MODELING SLOPE UNCERTAINTY DERIVED FROM DEMS*: A CASE STUDY IN CHINA LOESS PLATEAU AREA

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ABSTRACT:

Slope is one of a crucial terrain variables in spatial analysis and land use planning, especially in China Loess Plateau area where suffer from serious soil erosion disasters. DEM based slope extracting method has been widely accepted and applied in practice. However slope accuracy derived per this method usually does not match with their popularity. A quantitative simulation to slope data uncertainty is important not only theoretically but also necessitous to applications. This paper focuses on how resolution and terrain complexity impact on the accuracy of mean slope extracted from DEMs of different resolutions in Loess Plateau of China. Six typical geomorphology areas are selected as test areas, representing different terrain types from smooth to rough. Their DEMs are produced from digitizing contours of 1:10000 scale topographical maps. Field survey results show that 5m should be the most suitable grid size for representing slope in Loess area. Comparative and math-simulation methodology was employed for data processing and analysis. A linear correlativity between means slope and DEM resolution was found at all test areas, but their regression coefficients related close with the terrain complexity of the test areas. If taking stream channel density to represent terrain, mean slope error could be regressed against DEM resolution (X) and stream channel density (S) at 8 resolution levers and expressed as $(0.0015S^2+0.031S-0.0325)\cdot X-0.0045\ S^2-0.155S+0.1625$, with a R2 value of over 0.98. Practical tests also show an effective result of this model in applications. The new develop methodology applied in this study should be helpful to similar researches in spatial data uncertainty researches.

1. INTRODUCTION

Slope is a key topographic variable impacting the degree of soil erosion and land use types. Mean slope is commonly accepted as the best factor revealing the relief roughness of a given area. At present, digital elevation model based GIS spatial analysis has commonly accepted as a convenient and effective approach in deriving topographic variables. DEMs of different spatial scale were constructed, which builds up a good basis for further terrain analysis. However, there is an obvious accuracy difference in extracting slope gradient from DEMs of different scale and resolution (grid size). Beside of this, the other factors, i.e. the arithmetic for extracting slope and the surface complexity characteristics, all contribute the complexity and the uncertainty of slope derived from DEMs.

The accuracy of slope gradient extracted from DEMs is affected by a variety of factors. These include the quality of source data, the algorithm for calculating gradient, grid size and terrain complexity. E.Hodgson (1995) compared the accuracy and applicability of the deriving algorithms (Ahmadzadeh & Petrou, 2001). Chang (1991), Gao(1997) and Tang(2001) revealed the a variation tendency of slope accuracy along with grid size. A lot recent works are concerning about the propagation of slope error in terrain analysis. Comparatively speaking, less work has been done in investigation quantificationally how resolution and terrain impact the accuracy of mean slope derived, as well as the spatial distribution pattern of the errors, which is of critical significant is both in theory and applications.

This paper focus mainly on the accuracy of mean slope derived in China Loess Plateau area. A comparative and math-simulation methodology was employed in this research to investigate the impact of resolution and terrain roughness to the accuracy of mean slope derived from grid DEMs. Six test areas from different terrain types were taken as test areas in this study. Supported by the experiment results from both field survey and math-simulation, an empirical model of mean slope error was constructed which can effectively revealing the mean slope error impacted from DEM resolution and terrain complexity. This result is significant not only in the theory, but also in the applications of many different fields, especially in building up a standard of spatial data application in the Loess Plateau area, where is a key developing area in west China.

2. RESEARCH BASIS

2.1 Test Area

To represent the terrain types in loess yuan, loess hill, loess liang, loess mao and loess gully hill respectively, six 5km× 5km areas in different relief complexity areas in the Loess Plateau area are selected as test area. Table 1 shows their major topographic characteristics.

