The Application of Unascertained Measurement Theory in Soil Erosion Severity Evaluation

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ABSTRACT

Uncertained measurement theory and Analytic hierarchy process(AHP) methods were combined and applied to evaluate soil erosion severity. According to influence factors and grading standards of soil erosion severity, ten indicators, such as selected slope angle, rainfall intensity, soil properties, water erosion modulus, thickness of covering soil and permeability (particle size), etc, were used to evaluate soil erosion severity. Uncertained measurement functions of evaluation of soil erosion severity were obtained by using uncertainty measurement theory. AHP was used to calculate weights of the evaluation indexes of soil erosion severity. Credible degree recognition criteria was used to evaluate hazard assessment of debris flow. Finally, the comparative analysis was made with examples. The results showed that uncertained measurement theory is reasonable and reliable. It was the first time that the AHP and uncertained measurement theory was applied to the severity of soil erosion assessment, which provided a new analysis method for the study of the soil and water loss danger division.

KEYWORDS: Uncertained measurement theory; Analytic hierarchy process; Soil erosion; Severity; Evaluation

INTRODUCTION

Soil and water loss is the process of material and energy migration, and it is constantly changing topography(Pimentel et al, 1995 and Luo et al, 2004)[1-2]. Specifically, surface soil layer are eroded under stream action, including direct and indirect effects. Because soil nutrients are carried by runoff, soil and water loss includes runoff loss, soil erosion, and nutrient loss(Bakker et al, 2008, Nyakatawa et al, 2007 and Terranova et al, 2009)[3-5]. Soil erosion not only causes destruction of land resources, serious soil degradation, frequent floods and droughts, environmental degradation and ecological imbalance, but also is a direct threat to the safety of human life and property. The second remote sensing investigation of soil and water loss of China(Liu, 2002)[6] showed that Chinese area of soil and water loss readied 3.56 million square kilometers, including water erosion regions 1.56 million square kilometers and wind erosion regions 1.91 million square kilometers. Moreover, soil erosion of mine slope is often neglected(Li et al, 2015)[7]. Soil and water conservation measures of intensive erosion mine slope and slight erosion mine slope are quite different. Therefore, it is very important to accurately evaluate the severity of slop soil and water loss.

In 1990, Chinese scholar Guangyuan Wang(Wang, 1990)[8] proposed unascertained information and mathematics processing theory. Uncertained information is a new uncertain information, which differs from fuzzy information, random information and gray information. Uncertainty measurement theory is a important achievement of uncertainty mathematics theory, and has been applied to many fields now. Among results of unascertained mathematics, unascertained measure evaluation model is most widely used(Liu et al, 1999, Li et al, 2006 and Cao et al, 2000)[9-11]. Therefore, we used unascertained measure evaluation model for reference, evaluated water and soil loss severity based on uncertained measurement theory and AHP. It can quantitatively evaluate water and soil loss severity, and solve the uncertainty problem of soil erosion severity assessment system. Firstly, constructed unascertained measure function of each index based on unascertained measure theory, and calculated unascertained measure value of each index; then, used AHP to determine weights of evaluation factors of soil erosion severity; finally, used the credible degree rule to judge the grade of soil erosion severity. Follow the steps above, calculated the grades of eight soil erosion areas of Jiaozuo City in China, and the evaluation results were compared with engineering practice. The results showed that uncertained measurement theory is reasonable and reliable; and it is a new method for evaluating soil erosion severity.

UNCCERTAINED MEASUREMENT THEORY

Let x_1, x_2, …, x_n is evaluation objects, namely evaluation objects space $R=\{R_1,R_2,\cdots,R_n\}$. Each evaluation object R_i (i =1,2, …, n) has m individual evaluation index space, namely $X=\{X_1,X_2,\cdots,X_m\}$. Each evaluation object R_i is expressed as m dimensional vector $R_i=\{x_{i1},x_{i2},\cdots,x_{im}\}$, where x_{ij} is measured values of evaluation index X_j of evaluation object R_i. Suppose each term x_{ij} (i =1,2, …, n ; j =1,2, …, m) has p evaluation grades $\{C_1,C_2,\cdots,C_p\}$.

