Calculation of Earthwork Volume Using Digital Elevation Model in Strip Road Construction: Influence of Terrain Complexity on Volume Error

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Abstract:
The aim of this study is to analyse the relationship between the earthwork volume error obtained by digital elevation model (DEM) calculations and the terrain complexity. The error is derived from the difference between the value obtained using the DEM and the survey value. In this paper, terrain complexity is defined as the dispersion of aspects. This analysis shows that the volume error obtained using the DEM is correlated with terrain complexity, regardless of the volume type, i.e. cutting, banking, or the sum of them. When the correlation between volume error and terrain complexity is analysed, the coefficient of determination of cutting volumes is lower than that of other kinds of volume. This could be because the degree of cut slope is fixed at 90°, implying that the actual dispersion of slope is not reflected in the volume calculation.

Keywords: high-resolution digital elevation model, hillside slope, dispersion of aspect, survey, GPS

1 Introduction

A strip road is different from a forest road and is constructed without drawing any drafts or adhering to standards. Hence, if a poor route is selected, the earthwork volume may be very large or the slope may be too high for the machine arm to perform productive work. Hence, good route selection is essential not only for minimizing construction cost and for averting disasters but also for logging operation efficiency.

Proper route planning requires considerable knowledge and experience, but the use of a digital elevation model (DEM) makes appropriate route selection easier (Suzuki *et al.*, 2008), especially for beginners. Although there are several important and effective uses of the DEM in route planning, one of the most effective uses is to calculate the earthwork volume of alternative routes for comparison. Using this advanced technique, we can search for better solutions through calculating the earthwork volume for different routes. However, it has not previously been determined by how much the volume error rises when using these DEMs or which factors are the sources of this error. Large volume errors could render comparison of volumes meaningless. These errors must therefore be determined, in order to make meaningful volume comparisons for route selection possible.

The accuracy of the volume is dependent on the accuracy of the DEM, as a DEM represents only a small fraction of the total surface information, especially for highly complex terrain. It appears that the DEM accuracy decreases with terrain complexity and the volume error also increases with terrain complexity. Hence, the aim of this study is to analyse the relationship between the earthwork volume error and the terrain complexity.

2 Analysis Method

2.1 Study area

The study areas are shown in Figure 1 and outlined in Table 1. The objective working compartments around the strip road are not set in some areas. In these cases, road extension is shown instead of road density in Table 1 and the underlined values are from the area 150 m from the roads, determined by the buffering function of a geographic information system (GIS).

These strip roads were arranged for forest thinning, and the working system mostly involves felling using chainsaws, skidding using winches, or bunching using grapples, and forwarding using hauling crawlers or dump trucks. These roads are mostly constructed by using excavators and partly by using bulldozers.