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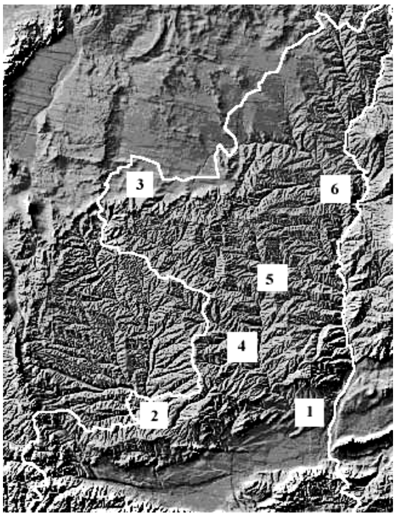
Terrain parameters	Loess Yuan I	Loess Yuan II	Low Hill	Loess Liang	Loess Mao	Gully hill
Mean elevation（m）	852 m	1145 m	1770 m	1549	1161 m	1032 m
Mean slope	6.54°	11.23°	16.47°	23.83°	28.24°	30.16°
Stream density（km/km^2）	1.95	2.48	3.10	4.51	5.05	6.44
Surface roughness	1.0140	1.0704	1.0751	1.1719	1.2001	1.4664
Profile curvature	11.70	14.22	19.43	26.20	31.42	34.92

Table 1. Major topographic variables and the accuracy of original DEM



1 — Loess plain I 2 — Loess plain II
3 — Loess low hill 4 — Loess liang hill
5 — Loess mao hill 6 — Loess gully hill

Figure 1. The distribution of test areas in North Shanxi

2.2 Original Data and Their Accuracy

Original DEM all have a 5m spatial resolution, so as to give six 2000 cells subsets. They are derived by means of digitized contour of 1:10,000 scale topographic maps.

A series of experiments were done to investigate the accuracy of original DEMs. Besides of a careful comparison the difference between original contours and DEM derived ones, more work is done to measure and calculate the elevation difference between the benchmarks available on the topographic map and the corresponding elevation values of the DEMs. Table 2 shows the results.

Test area	RMSE (m)	Standard deviation (m)	Mean (m)
Loess Yuan I	0.41	0.29	0.27
Loess Yuan II	0.46	0.37	0.31
Low Hill	1.03	0.94	0.90
Loess Liang	1.78	1.43	1.35
Loess Mao	2.21	1.89	1.70
Loess Gully hill	1.35	1.23	1.11

Table 2. Accuracy of original DEMs

This experiment takes 1828 random sampling points in field in the 6 test areas and measure their slope gradient and geographical coordinates.

Then, a comparison with slope extracted from DEMs shows that the error could be kept at rather small lever. if the DEM resolution is lower than 5m (see Table 3). Hence, in this study, the slope value from 5m resolution DEM was taken as a criteria to test the slope accuracy from other resolution DEMs.

3. EXPERIMENT RESULT AND DISCUSSION

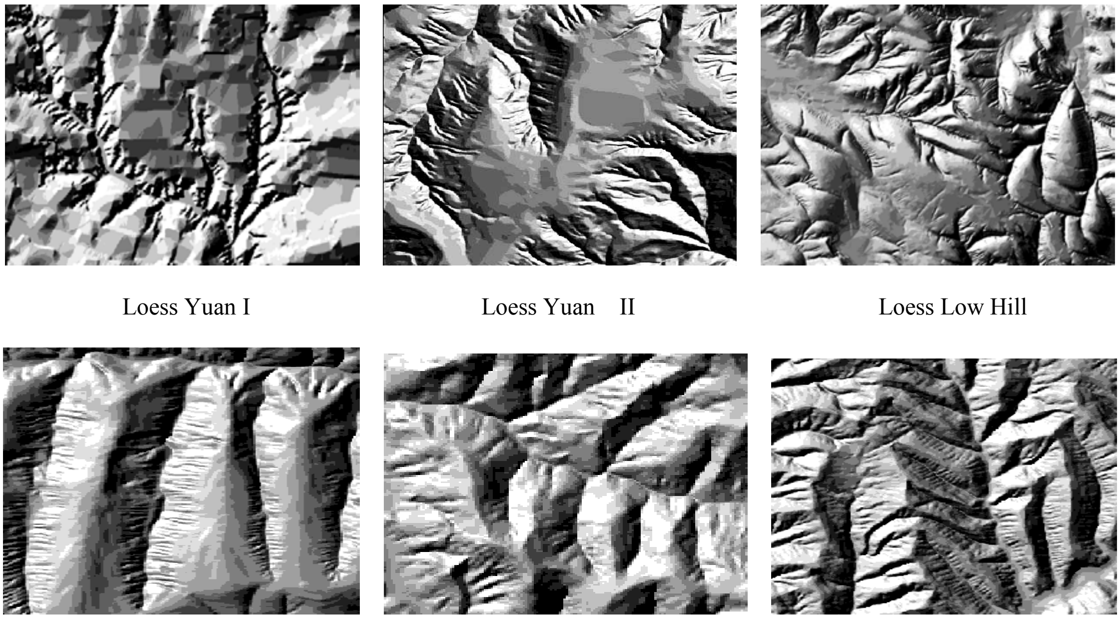
3.1 Resolution, Terrain and Slope Spectrum

