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Procedia - Social and Behavioral Sciences 96 (2013) 1277 – 1285

Procedia
Social and Behavioral Sciences

13th COTA International Conference of Transportation Professionals (CICTP 2013)

Accuracy Comparison of Roadway Earthwork Computation between 3D and 2D Methods

Jian-chuan Cheng[a,b,]* , Long-jian Jiang[a,b]

[a]School of Transportation, Southeast University, Nanjing 210096, China
[b]Jiangsu Provincial University-Enterprise Base for Graduate Education on Roadway Safety Design and Evaluation, Nanjing 210005, China

Abstract

This study aims to calculate the earthwork volume in 3D method that has been seldom used before in roadway engineering, and to reconfirm the feasibility of average-end-area method for earthwork volume that is widely used in literature. After reviewing the related studies and comparing various CAD packages, the analysis of accuracy difference between 3D method and average-end-area method is conducted. It shows that in average-end-area method the critical value of interval distance between two consecutive cross sections is 30m. It also shows that the Change Rate of Cut-Fill (CRCF) value, an index firstly proposed to represent the cut-fill variance frequency associated with roadway terrain, alignment and profile design, has no significant impacts on the accuracy of 2D result. It is concluded that the 3D method could be easily used in practice with the CAD software. Meanwhile, average-end-area method with less than the critical interval distance between two consecutive cross sections can guarantee the earthwork calculation accuracy.

Keywords: earthwork volume; highway design; 3D method ; average-end-area method

1. Introduction

Reliable and accurate earthwork volume calculation is one of the most important components in roadway engineering that can influence the choosing of roadway alignment, the cost and construction.

As the appearance and widely application of Digital Terrain Model (DTM), roadway design has stepped into 3D era and accordingly 3D method for earthwork volume calculation is also developed. But the concept of adopting average-end-area method (hereinafter also as 2D method) is deep-rooted in roadway design. According to an investigation in US, 87% and 91% designers use average-end-area for design estimates and final quantities

* Corresponding author. Tel.:+86-025-8379-0385; fax: +86-025-8379-5184.
E-mail address: jccheng@seu.edu.cn

doi:10.1016/j.sbspro.2013.08.145

respectively, and 97% of the respondents recognize average-end-area in their policies, standards, and procedural documents. All these data show 2D method still enjoys popular support (Hintz & Vonderohe [1], 2011). Obviously the result of average-end-area method is just an approximate value, and theoretically speaking, result by calculating the volume between existing ground and design surface is the precise value of earthwork-which is also usually called surface-to-surface method that based on DTM technology. From this point of view, DTM has its technical advantage in earthwork volume calculation.

Civil 3D software package, developed by Autodesk Corporation in this context, is a Building Information Modeling (BIM) solution for civil engineering that can be used in transportation, land development and water conservancy project, supporting 3D volume calculation based on DTM. This study chooses Civil 3D package as the tool to compute earthwork volume in 3D method.

This paper verifies the feasibility of calculating the earthwork volume in 3D method by Civil 3D software based on DTM and compares the accuracy difference between 2D and 3D methods for the reference of practical engineering. Moreover, the study also gives an explanation why inaccurate 2D method actually prevails in engineering and a critical interval distance to guarantee accuracy in practical use.

2. Literature Review

The earthwork volume is one of the most important objectives in horizontal and vertical alignment optimization, so most researches firstly focused on the cut-fill balancing to minimize the cost. Stark and Nicholls (1972) started to employ linear programming into earthwork optimization and this method was developed by Mayer and Stark (1981) and Nandgaonkar (1981). Easa (1988) [2] integrated the selection of roadway grades and the minimizing of earthwork into one problem by enumerating all technically feasible grades and solving the linear programming problem. But Easa's method couldn't guarantee the global optimality, so Moreb (1996) [3] proposed a model that succeeded not only in reducing the time problem but also arriving at global optimality based on Easa's theory. Goktepe and Lav (2003) [4] then developed a method called "weighted ground elevation" that considered the material properties in grade line selection to balance the cut and fill volume. All this researches were conducted by average-end-method.