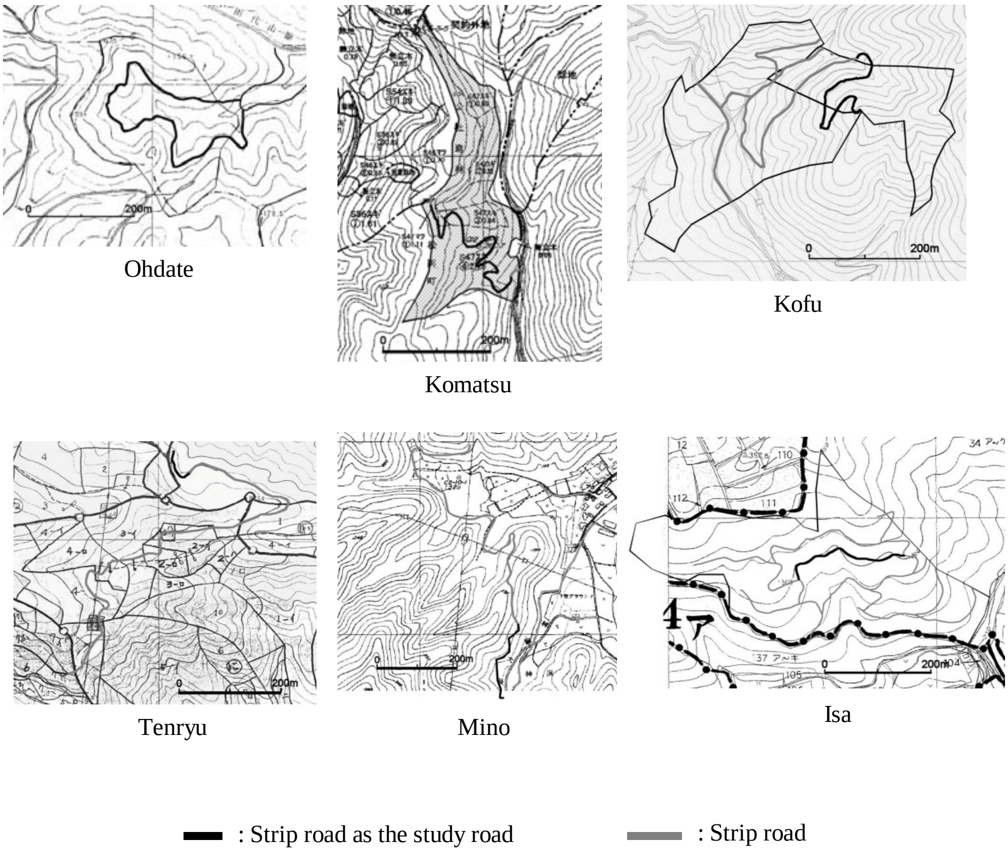

Figure 1: Maps of study areas

Table 1: Outline of the study areas *The underlined values are from the area 150 m from the roads and the values of average slope and dispersion of aspects are obtained from these areas.

	Area (ha)	Road density (m/ha) [Road extension (m)]	Average slope (°)	Dispersion of aspects (°)
Ohdate	6.7	104	15.0	22.7
Komatsu	5.5	98	26.1	14.7
Kofu	11.5	130	26.3	13.3
Tenryu	<u>31.6</u>	[1,040]	22.2	16.0
Mino	<u>34.4</u>	[1,163]	23.8	19.5
Isa	12.0	174	16.6	9.8

2.2 Calculation of earthwork volume

In each area, the general road sections were chosen as the study roads (Figure 1). For getting the survey values, the cross sections were surveyed using poles and a clinometer. At the same time, the routes were measured using a differential global positioning system (DGPS) or a stand-alone GPS. The routes were then overlapped on the GIS map, which also included a DEM layer. This is a 10 m DEM produced by the Geospatial Information Authority of Japan. This is the highest-resolution DEM that covers all of Japan and that users can download freely. The earthwork volumes were calculated using the average end-area method, which uses the following formula:

$$V = \sum_{i=1}^{n-1} \frac{(A_i + A_{i+1})}{2} \cdot {}_iL_{i+1} \quad (1)$$

where V (m^3) is the earthwork volume, A_i (m^2) is the area of cross section i, ${}_iL_{i+1}$ (m) is the interval between cross section i and i+1, and n is the number of sections.

Computer software that operates on the GIS platform was developed for volume calculation. In this program, the triangulated irregular network (TIN) generated from the DEM and the cross sections are drawn and used for volume calculation. The planner can draw the proposed route using the mouse device on the screen and can apply the gauge parameters (Figure 2). In this study, the GPS values of the existing routes are used for volume calculations, instead of freely drawing the proposed route.

In a previous investigation (Umeda *et al.*, 2007), it was found that generally, the cut slope gradient in strip roads is approximately 90°. Hence, the degree of the cut slope is fixed at a value of 90°.

2.3 Evaluating volume error

The volume error calculated using the DEM is derived from the difference between the value obtained using the DEM and the true value. It is assumed in this study that the true value is the volume calculated from the cross sections obtained from surveys. The volume errors are evaluated in terms of relative error as follows:

$$RE = \frac{|V_S - V_D|}{V_S} \quad (2)$$

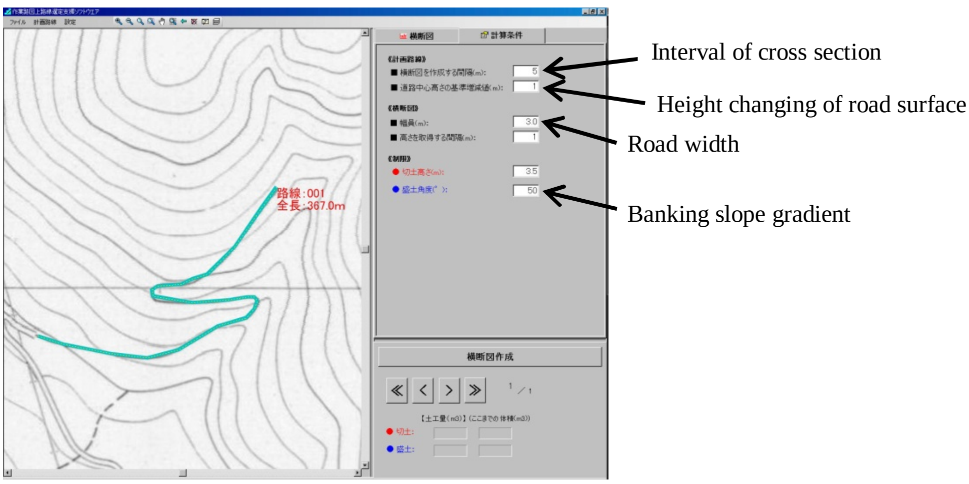

Figure 2: Gauge parameter input window of the software

where *RE* is the relative error, V_S is the earthwork volume obtained from the survey (m^3/m), and V_D is the earthwork volume obtained using the DEM (m^3/m). Because the volume values vary with the road extension, the values are converted to volumes per unit distance.

2.4 Terrain complexity

As noted by Huaxing (2008), terrain complexity is an ambiguous terrain feature. The indices of complexity are classified into three types: statistical, geometrical, and semantic sense. In this paper, the complexity is described by the aspect statistics. The average of the aspect differentials between a mesh and the surrounding meshes is the terrain complexity of a mesh. The terrain complexity in each area is calculated as the average of meshes' value as follows:

$$C_j = \sum_{i=1}^{8} \frac{|As - As_i|}{8} \qquad (0 \le |As - As_i| \le 180) \tag{3}$$

$$C = \sum_{j=1}^{m} \frac{C_j}{m} \tag{4}$$

where C_j is the dispersion of aspects of mesh *j*, *As* is the aspect of a mesh in the objective area, As_i is the aspect of the surrounding mesh, *C* is the terrain complexity in the area determined from dispersion of aspects, and *m* is the number of meshes in the area.

3 Results and Discussion

The gauges obtained for the road structure in this study are listed in Table 2. It is noteworthy that the road width or the slope gradient varies widely among the cross sections as well as the areas. It seems that these gauges change in response to the micro-topography or the local soil type. For instance, the width decreases when the slope is steep because of earthwork volume reduction or deterrence of road collapse. These variances, especially of width, are not common in forest roads, as they have regulations about the gauges of their structures. This means that the accuracy of volume measurements decreases for strip roads because we can rarely apply the actual parameters to each cross section. For these roads, we apply single parameters, typically an average, to simplify the calculation.

Table 2: Gauges obtained for the road structure

	Road length (m)	Sample number of cross section	Width (m)		Banking slope gradient (°)	
			Ave.	S.D.	Ave.	S.D.
Ohdate	860	59	2.6	0.2	51	12.4
Komatsu	525	22	3.5	0.7	50	11.6
Kofu	368	63	3.2	1.3	39	6.2
Tenryu	80	23	3.1	0.4	57	10.7
Mino	233	23	3.7	0.5	40	1.6
Isa	244	29	3.4	0.7	53	9.8

Dispersion of aspects as a measure of terrain complexity is listed in Table 1. The maximum value is 22.7° in Ohdate, and the minimum value is 9.8° in Isa. Terrain complexity is not related to the steepness of slope, when dispersion of aspects is compared with the average slope in Table 1. Generally speaking, this value becomes high in ridges and valleys (Figure 3).