Slope composition pattern in an equal-interval classification can be defined as slope spectrum. A comparison of slope spectrum at different terrain test area reveals the impact of resolution and terrain on slope accuracy.

Resolution affects gradient in that slope with an intermediate gradient become predominant, whereas the extremely large gradients lose their members as resolution decrease from 5m to 65m. The slope spectrums at the three terrain types take a different distribution pattern with a five-degree equal-interval gradient classification. Figure 3 shows the slope spectrum takes a almost similar composition pattern at different resolution lever. the loess yuan. However, in loess gully-hill area, although all the slope spectrums take a bell-shaped distribution with gradient, but their peaks move toward lower class, with decrease of resolution, which reveals smooth slope get predominant as well as lost extreme large gradient.

3.2 Modeling Mean Slope Error

Arc/View spatial analysis function was employed as a basic platform for deriving slope gradient. SPSS was used for statistic and data processing. Mean slope from different resolution lever could be extracted. The values of mean slope are plotted against resolution to investigate their relation in Figure 4. These plot show that a linear decrease with the increase of grid size from 5m to 105m. The finer the DEM resolution, the more accurately the terrain is represented. Such a finding result from a basic fact that the approximation of a continuous terrain with a grid based DEM is more accurate if the grid cell has a smaller size. The finer the resolution, the better the elevation of a cell approaches within the terrain it covers. In addition, a finer resolution means that the DEM cell size is smaller and more elevation is sampled. A larger sample size undoubtedly captures the terrain better.



Loess Yuan I　　Loess Yuan II　　Loess Low Hill

Loess Liang Hill　　Loess Mao Hill　　Loess Gully Hill

Figure 2. Hillshade image of the test areas (part)

Test area	Field sampling points	Resolution (m)				
		1m	2.5m	5m	12.5m	25m
Loess Yuan I	113	0.079	0.084	0.193	0.648	1.973
Loess Yuan II	170	0.197	0.205	0.324	2.793	4.866
Loess Low Hill	249	0.188	0.190	0.319	3.405	5.158
Loess Liang	243	0.264	0.391	0.698	3.802	6.961
Loess mao	456	0.793	0.915	1.003	4.887	7.409
Loess Gully hill	597	0.756	1.373	1.783	6.941	11.001

Table 3. Accuracy of original DEMs

$$\text{Mean slope } Y = \begin{cases} -0.2274X + 30.518 & \text{(loess gully-hill)} \\ -0.1596X + 27.456 & \text{(loess liang)} \\ -0.1375X + 24.515 & \text{(loess mao)} \\ -0.0772X + 16.407 & \text{(loess low hill)} \\ -0.0542X + 11.158 & \text{(loess yuan II)} \\ -0.0327X + 6.5795 & \text{(loess yuan I)} \end{cases} \qquad (1)$$

Figure 4 shows that these error statistics all appear to have a negative linear correlation with DEM resolution. To explore how DEM resolution affects mean slope extracted quantitatively, mathematical simulation are made with a series of regression analyses. Mean slope values from different resolution and terrain test areas are regressed against the resolution respectively. Figure 4 shows that all the mean slope value variation has a perfect linear correlation relationship with the resolution at all terrain areas. All correlation coefficients are over 0.99 and are significant at 0.01 lever.