When some researchers realized the imprecision and limitations of 2D method in volume calculation (Easa, 1989 [5] & 1992 [6]), they started to develop some improvements in average-end-method. The prismoidal formula which can enhance the accuracy is the most familiar improvement to us. Anderson, Hikhail and Woolnough [7] (1985) presented a Pappus-based model to compute the volume in horizontal curved area. Easa (1992) [8] developed a mathematical model that calculates earthwork volumes based on triple integration in horizontal curve, but it was applicable when the longitudinal ground profile linearly varied between the stations and the ground cross slope between the stations was linear and constant. So Easa (2003) [9] estimated earthwork volumes of curved roadways in Monte Carlo simulation method but this model still wasn't extended to the case of combined roadway alignments (where horizontal and vertical curves overlap). Kim and Schonfeld (2001) [10] introduced two methods using vector and parametric representation for precisely estimating cross sectional areas of excavation or fill to minimize errors in the total earthwork cost calculation.

Aruga, Sessions and Akay (2005) [11] developed a forest road design program based on a high-resolution Digital Elevation Model (DEM) from a light detection and ranging (LIDAR) system. After a designer had located the intersection points on a horizontal plane, the model firstly generated the horizontal alignment and the ground profile, and then it could precisely generate cross-sections and accurately calculate earthwork volumes using a high-resolution DEM. A shortage of this model was that it couldn't properly optimize horizontal and vertical alignments simultaneously. Li and Han [12] (2007) used DTM to calculate cross section area, but still completed volume computation by 2D rule. These programs had begun to bring DTM into roadway design and volume calculation, but actually it wasn't the completely 3D concept because they still use average-end-area or prismoidal method to compute earthwork volume finally.

Du and Teng (2007) [13] used 3D laser scanning and GPS technology to compute volume of landslide earthwork. They employed these two advanced technology to create the contour after landslide. The original contour of this area could be obtained from the government of the Forestry Bureau. The volume of collapse was estimated by the difference between before and after landslide of terrain contours by the contour method with the Simpson's rule. We consider this research as the transition form from 2D method to 3D method because it has the 3D concept but still solve the problem with 2D formula and procedure.

Bao (2011) [14] applied DTM on the earthwork calculation of land consolidation where the MapGIS DTM analysis function was utilized to transform the elevation points into Triangulated Irregular Network (TIN) and fixed the layout elevation by iterative calculation aimed at the balance between cut and fill. This application of 3D method could also be used in roadway design and volume calculation.

The latest report of roadway earthwork volume calculation by 3D method was conducted by Kerry, Dianne and James [15] (2012). The researchers employed three-dimensional laser scanning to create a surface of the original terrain based on the finite element method. Then this surface was converted to TIN file and earthwork quantities were computed by comparing the TIN of original terrain to that of the finished project. This methodology had already shown the 3D concept and used 3D procedure, but it was only applicable for the computation of the final quantities of roadway. As to the design estimation, another methodology should be developed. Still, the new 3D method was constrained by the problems such as data size, scanning accuracy and data processing.

As reviewed above, 2D methods such as average-end-method, prismoidal formula and other models improved based on them, are not accurate in theory but practically used in engineering. The real and accurate volume could be got by DTM method, especially with the help of updated CAD software, GIS, GPS and laser scanning technology (Uddin [16], 2008). More and more researchers start to transfer their focus and interest from 2D method to 3D method (Bhatla, Choe, Fierro & Leite [17], 2012). However, 3D method is currently only applied in the area of landslide volume computation and land consolidation. The objective of next phase is to bring 3D method based on DTM into roadway earthwork calculation and give an accuracy comparison between 3D method and prevailing 2D method.