Suppose U is evaluation space, namely $U=\{C_1,C_2,\cdots,C_p\}$. C_k (k =1, 2, …, p) is the k-th evaluation grade. If C_k meets $C_1>C_2>\ldots>C_p$, namely the risk of front evaluation grade is high than latter evaluation grade, $\{C_1,C_2,\cdots,C_p\}$ is a ordered partition class of U [5].

Single index measure

$\mu_{ijk}=\mu(x_{ij}\in C_k)$ represents measured value x_{ij} belongs to the k-th evaluation grade, and meets:

$$0\le\mu(x_{ij}\in C_k)\le 1 \tag{1}$$

$$\mu(x_{ij}\in C_k)=1 \tag{2}$$

$$\mu[x_{ij}\in\bigcup_{l=1}^{k}C_l]=\sum_{l=1}^{k}\mu(x_{ij}\in C_l)\quad(k=1,2,\cdots,p) \tag{3}$$

Formula (2) is called “unity”; formula (3) is called “additivity”. If μ meets formula (1) (2) (3), μ is called unascertained measure(Liu et al, 1999, Liu et al, 1997 and Li et al, 2006)[12-14].

$(u_{ijk})_{m\times p}$ is individual index measure evaluation matrix:

$$(\mu_{ijk})_{m\times p}=\begin{bmatrix}\mu_{i11} & \mu_{i12} & \cdots & \mu_{i1p}\\ \mu_{i21} & \mu_{i22} & \cdots & \mu_{i2p}\\ \vdots & \vdots & \ddots & \vdots\\ \mu_{im1} & \mu_{im2} & \cdots & \mu_{imp}\end{bmatrix} \tag{4}$$

Multi-index comprehensive measure evaluation matrix

$\mu_{ik}=\mu(R_i\in C_k)$ represents the level of evaluation object R_i belongs to the k-th evaluation grade(C_k):

$$\mu_{ik}=\sum_{j=1}^{m} w_j\mu_{ijk}\quad (i=1,2,\cdots,n;k=1,2,\cdots,p) \tag{5}$$

$$0\le \mu_{ik}\le 1 \tag{6}$$

$$\sum_{k=1}^{p}\mu_{ik}=1 \tag{7}$$

Where: w_j is the weight of X_j.

Confidence criterion

In order to calculate risk grade of evaluation objects, introduced confidence criterion. Suppose λ is confidence [13] (≥0.5), and

$$k=\min\left(k:\sum_{l=1}^{k_p}\mu_{il}\ge\lambda,1\le l\le k\right) \tag{8}$$

Therefore, the risk grade of evaluation object R_i is C_{k0}.

Sorting

In addition to the determination of the evaluation grade, and sometimes also sort evaluation object R_i according to importance[5]. If $C_1>C_2>\ldots>C_p$, I_l is score of C_l, and

$$q_{R_i}=\sum_{l=1}^{p}I_l\mu_{il} \tag{9}$$

Where: q_{R_i}- unascertained importance of evaluation object q_{R_i}; $q=\{q_{R_1},q_{R_2},\cdots,q_{R_n}\}$- unascertained importance vector, sorting R_i according to q_{R_i}.

EVALUATION FACTORS OF SOIL EROSION SEVERITY

Selecting eight soil erosion areas of Jiaozuo City in China as study areas[3]. Then, according to hydrogeology condition and environmental factorserosion of areas, selecting evaluation factors.

Mine Slope Shape

Mine slope shape is the dominant influencing factor of soil erosion, including slope angle, slope length, surface morphology and so on. Slope angle is the decisive factor in plant growth and soil erosion severity. The larger the slope angle, the larger the amount of soil erosion. On one hand, the increasing of slope angle is conducive to the downward movement of soil particles; on the other hand, infiltration capacity is inversely proportional to slope angle.

Vegetation

Vegetation is the key factor in preventing soil erosion(Tongway et al, 2001, Boix-Fayos et al, 2006, Gallego et al, 2004 and Garcia-Estringana et al, 2010)[15-18]. Vegetation can conserve water and soil. Soil and plant roots compose complex, increase the shear strength and additional cohesion of the soil, enhance the stability of the soil.

Rainfall

Rainfall is the inducing factor of soil erosion(Delima et al, 2002, Morin et al, 2006 and Nadal-Romero et al, 2008)[19-21], especially slop with higher slope angle, less soil and high content of soil particles. Slope runoff produced by rainfall erode slope, the higher the rainfall intensity, the greater slope runoff and soil erosion severity.