Figure 4 also reveals a good explanation of how mean slope change with the terrain complexity at a global lever. First of all, the regression lines for the loess gully-hill area lie on the top and that for the loess yuan area lies at the bottom. This result indicate that mean slope is inversely associated with terrain complexity, namely a rough terrain is less accurately represented than a simple terrain at the same resolution lever. In order to be represented at the same accuracy lever, a rough terrain requires a finer resolution than a smooth terrain does. However, in Figure 4, the six values are extremely close at a finer resolution. Their discrepancy grows increasely wider as resolution decrease, even through all of them rise progressively. Therefore, mean slope in a rough terrain is more sensitive to the resolution reduction than those in smooth areas. Secondly, the regression equation listed in Figure 4 show that the terrain complexity is obviously related to the regression coefficients. Rearranging these expressions, we can get a group of regression equations (Equation 1).

Rewriting the above equation, we can get a general equation.:

$$Y = a \cdot X + b \qquad (2)$$

Coefficient *a* and *b* appeared to have a liner correlation with ground surface roughness (Figure 5 and 6). A series of correlation analyses show that stream density can get the best correlation result (correlation coefficient r>0.99 with the significance at 0.01 lever).

Let S denote the stream density, the regression models in the figure can be rewritten as:

$$a=-0.0015S^2-0.031S+0.0325\ (r=0.9999\ ,\ r^2=0.9999,\ p<0.01) \qquad (3)$$

$$b=-0.933S^2+13.186S-15.652\ (r=0.9999,\ r^2=0.9994,\ p<0.01) \qquad (4)$$

substituting (3),(4) to (2), we have:

$$Y=(-0.0015S^2-0.031S+0.0325)X+(-0.933S^2+13.186S-15.652) \qquad (5)$$

where S and X represent stream density and resolution, respectively. If we treat the mean slope Y_5 with the resolution of 5m as true value, the mean slope error E can be derived by calculating the difference between Y_5 and Y. we have then:

$$E = Y_5 - Y = (0.0015\ S^2+0.031\ S - 0.0325\ )\cdot X - 0.0045\ S^2-0.155S+0.1625 \qquad (6)$$