3. Method and Conditions for Test Cases

DTM usually means joining the finite mass points together forming a series of surface or plane to approach the original terrain, so its mathematical definition is the set of plane M formed by the mass points or interpolated points P_j in area D in a specific rule ζ (i-the number of mass points; j-the number of plane) (Tang, Liu & Lv [18], 2005):

$$\mathrm{DTM} = \left\{ \mathrm{M}_i = \zeta\left(\mathrm{P}_j\right) \mid \mathrm{P}_j(\mathrm{x}_j, \mathrm{y}_j, \mathrm{H}_j) \in \mathrm{D}, \mathrm{j}=1,2,\cdots,\mathrm{n}; \mathrm{i}=1,2,\cdots,\mathrm{m} \right\} \tag{1}$$

When the rule ζ is triangulation, it produces the Triangulated Irregular Network (TIN), whereas the rule is grid it produces Grid Network (GN). Taylor, Kudowor and Fairbaim (2001) [19] proved TIN to be a more solid and better organization method.

The original terrain surface and roadway design surface can be easily represented in TINs. Through the operations of projection and re-triangulation between these two TINs we can get the triangle pairs as shown in Fig.1 (in the situation of one triangle pair, plane ABC and $A'B'C'$ stand for original or design surface respectively) (Cheng [20], 2005; Zhou & Cheng [21], 2006). Next step is to compute the volume of these triangular prisms-when the original surface is up and design surface is down, it’s excavation and contrariwise it’s fill-and sum all these volumes to obtain the final cut or fill volume.

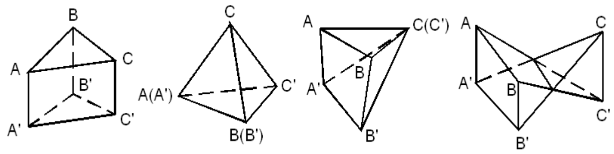

Fig. 1. The cut and fill relations between two TINs

In order to analyze the accuracy difference between 2D method and 3D method, we have following cases.

The test data of plain area is an electronic geographic map with the area of 50,000 square meters and 68740 elevation points, flat, minimum elevation 36.19m, maximum elevation 60m, and average elevation 47.047m. The test data of mountainous area is an electronic geographic map with the area of 2 million square meters in Tibet and 211043 elevation points, hilly, minimum elevation 4110.00m, maximum elevation 5175.001m, and average elevation 4437.492m. All the test roadways are single carriage way, 2km long, 2×3.75m wide, without central median.

Under the different conditions of cut and fill in plain and mountainous area, we design a series of intervals by the step length of 10m:10m,20m,30m,40m,50m,60m. In DTM method the volume result should have nothing to do with the interval value because it's computed by surface-to-surface. However, this study still calculates the 3D volume between two successive cross sections and sums them to get the final volume to compare in detail with the 2D method. According to DTM theory this value of earthwork volume can be recognized as the "real" value.

With the purpose of considering the influence of different longitudinal design line on the earthwork computation result, this study comes up with the index of CRCF-Change Rate of Cut-Fill, namely the number of intersection points between vertical alignment and original ground line in one kilometer-to evaluate the different cut-fill condition of the roadway. Smaller value of CRCF indicates that the vertical alignment and ground profile intersects less, so it could be the section of deep digging or high filled subgrade. Larger CRCF value on the contrary indicates the vertical alignment is close to the ground profile but the switch between cut and fill is more frequent.

The tests are conducted on two topographies for many times and under different roadway alignment designs. However, this paper only shows the typical results because of the limited length of article.

4. The Accuracy Comparison Between 3D and 2D Methods

4.1 Mountainous area

Tab.1 shows the errors between two methods when CRCF=2.5 in mountainous area. The detailed errors of other CRCF values are not listed here for reasons of space.

