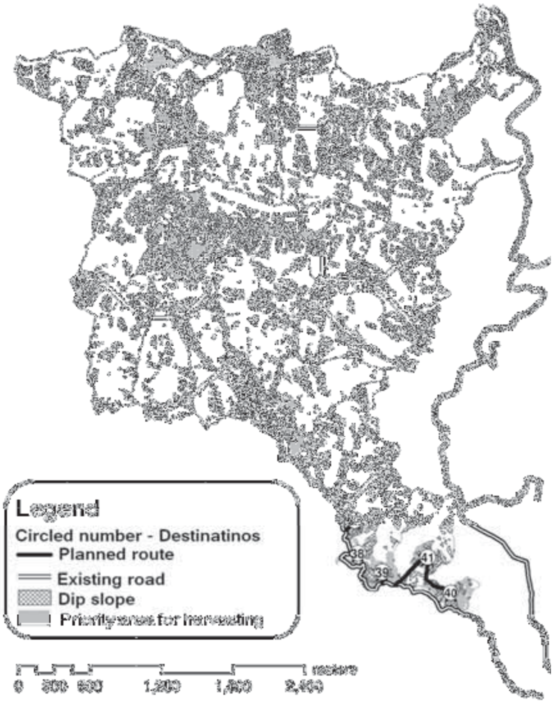


Figure 8. Results of forest road network not considering dip slope

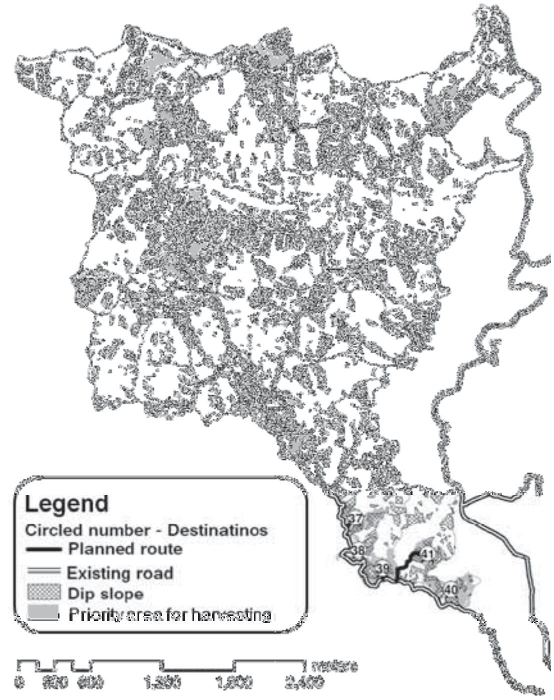


Figure 9. Results of forest road network considering dip slope

were similar to those from the topological network because; (1) these results depended mainly on the location of the plantation area, (2) the same unit cost for road construction was used for dip and opposite slopes, and (3) there were some sections already constructed on dip slopes, which eliminated the clear difference.

Roads were divided into sections between destinations and existing roads. Divided road sections were numbered the same number as destination number farther from existing road. For example, the section No. 3 means the section between destination No. 3 and 4, and similarly, section No. 15 was road between destination No. 15 and existing road. At the investigated site,

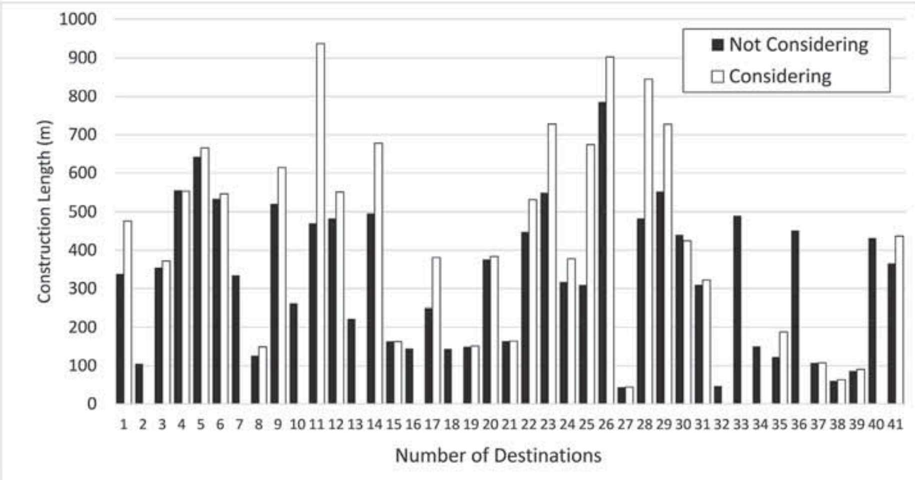


Figure 10. Construction length of each section
Note : Numbers are named route sections

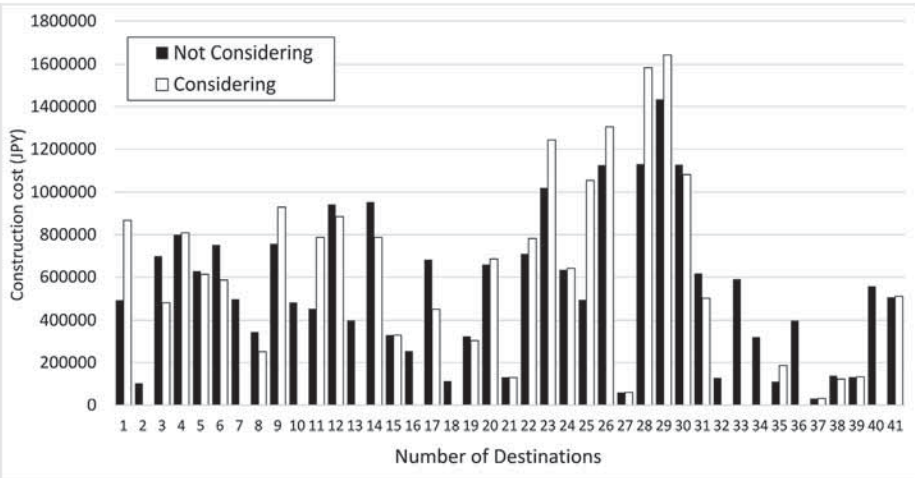


Figure 11. Constructing cost of each section
Note : Numbers are named route sections