Soil Properties

The effect of soil properties manifests in grain composition of soil. The higher fine particle content, the larger slope runoff. What's more, the physicochemical properties of slop soil affect soil erosion severity.

Based on above analysis, selecting the following 7 indicators as evaluation indexes of soil erosion severity: slope angle(X_1,º), vegetation coverage(X_2,%), rainfall intensity(X_3,mm), soil properties (density)(X_4,g·cm-3), water erosion modulus(X_5,t·km-2·a-1), thickness of covering soil (X_6,mm), permeability (particle size)(X_7,mm). Based on the data concerned, soil erosion severity was divided into five grade: Ⅰ- severe erosion; Ⅱ- strong erosion; Ⅲ- moderate erosion; Ⅳ- mild erosion; V- slight erosion. And evaluation set was {C1,C2,C3,C4,C4}. Grading standard was presented in the Table 1.

Table 1: Classification criterion of evaluation indexes of soil erosion severity

Severity	Evaluation indexes						
	slope angle (X_1, °)	vegetation coverage (X_2, %)	rainfall intensity （X_3, mm）	soil properties (X_4, g·cm-3)	water erosion modulus (X_5, t·km-2·a-1)	thickness of covering soil (X_6, mm)	Permeability (X_7, mm)
Ⅰ	40~45	0~25	660~700	0.9~1.1	7000~8000	0~10	0.5~2
Ⅱ	30~40	25~40	620~660	1.1~1.3	5000~7000	10~20	0.15~0.5
Ⅲ	20~30	40~60	580~620	1.3~1.6	2500~5000	20~30	0.1~0.15
Ⅳ	10~20	60~75	500~580	1.6~1.9	1000~2500	30~40	0.05~0.1
Ⅴ	0~10	75~90	420~500	1.9~2.1	0~1000	40~50	0~0.05

EXAMPLE ANALYSIS

Selected eight soil erosion areas of Jiaozuo City in China as study areas[8]. And measured data was presented in the Table 2. Built evaluation model of soil erosion severity on the basis of analysis of evaluation factors.

Table 2: Measured data of evaluation indexes of soil erosion

NO.	Location	Evaluation indexes						
		X1	X2	X3	X4	X5	X6	X7
1	Yanmazhuang	30	65	695.7	1.42	1350	34	0.122
2	Jiulishan	38	22	594.4	1.5	1000	41	0.085
3	Dragon Temple	31	28	607.9	1.36	1200	28	0.076
4	Fengyingkuang	33	32	594.4	1.44	2300	32	0.052
5	Zhongzhanqu	16	60	695.7	1.56	1800	19	0.142
6	Chunlin	36	58	695.7	1.45	2000	33	0.185
7	Shangliuzhuang	16	40	637.8	1.39	2500	29	0.212
8	Hanwangkuang	30	58	594.4	1.29	1500	31	0.108

Single Index Measure Function

Constructed single index measure function of evaluation indexes of soil erosion severity based on Table 1 and definition of measure function (see Figure 1-7). Calculated single index measure evaluation matrix on the basis of Table 2 and measure function. For example, single index measure evaluation matrix of R_1(Yanmazhuang) is:

$$(\mu_{1jk})_{7\times 4}=\begin{bmatrix} 0 & 0.500 & 0.500 & 0 & 0 \\ 0 & 0 & 0.143 & 0.857 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 0.120 & 0.880 & 0 & 0 \\ 0 & 0 & 0 & 0.467 & 0.533 \\ 0 & 0 & 0.100 & 0.900 & 0 \\ 0 & 0.060 & 0.940 & 0 & 0 \end{bmatrix}$$