Table 1. Errors of CRCF=2.5 in mountainous area

Station Interval	2D (Average-end-area) Cut (m^3)	2D (Average-end-area) Fill (m^3)	3D (DTM) Cut (m^3)	3D (DTM) Fill (m^3)	Error of Cut	Error of Fill	
10m	232248.79	533925.6	232168.04	533984.44	0.03%	-0.01%	CRCF=2.5
20m	234565.38	533755.97	232168.04	533984.44	1.03%	-0.04%	
30m	234851.84	533055.74	232168.04	533984.44	1.16%	-0.17%	
40m	230769.59	530812.9	232168.04	533984.44	-0.60%	-0.59%	
50m	217166.45	529227.56	232168.04	533984.44	-6.46%	-0.89%	
60m	250463	525517.78	232168.04	533984.44	7.88%	-1.59%	

The line charts of different CRCF values are drawn as following to easily analyze how the error of volume relates with CRCF and interval. In Fig.2, the errors are absolute value.

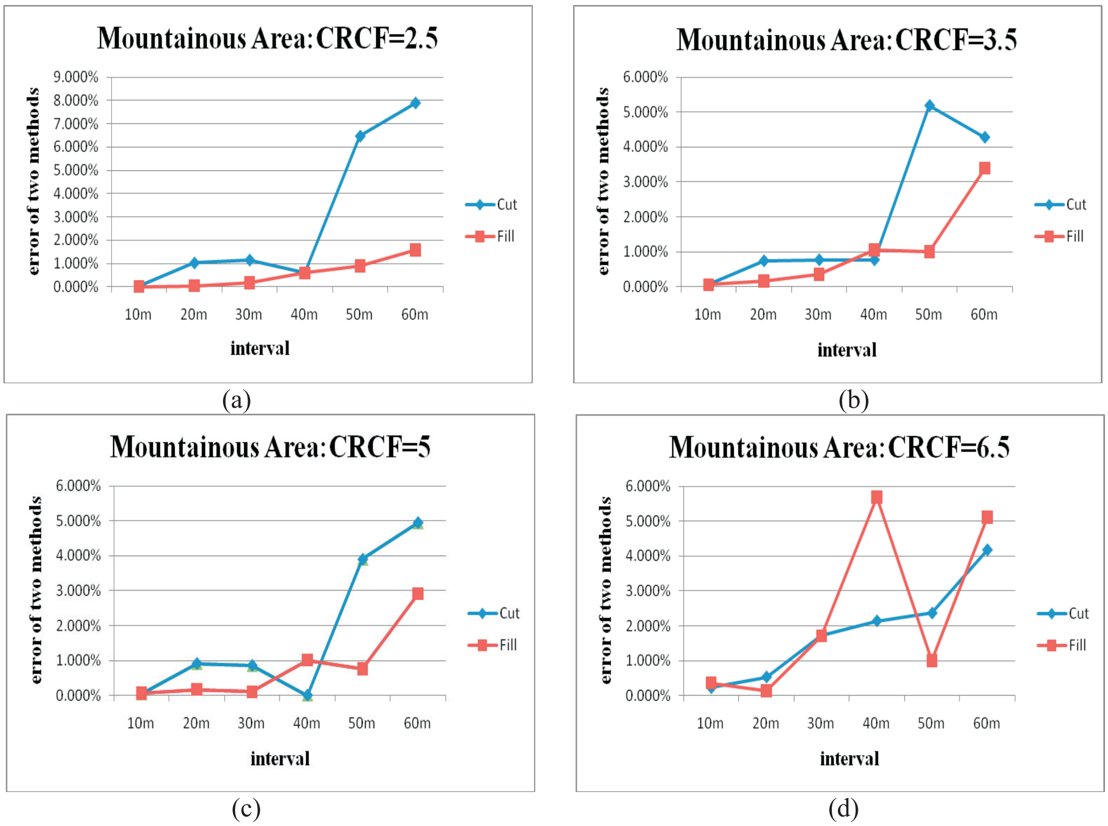

Fig. 2. Errors of two methods with different CRCF values in mountainous area

From Tab.1 we can easily find that with the interval increasing from 10m to 60m, the results of DTM method keep the same value, because DTM method calculates the volume by overlaying two surfaces. So different intervals just section the total volume into different parts and don't affect the sum and accuracy of algorithm.