The earthwork volumes found in this survey have a minimum value of 1.0 m^3/m in Ohdate and a maximum value of 6.5 m^3/m in Mino. The relative errors are shown in Figure 4. The errors vary for different areas and different types of volume, with a range from approximately 0.1 to 0.3. The relationships between dispersion of aspects and relative error of volumes are shown in Figure 5. It seems that the relative errors are correlated with the dispersion of aspects for every type of volume. The regression lines and coefficients of determination are also shown in Figure 5. Both x and y are variables in this regression. In this regression analysis, the relative error should be 0 when the dispersion of aspects becomes 0. It is interesting that the slopes of the regression lines are almost same for every type of volume. However, it must be determined whether the slopes are the same by accident or whether this slope value shows a universal relationship between terrain complexity and the earthwork volume error of road construction. It can at least be concluded that the volume error obtained using the DEM is correlated with terrain complexity. The coefficient of determination for the cutting volume is relatively low. This could be because the cut slope is fixed at 90° and the actual dispersion of slope is not reflected in the volume calculation.

There are some causes of the volume error in addition to DEM accuracy. For instance, the gauges differ in size or degree in each cross section, or the location of the study road has an error arising from GPS accuracy. In this study, the DGPS beacon system was used in most areas and a stand-alone positioning system was used in Komatsu. The positioning error of DGPS is a few meters or less under favourable conditions. Hence, this has little influence on the volume error when using a 10 m DEM.

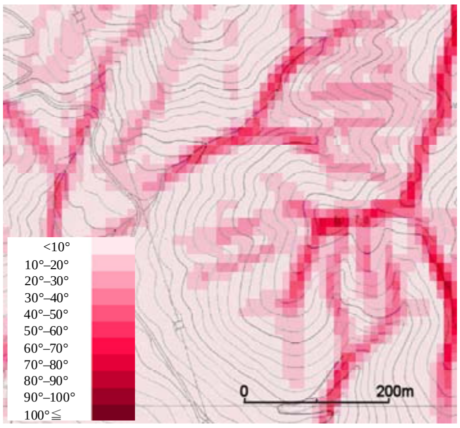

Figure 3: Dispersion of Aspect in Kofu

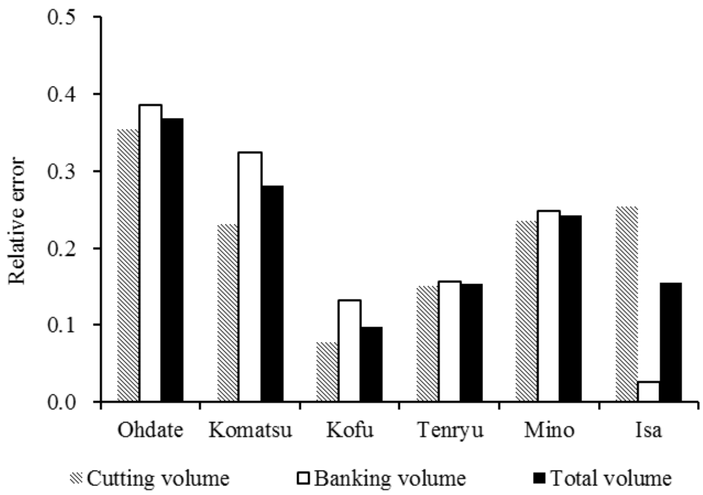

Figure 4: Relative error of cutting, banking, and total volume

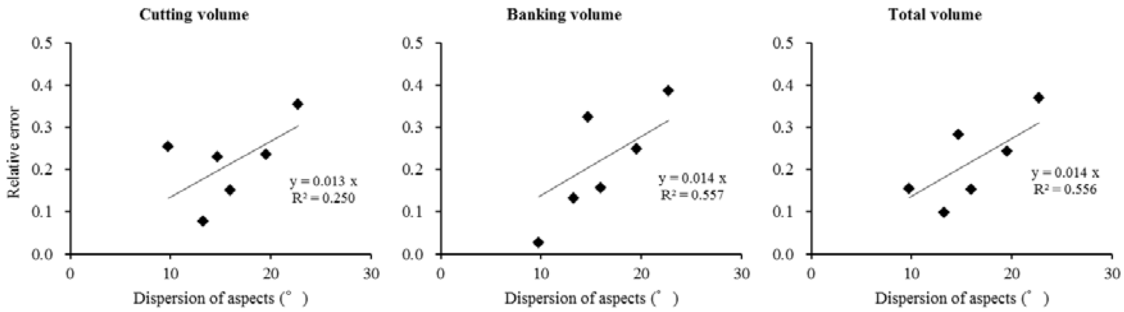

Figure 5: Relationship between dispersion of aspects and relative error of volumes

4 Acknowledgements

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