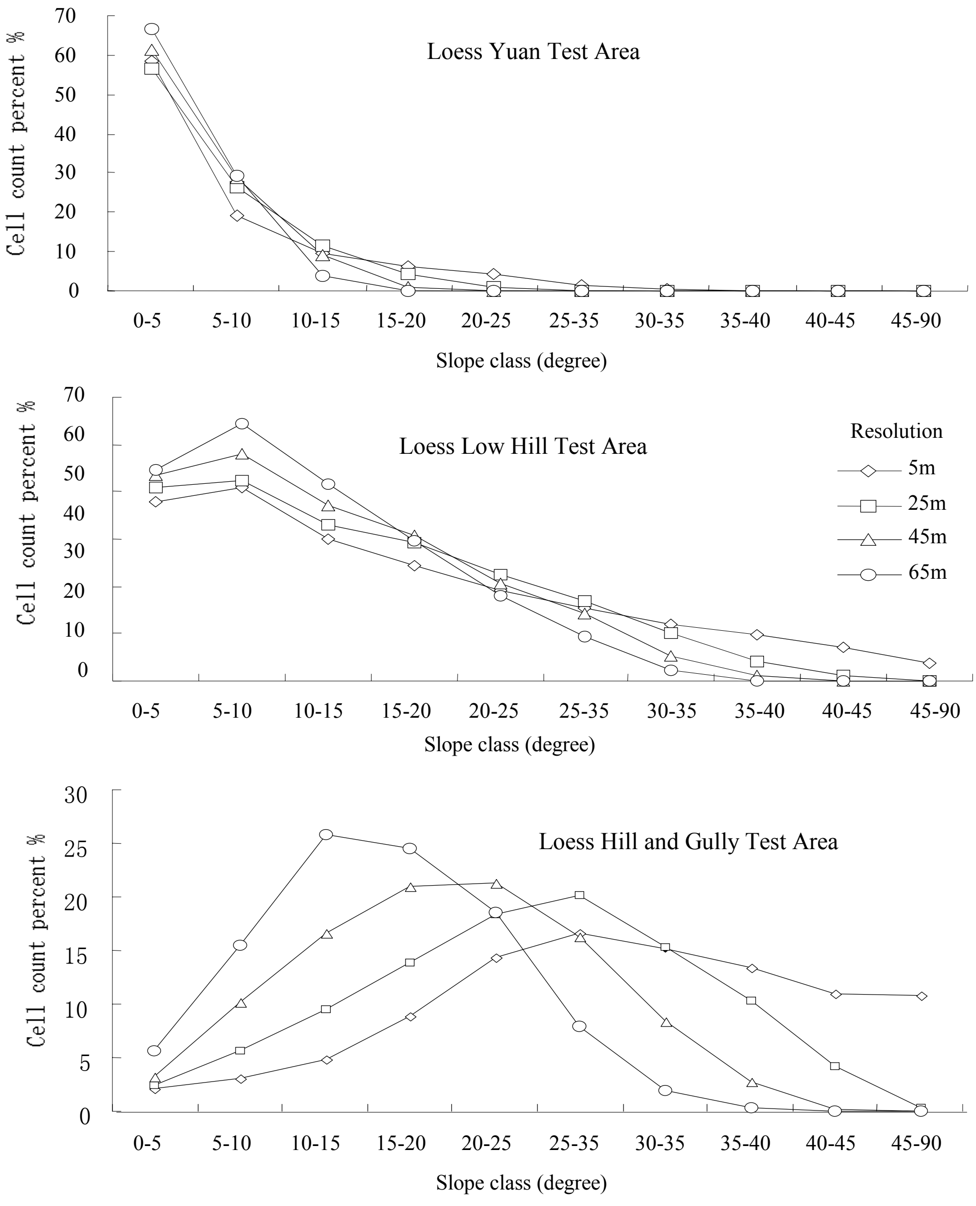


Figure 3. Slope spectrum from different test areas

This mean slope error model should be significant in assessing slope accuracy derived.

Besides of this, this model can also be used to determine the DEM resolution appropriate to the slope accuracy requirement of a particular user.

3.3 The Validity of the Error Model

Regarding the validity of mean slope error model, a basic fact is mean slope data are extracted from rather big area test sites. It is deemed that this model will be invalid if it is applied to some relatively small areas. Hence, an apparent question should be how big a working area should necessarily to guarantee the stable of mean slope derived. To answer this question, an experiment is designed. At least 30 test sites of different size areas are taken from the six original test areas and the values of the mean slope are derived from each of the test areas, respectively. Table 4 shows the statistics results.

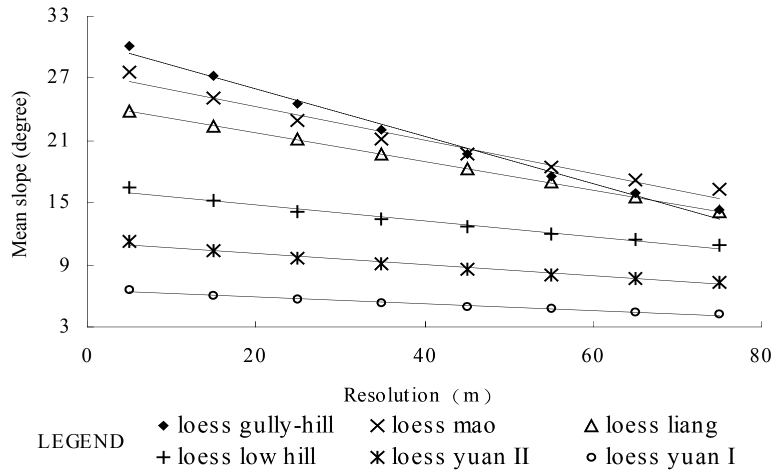


Figure 4. Mean slope regression models (mean slope against resolution)