Fig.2 indicates that when the interval increases from 10m to 30m, the error between average-end-area method and DTM method keeps in a low level-under 2%. However the error increases rapidly and fluctuates if the interval increases up to 30m. This phenomenon shows that the 2D method can't get a reliable and stable result when the interval is up to 30m. We define the range from 0 to 30m as the valid zone and range up to 30m as the invalid zone. Comparing the charts of different CRCF values, it can be concluded that in valid zone CRCF value has no obvious effects on the errors of two methods and the errors with different CRCF values are controlled below 1% on the whole, no more than 2% in maximum.

The smaller the interval is the more accurate results of average-end-area method are. It can be thought that the ground varies in linear way when the interval is small enough. Inversely with the increment of interval the ground may not vary in linear way so the accuracy of 2D method will gradually descend as shown in the zone from 0 to 30m in the figure. When the interval increases to a critical value, two consecutive cross sections will lose the control to the ground variation between them, which means the ground may has an abrupt change but this exception doesn't reflect on the start and end cross sections influencing the accuracy of average-end-area method. From the data and analysis above, it can be inferred that this critical value is about 30m and the volume will be unexpected when the interval exceed this value.

Compared with the influence of interval on the result, CRCF value seems to have no significant effect on the accuracy. According to the formula of average-end-area, two factors-cross section areas and interval-have effects on the result. As long as the interval is less than critical value, 2D method is already exact enough to contain and depict terrain changes. No matter how the vertical alignment is close to or devious to the ground profile it doesn't influence the calculation of cross section area-the other factor that may impact on the accuracy. When it comes to the invalid zone, CRCF is also meaningless to results. In Fig.4 the errors of different CRCF distribute randomly because the interval which plays a more significant role in volume computation has already lost the control to terrain change.

4.2 Plain Area

Tab.2 shows the errors between two methods when CRCF=3 in plain area. The detailed errors of other CRCF values are not listed here for reasons of space.

Table 2. Errors of CRCF=3 in plain area

Station Interval	Average-end-area		DTM		Error of Cut	Error of Fill	
	Cut（m^3）	Fill（m^3）	Cut（m^3）	Fill（m^3）			
10m	26523.6	122744.57	26530.15	122667.7	-0.02%	0.06%	CRCF=3
20m	26577.41	122946.56	26530.15	122667.7	0.18%	0.23%	
30m	26895.46	123208.41	26530.15	122667.7	1.38%	0.44%	
40m	26520.77	123086.66	26530.15	122667.7	-0.04%	0.34%	
50m	27552.69	122572.7	26530.15	122667.7	3.85%	-0.08%	
60m	26467.89	126466.77	26530.15	122667.7	-0.23%	3.10%	

The line charts of different CRCF values are drawn as following and in Fig.3 the errors are absolute value.