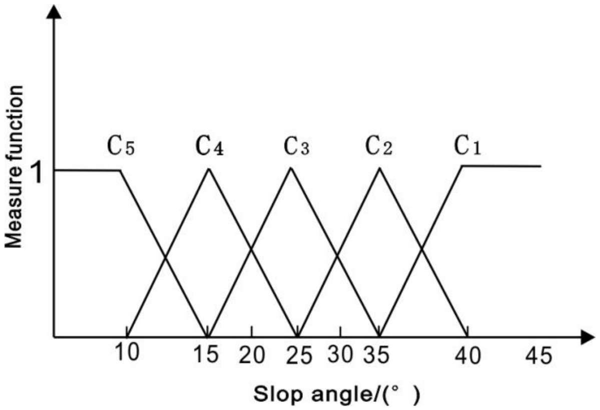

Figure 1: Unascertained measure function of slop angle

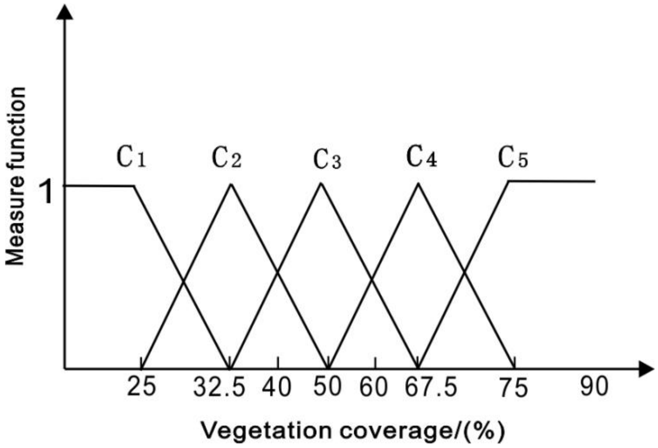

Figure 2: Unascertained measure function of vegetation coverage

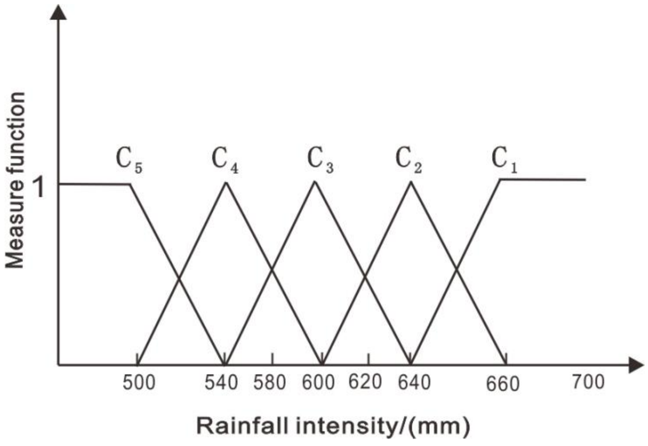

Figure 3: Unascertained measure function of rainfall intensity

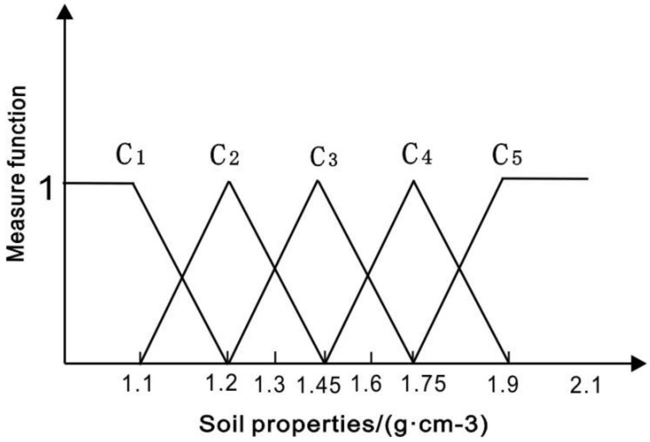

Figure 4: Unascertained measure function of soil properties

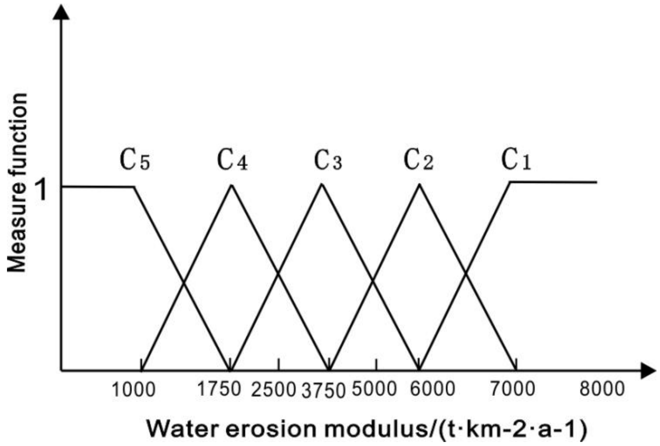

Figure 5: Unascertained measure function of water erosion modulus

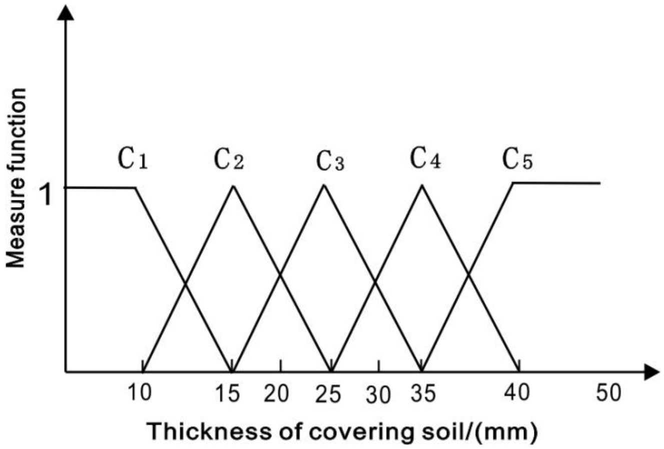

Figure 6: Unascertained measure function of thickness of covering soil

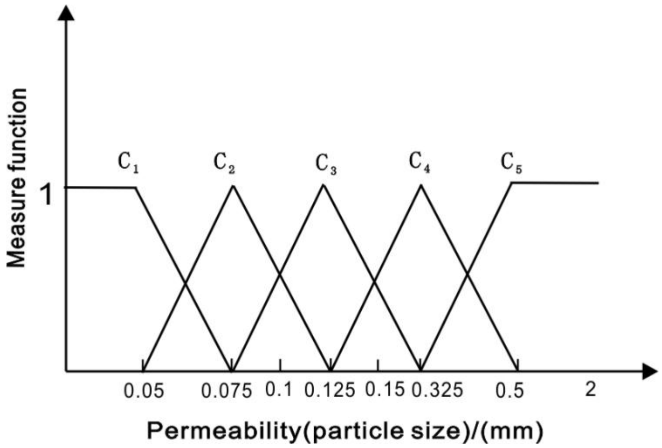

Figure 7: Unascertained measure function of permeability(particle size)

Calculating Weights of Soil Erosion Severity Evaluation Factors

Analytic hierarchy process decomposes elements about decision-making into objective, criterion, project and other levels, then do qualitative and quantitative analysis. AHP expresses and treats subjective judgment of decision-makers by means of quantitative form(Hu et al, 2007)[22]. Using Delphi method and 1-9 scale method to establish judgment matrix of important degree of factors and calculate weight of factors (see table 3 and 4).