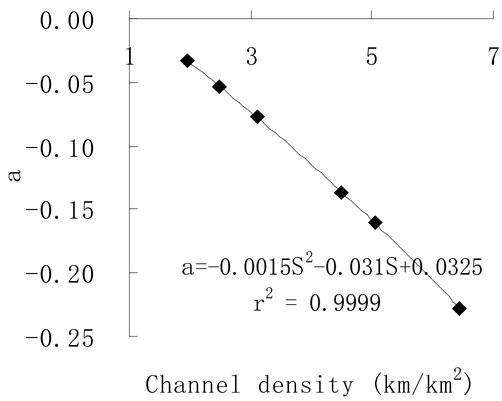


Figure 5. Rregression model of formula coefficient *a* against stream channel networks S

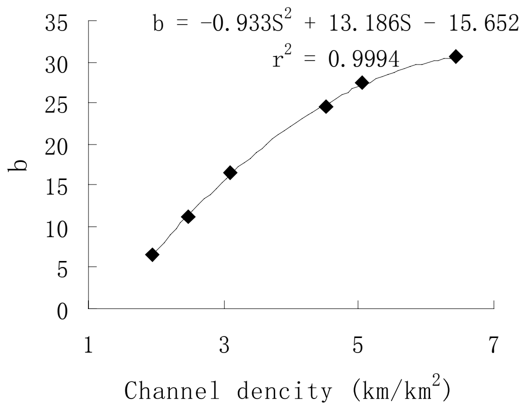


Figure 6. Regression model of formula coefficient *b* against stream channel networks S

	Loess Yuan I	Loess Yuan II	Low Hill	Loess Liang	Loess mao	Gully-hill
Number of test sites	32	32	34	30	33	39
平均坡度稳定的临界面积（km^2）	2.30	1.87	0.63	0.46	0.22	0.16

Table 4. The minimum area for a steady mean slope in the 6 test areas

Test area	Terrain type	Area	The correctness
Xingdiangou watershed	loess gully hill	2.34 km^2	99.2%
Lijiagou watershed	loess liang and mao	5.71km^2	92.2%
Tiegou watershed	loess yuan	13.99km^2	89.7%
Shisanlipu area	Loess hill	46.18 km^2	95.31%
Yanan area	Loess hill and plain	100 km^2	94.75%

Table 5. The correctness of error applied in verifying test area

3.4 Testing the Applicability of the Error Model

To verify the correctness and applicability of the error model, a test experiment was done. Five different terrain complexity tests were taken to verifying the correctness of the error model. Table 5 shows this model can effectively correct mean slope error result in north Shaanxi Loess Plateau area.

4. CONCLUSION

Both field and statistic show 5m is a suitable resolution value to represent slope in the loess plateau area.

There was a statistically significant correlation between mean slope derived from grid based DEM with grid size as well as stream network density.

Mean slope derived decrease linearly with its spatial resolution from 5m to 75m. The accuracy of representing a slope with gridded DEM becomes lower and lower as the resolution decrease. The decrease in accuracy is higher at coarse resolution but minimal at a fine resolution. The accuracy of terrain representation is also inversely correlated with terrain complexity. The slope representation accuracy is more sensitive to resolution reduction for a complexity terrain than a simple terrain. Having consistent ratios to mean slope for all six terrain types, the density of stream channel-works is a better indicator of the representation accuracy than other terrain variables. The relation among resolution X, terrain complexity S and the derived mean slope error E may be expressed as $E = (0.0015S^2 + 0.031S-0.0325)\cdot X-0.0045\ S^2-0.155S + 0.1625$. This model is verified to be of a higher correctness in Northern Shaanxi Loess Plateau. This model can also be used to determine the DEM resolution appropriate to the slope accuracy requirement of a particular user.

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