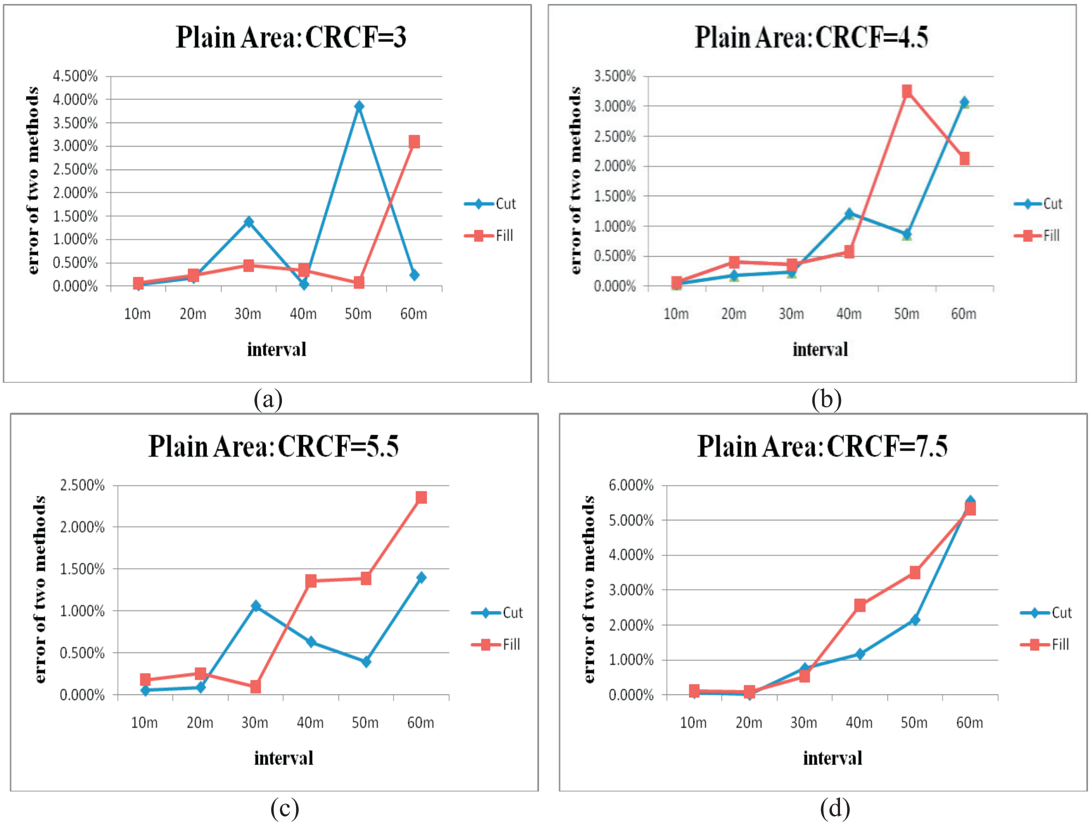

Fig.3. Errors of two methods with different CRCF values in plain area

The situation of plain area is similar to that in mountainous area: the critical value of interval lies at about 30m; however, in the valid zone (0 to 30m) the errors of 2D method are generally controlled beneath 0.5% which is better than that in mountainous area with 1 % and the maximum error is 1.38%, also lower than that of 1.72% in mountainous area. This comparison shows that in general the average-end-area is more accurate in plain area than in mountainous area. The CRCF values show no significant influence on the accuracy. When CRCF values vary from 3.0 to 7.5 in valid zone the errors are mostly kept under 1%, and 1.5% at most.

4.3 Summary

From the experiments with different CRCF values in two topographies, we can infer that the average-end-area method has its limitations: different accuracies for different terrains, affected by many random factors and hard to decide the reasonable interval. This study shows the critical value of interval is 30m and the CRCF value, namely the cut-fill condition of roadway, has no significant effects on the final volume.

Contrast to the 2D method, DTM method can avoid all these problems to get the accurate results and it's totally feasible at present by the advanced software package and computer hardware devices. This analysis proves the DTM method to be a better way to calculate earthwork volume than average-end-area method.

5. Conclusions

(1) 3D method of earthwork calculation by the latest software such as Civil 3D could be easily used in practice than ever before. 3D method possesses a higher accuracy than 2D method without consideration the error of the raw terrain data.

(2) Average-end-area method performs a higher accuracy in flat area than in mountainous area. There exists a critical station interval 30m which means 2D method could keep a relevant high accuracy below this value. What's interesting is the CRCF value, an index firstly proposed to represent the cut-fill variance frequency associated with roadway terrain and alignment design, has no significant impacts on the accuracy. In other words 2D method with appropriate interval is suitable for different kinds of design plans. These all reconfirm why 2D method could be used worldwide although it has limitations.

References

[1] Hintz, C., & Vonderohe, A.P. (2011). Comparison of Earthwork Computation Methods. *Proceeding of TRB 2011 Annual Meeting*, Washington DC,.

[2] Easa, S. (1988). Selection of Roadway Grades that Minimize Earthwork Cost Using Linear Programming. *Transportation Research*, 22(2), 121-136.

[3] Moreb, A.A. (1996). Linear Programming Model for Finding Optimal Roadway Grades that Minimize Earthwork Cost. *European Journal of Operational Research*, 93,148-154.

