Hindawi
Mathematical Problems in Engineering
Volume 2019, Article ID 7910752, 10 pages
https://doi.org/10.1155/2019/7910752

Research Article

Novel Prediction Method for Highway Distresses in Permafrost Regions Based on Qualitative Reasoning of Multidimensional and Multirules Cloud Model

Chi Zhang,[1,2] **Hong Zhang**,[1] **Min Zhang**,[3] **and Quanli Gong**[1]

[1] *Key Laboratory for Special Area Highway Engineering of Ministry of Education, Chang'an University, Xi'an 710064, Shaanxi, China*
[2] *CCCC First Highway Consultants Co., Ltd., Xi'an 710075, Shaanxi, China*
[3] *Traffic Engineering Research Institute, School of Highway, Chang'an University, Xi'an 710064, China*

Correspondence should be addressed to Hong Zhang; 1191080464@qq.com

Received 23 October 2018; Accepted 4 December 2018; Published 28 January 2019

Academic Editor: Anna M. Gil-Lafuente

Highway in permafrost regions has numerous diseases during operation, due to instability and degradation of permafrost. To predict distress sections of a newly built highway in permafrost regions, we proposed a new method based on the multidimensional and multirules reasoning cloud model. Herein, the evaluation parameters affecting the highway distresses in permafrost regions, i.e., annual average ground temperature, ice content, and frozen-heave factor, were as the data input, whereas the distress degree was as the data output; all of the aforementioned were described by a cloud model. Based on the analysis of distress large data, inference rules and a cloud reasoning prediction model were established. Subsequently, distress degrees of the 10 equidistance highway sections were predicted on the Qinghai-Tibet highway by using the cloud model, and actual distress degree and predicted distress degree were compared by using the regression analysis algorithm. The results showed that the relevance between the actual distress degree and the predicted distress degree was 0.738. The study provides a feasible and effective method to predict the potential distress sections of the newly built highway and better plan infrastructure project on permafrost regions.

1. Introduction

Owing to the complicated geological conditions and the fragile ecological environment in the permafrost regions, serious highway distresses that lead to significant economic losses can easily occur [1]. Therefore, the prediction of highway distresses in permafrost regions has profound significance to obtain the potential distress sections and for a rational route planning; it is also essential in assisting decision making and improving the quality of engineering in permafrost regions [2].

In the process of highway distress production in permafrost regions, many factors, including the annual average ground temperature, ice content, and others, have different effects on the highway distresses in permafrost regions [3, 4]. In recent years, domestic and foreign scholars have explored the relationships between highway distress and their influencing factors [5]. However, few meaningful results have been achieved for highway distress prediction in permafrost regions. Some scholars established a probability model for the subgrade distress susceptibility of the Qinghai-Tibet highway in permafrost regions to forecast the probability of awareness of subgrade distress based on the original data [6]. Some researchers selected the moisture content, the maximum frozen depth, thaw-settlement coefficient, frozen-heave factor, and depth as the influencing factors and established the corresponding relationship between the scale score of controlling factors and highway distress grades [7]. By using the annual average ground temperature and ice content as indexes, Xu Anhua and other scholars [8] calculated the sensitivity of the pavement distresses along the Qing Kang highway according to the indexes. However, these studies had obvious subjectivity and randomness. Further, the method of highway distress prediction in permafrost regions has not been studied. Based on fuzzy mathematics theory and fuzzy expert systems, scholars have proposed a variety of prediction methods for highway distress. This paper introduces the fuzzy mathematics theory and establishes the roadbed distress early-warning system of the Qinghai-Tibet highway in permafrost regions based on the rules for describing the relationship between influencing factors and the distress intensity [9]. Some scholars used the fuzzy expert system, based on the division of changing factors of frozen soil, and finally established a prediction model of highway distresses in permafrost regions [10]. However, these methods still have many defects; they transform the uncertainty into deterministic formality; thus the generalization ability is weak and the accuracy is low. The membership functions employed in these theories are typically determined by the prior knowledge of experts or statistical methods, whose randomness and objectivity were ignored.

Highway geological factors and a large number of empirical expert knowledge of permafrost distress are ambiguous and incomplete. In the process of data statistic and actual measurements, an active subjectivity exists on the regional selection. The data obtained do not correspond to the complete information about the permafrost regions; instead, it reflects the uncertainty information. Different concepts of highway distress described by the natural language are ambiguous. Further, the environment of the permafrost region is highly complicated that the values of the indexes may be not reflecting the characteristics of permafrost precisely. Therefore, the uncertainty theory is more suitable to express the information about highway distress and geological factors, which can reveal the actual situation.