Table 3: Comparison matrix in APH of evaluation index of soil erosion severity

Evaluation indexes	X_1	X_2	X_3	X_4	X_5	X_6	X_7
X_1	1	2	3	4	6	9	9
X_2	1/2	1	2	2	4	6	9
X_3	1/3	1/2	1	1	2	4	6
X_4	1/4	1/2	1	1	2	3	4
X_5	1/6	1/4	1/2	1/2	1	2	2
X_6	1/9	1/6	1/4	1/3	1/2	1	1
X_7	1/9	1/9	1/6	1/4	1/2	1	1

Table 4: Weight coefficients of various factors

Labeling	Evaluation indexes	Importance ranking	Weight
X_1	slope angle	1	0.3825
X_2	vegetation coverage	2	0.2370
X_3	rainfall intensity	3	0.1346
X_4	soil properties(density)	4	0.1163
X_5	water erosion modulus	5	0.0629
X_6	thickness of covering soil	6	0.0357
X_7	permeability (particle size)	7	0.0309

The largest eigenvalue $\lambda_{\max}=7.0662$, CI=0.0110, CR=0.0084<0.1, through consistency check.

Constructing multi-index comprehensive measure evaluation matrix

According to calculation results of AHP, the weights of evaluation indexes of R_1: $\{w_1, w_2, \ldots, w_n\}$={0.3825, 0.2370, 0.1346, 0.1163, 0.0629, 0.0357, 0.0309}. Based on single index measure evaluation matrix of R_1 and formula (5), multi-index comprehensive measure evaluation vector: {0.1346, 0.2071, 0.3601, 0.2646, 0.0335}.