[4] Goktepe, A.B., & Lav, A.H. (2003). Method for Balancing Cut-Fill and Minimizing the Amount of Earthwork in the Geometric Design of Highway. *Journal of Transportation Engineering*, 129(5), 564-571.

[5] Easa, S. (1989). Discussion of "Precision in Cross - Sectional Area Calculations on Earthwork Determination" by Youssuf M. Siyam (October, 1987, Vol. 113, No. 3). *Journal of Surveying Engineering*, 115(3), 356-359.

[6] Easa, S. (1992). Discussion of Cut and Fill Calculations by Modified Average-End-Area Method by James W. Epps and Marion W. Corey (September-October, 1990, Vol. 116, No. 5). *Journal of Transportation Engineering*, 118(4), 600-601.

[7] Anderson, J. M., Hikhail, E. M., & Woolnough, D. F. (1985). *Introduction to surveying*, New York: McGraw-Hill.

[8] Easa, S. (1992). Estimating Earthwork Volumes of Curved Roadways-Mathematical Model. *Journal of Transportation Engineering*, 118(6), 834-849.

[9] Easa, S. (2003). Estimating Earthwork Volumes of Curved Roadways-Simulation Model. *Journal of Surveying Engineering*, 129(1), 19-27.

[10] Kim, E., & Schonfeld, P. (2001). Estimating Highway Earthwork Cross Sections Using Vector and Parametric Representation. *Proceeding of TRB 2001 Annual Meeting*, Washington DC,.

[11] Aruga, K., Sessions, J., & Akay, A.E. (2005). Application of an Airborne Laser Scanner to Forest Road Design with Accurate Earthwork Volumes. *Journal of Forest Research*, 10(2), 113-123.

[12] Li, Z.Q. & Han, F. (2007). Fast Calculation Method for Cubic Metering of Earth and Stone of Road Line Based on GIS. *Journal of Lanzhou University of Technology*, 33(5), 128-131.(In Chinese)

[13] Du, J.C., & Teng, H.C. (2007). 3D Laser Scanning and GPS Technology for Landslide Earthwork Volume Estimation. *Automation in Construction*, 16, 657-663.

[14] Bao, Y. (2011). Applications of the MapGIS-based Digital Topographic Model on Earthwork Calculation on Land Consolidation. *Proceeding of International Conference on Computer Distributed Control and Intelligent Environmental Monitoring*, China.

[15] Kerry, T.S., Dianne, K.S., & James, P.P. (2012). Road Construction Earthwork Volume Calculation Using Three-Dimensional Laser Scanning. *Journal of Surveying Engineering*, 138(2), 96-99.

[16] Uddin, W. (2008). Airborne Laser Terrain Mapping for Expediting Highway Projects-Evaluation of Accuracy and Cost. *Journal of Construction Engineering and Management*, 134(6), 411-420.

[17] Bhatla, A., Choe, S.Y., Fierro, O., & Leite, F. (2012). Evaluation of Accuracy of As-built 3D Modeling from Photos Taken by Handheld Digital Cameras. *Automation in Construction*, 28, 116-127.

[18] Tang, G.A, Liu, X.J., & Lv, G.N. (2005). *Digital Elevation Model and Geoanalysis: Priciples and Methods*. Beijing: Science Press. (In Chinese).

[19] Taylor, G., Kudowor, A.Y.T., & Fairbairn, D. (2001). Empirical Method of Error Analysis in Volume Estimation-Monte Carlo Simulation under Kriging and Triangulation. *Journal of Surveying Engineering*, 127(2), 59-77.

[20] Cheng, J.C. (2005). 3-Dimensional Calculation of Roadway Earthwork Volume. *Journal of Southeast University,* 21(1), 88-91. (In Chinese)

[21] Zhou, C., & Cheng, J.C. (2006). Earthwork Volume Calculation based on Digital Multi-layer Terrain Model. *Proceeding of the 2006 Annual Conference of China Highway & Transportation Society*, China. (In Chinese)