there was a slight difference in road section between CD and ND as mentioned above. Construction length and cost from each section can be shown in Figures 10 and 11 together with CD and ND. Since destinations No. 2, 10, 13, 16, 18, 32-34, 36 and 40 were in the dip slope area, they were not used for road network planning at CD.

In Figure 10, detours caused by consideration of the dip slope increased the length of road, for example, sections No. 25, 28, and some other sections. However, the constructing cost was not affected by considering a dip slope, because the road detouring the dip slope might pass a mild slope area, and the construction cost would not be increased. For example, in sections No. 3, 5, 6, 8, 12, 14, 17, 31, 35, and 38, the cost was decreased after considering the dip slope.

The locations in Figure 9 successfully avoided dip slopes, e.g. sections No. 25 or 28. However the difference in construction unit cost between the dip slope and opposite slope was not clear due to lack of precise information, and the results would be improved if more precise data for road construction and maintenance cost on the dip slope and opposite slope could be obtained. However, when the road construction cost on the dip slope was assumed to be twice that in formula (2), the results of road network was the same as in Figure 11 because the increase of cost in the dip slope areas was avoided by making a detouring route.

4. Conclusion

We developed a new method for planning a rational forest road network by determining the dip slope areas in advance automatically to build a stable forest road that would not collapse after construction and be cost-efficient in the long-term. The method was designed to obtain a forest road network with the minimum cost taking into consideration the zones with a high risk of collapsing after construction.

The study verified that the extracted dip slope was actually a dip slope, and the method proposed in this study could be applied as basic data for planning of forest roads. One network which took into consideration the dip slope, and other method which did not, were compared and reviewed to verify the effectiveness of the proposed method through the simulation.

Actually, the UTCBF once failed in construction of a forest road on a dip slope and caused collapse of the cut slope in the marked area in Figure 6. The method to distinguish a dip slope showed in this study will be available for planning a stout forest road network with less maintenance. Repeated comparison of route selections and reviewing the plan with a rough estimated construction cost as in Figures 10 and 11 using GIS can also lead to cost reduction of road construction.

Although the volcanic terrain of a granite area appearing among accretionary wedges has no distinct inclined stratum and the geological structure, the analyzed area was more complicated than other areas such as Shimanto metamorphic belt. The distinguishing dip slope method presented in this study could be a useful tool. Finally, before constructing a forest road, reconnaissance is indispensable, and the prediction of dip slope area in advance will help save time and man power.

However, it must be noted that the routes are roughly located because they must have windings to mitigate longitudinal slope of roads, and the actual road length will be longer, which is the limitation of applying the Dijkstra method in this study and more precise investigation will be required when making roads based on the results. Nevertheless, the results will be useful for efficient planning. Further research on the dip slope estimation method through more precise field investigation and application to more cases will improve the reliability and effectiveness of the proposed method.

5. Acknowledgements

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Summary

In forest road network planning, road sections on dip slopes are difficult to fill and the collapse of the cutting slope can raise maintenance costs. It is important to recognize dip slopes in advance in order to build a more stable and economical road network that can be used in the long term. By applying the theory of distinguishing the dip slope in advance using the combination of slope and the apparent dip (relative dip) of stratum, we tried to avoid dip slopes on GIS with DEM and geological maps. Areas larger than 1ha with a gentle slope under 35 degrees were chosen, and a forest road network planning system which connected such areas with the shortest pass, using the Dijktra method, avoiding dip slopes was constructed. The possibility of predicting dip slopes in advance from DEM and geological maps was recognized and it became possible to save much manpower in reconnaissance. The construction cost and length of each section were also estimated simultaneously by using GIS. These results should be useful for deciding the construction sequence and avoiding unnecessary routes according to the condition of the forest resources.

Keywords : forest road network planning, GIS, dip slope, opposite slope

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流れ盤斜面の判別と回避を組み込んだ GIS による森林路網計画手法の開発

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要　旨

森林路網計画において，流れ盤の区間は盛土がしにくく，切土は崩落の頻発等により維持管理費がかさむので，流れ盤を事前に判別することは丈夫な路網を配置する上で有用であり，長期的には安定して経済的な路網配置になる。斜面の傾斜と地層のみかけの傾斜（相対傾斜）の組み合わせから流れ盤を判別する理論を用いて，DEM と地質図により GIS 上で流れ盤を事前に判別することを試み，人工林 1ha 以上と傾斜 35 度以下の両方を満たす林分を，流れ盤を回避しながらダイクストラ法を用いて最短経路で結ぶ路網配置計画の手法を作成した。DEM と地質図による流れ盤の事前予測の可能性を確かめることができ，今後現地踏査の大幅な省力化と，GIS を用いることにより計画路線の距離と開設費用を見積もることができ，さらには森林の資源状態から開設順序，開設不要区間の決定を行うことが可能となる。

キーワード：森林路網計画，GIS，流れ盤，受け盤