The credible degree identification

Taking confidence λ=0.5, for evaluation object R_1, according to formula (8), from small to large, k_0=0.1346+0.2071+0.3601=0.7018>λ, so the risk grade of R_1 is grade Ⅲ; from large to small, k_0=0.0335+0.2646+0.3601=0.6582>λ, so the risk grade of R_1 is grade Ⅲ. Two judges had the same result, therefore, the risk grade of R_1 is grade Ⅲ (moderate erosion). Similarly, calculated risk grade of remaining seven soil erosion areas, the judgement results were presented in the Table 5.

Table 5: Evaluation results of soil erosion areas

Location	Comprehensive Unascertained Measure					Risk grade
	C1	C2	C3	C4	C5	
Yanmazhuang	0.1346	0.2071	0.3601	0.2646	0.0335	III
Jiulishan	0.4665	0.1777	0.2252	0.0319	0.0987	II
Dragon Temple	0.1422	0.4231	0.3612	0.0275	0.0461	II
Fengyingkuang	0.0443	0.5342	0.3383	0.0832	0	II
Zhongzhanqu	0.1346	0.0828	0.2577	0.5927	0	III
Chunlin	0.2111	0.3132	0.3031	0.1726	0	II
Shangliuzhuang	0	0.1963	0.3941	0.4096	0	III
Hanwangkuang	0	0.2762	0.5186	0.1842	0.0210	III

Analysis and Evaluation of Results

According to the soil erosion severity classification standard of Ministry of Water Resources of China[23-25] (see table 6) and the data of Jiaozuo City soil and water conservation station, soil erosion severity of study areas were obtained (see table 7). Where, Ⅰ- severe erosion; Ⅱ- strong erosion; Ⅲ- moderate erosion; Ⅳ- mild erosion; Ⅴ- slight erosion.

Results showed that the soil erosion severity evaluation results of extension theory were basically in accordance with the results of Ministry of Water Resources of China.

Table 6: Soil erosion severity classification standard of Ministry of Water Resources

Severity	I	II	III	IV	V
Annual average erosion modulus (t·km-2·a-1)	8000～15000	5000～8000	2500～5000	200,500,1000～2500	<200,500,1000

Table 7: Annual average erosion modulus and severity of study areas

Locations	Yanma zhuang	Jiuli mountain	Dragon temple	Fengyin gkaung	Zhongz hanqu	Chun lin	Shangliu zhuang	Hanwang kaung
Annual average erosion modulus	2800	6240	7020	5890	2320	5780	3600	4500
Severity	III	II	II	II	IV	II	III	III

From Table 7, the evaluation results of uncertained measurement theory were consistent with the actual situation, verified the feasibility and accuracy of the model.

CONCLUSIONS

Influencing factors of soil erosion severity are extremely complicated and various, including internal factors and external factors. For the shortcomings and deficiencies of the current evaluation and analysis methods of soil erosion severity, used uncertained measure evaluation model to evaluate soil erosion severity.

Used uncertained measure evaluation model to evaluate soil erosion severity. Firstly, selected seven influencing factors of soil erosion severity as evaluation indexes, made risk grading standard of soil erosion, and constructed single index unascertained measure function of soil erosion on the basis of unascertained measurement theory; then, calculated the weights of evaluation indexes based on AHP, obtained comprehensive measure function of soil erosion severity; finally, calculated risk grade of soil erosion areas based on confidence criterion. The evaluation results of uncertained measurement theory were consistent with the actual situation, verified the feasibility and accuracy of the model.

The soil erosion severity evaluation model based on uncertained measurement theory is reasonable and reliable. It not only overcomes subjectivity of expert scoring and limitation of single index evaluation, but also can determine risk grade of soil erosion severity and importance ranking. It was the first time that the AHP and uncertained measurement theory was applied to the severity of soil erosion assessment, which provided a new analysis method for the study of the soil and water loss danger division.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this article.

ACKNOWLEDGEMENTS

The research is supported by the National Natural Science Foundation of China, No.41272377.

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Editor's note.
This paper may be referred to, in other articles, as:

Junchao Ma, Chao Zhao, Wenqi Han, and Hongming Yu: "The Application of Unascertained Measurement Theory in Soil Erosion Severity Evaluation" *Electronic Journal of Geotechnical Engineering*, 2016 (21.16), pp 5441-5452. Available at ejge.com**.**