Currently, various methods including the probability theory, fuzzy sets, and rough sets are used to handle the uncertainty problem [11]. These approaches have been applied to each field. Effati considered the data uncertainty and proposed a new method for road hazardous segment identification using the geospatial information system (GIS) and fuzzy reasoning [12]. This paper handled the output of the fuzzy model with techniques of interval analysis to ensure the integrity of the uncertainty information of the final results and built a road environment evaluation model based on road safety and the fuzzy interval theory [13]. This paper employs triangular, trapezoidal fuzzy numbers and noncut concept to handle the imprecision and vagueness of the subjective judgment and presents a fuzzy AHP model to evaluate the bridge construction methods; AHP model is a systematic and hierarchical analysis which combines the qualitative and quantitative [14]. To handle the problem in emergency plan-matching of highway traffic where the incident description is incomplete, incident properties are unclear, and plan-matching is inaccurate. G Chai [15] proposed a plan-matching method based on fuzzy sets and rough sets, reflecting the advantages of rough sets and fuzzy sets in emergency plan-matching. However, these methods cannot describe the randomness of the subjects and data. They are not appropriate for the prediction of highway distresses in permafrost regions.

A cloud model is useful in the uncertain transforming between qualitative concepts and their expressions, which is proposed by academician De-Yi Li using fuzzy sets and the probability theory [16]. It has unique advantages in handling fuzziness and randomness. Compared with the probability theory, a cloud model also reflects the randomness. The membership function is reflected by a precise value, while the cloud model considers the randomness. The rough set measures the uncertainty of the research of two exact sets that are built on the background of precise knowledge; the cloud model also considers the uncertainty of the background. Qualitative knowledge reasoning based on the cloud model uses the concept as a basic representation, mining qualitative knowledge from the database to construct the rule generator. The rule base consists of qualitative rules.

Many scholars have applied the cloud model to some valuable research in various fields. S Shi and X Liu [17] used the highway alignment condition and horizon as the index and built a prediction model of operating speed based on a cloud model. JC Shen [18] compared a fuzzy evaluation with a fuzzy comprehensive assessment based on a cloud model and verified the advantages of the cloud model with an example. SB Zhang [19], based on the fuzziness, randomness, and uncertainty of the cloud model, applied it to the trust mechanism and realized the quantitative and qualitative transformation of the concept of trust. According to the measured data of the Three Gorges Reservoir, QW Zhang [20] analyzed the reservoir-induced earthquake of each unit using a multilevel fuzzy comprehensive evaluation method based on the cloud model. X Jia [21] improved the analytic hierarchy process using the method of principal component analysis and expert investigation and proposed a highway seismic damage assessment plan based on the cloud model. Zheng-Jie XU [22] used the fuzzy comprehensive evaluation method based on the cloud model to evaluate the risk of the railway signal system and applied the cloud model in the risk assessment. However, it is not related to the highway. For the complexity and ambiguity of the influencing factors of a tunnel collapse accident, the landslide factors were selected and the risk level assessment model of the tunnel landslide was set up based on the cloud model [23]. By considering the quantitative and qualitative index synthetically, some researchers applied the cloud model to the railway route selection. An evaluation model of railway route selection was formed [24]. Therefore, a significant number of fields had been investigated, but the highway distress prediction in permafrost regions has not been attained.

Therefore, we propose a new prediction method for highway distress in permafrost regions based on the cloud model theory. Based on analyzing a large-quantity data, this article represents the digital characteristic of multidimensional cloud and designed the generator on multifaceted and multirules for qualitative reasoning. Subsequently, through combining the reasoning rules in various modes, using the highway distress degree as the analytical index, the prediction of highway distresses in permafrost regions was realized with the evaluation parameters as the input conditions and the distress degree values as the output. Additionally, we verified the feasibility and effectiveness of the proposed method through the analysis of the sample highway sections.

2. Cloud Model Concept

2.1. Cloud Model Theory. Cloud model can characterize the uncertainty of the transition between qualitative concepts and their quantitative expressions. Let U be a set expressed by exact numbers, and let $C_P(y)$ be a qualitative term associated with U. U={ y } contains the field of real numbers. The membership degree (ranging from 0 to 1) of y to the qualitative term $C_P(y)$ is a random number with a stable tendency. Compatibility cloud is mapping from the real numbers field of set U to the unit interval [0, 1], as formula (1). The random distribution of y in U forms a membership degree cloud and each y is called a cloud droplet. Particularly, the membership degree cloud is not a clear curve but consists of numerous cloud droplets [25].

$$C_P(y) : U \longrightarrow [0,1]; \quad \forall y \in U \ y \longrightarrow C_P(y) \qquad (1)$$

The membership degree of y to qualitative term $C_P(y)$ (ranging from 0 to 1) is a probability distribution rather than a fixed value, which is different from the fuzzy logic [26]. Cloud model shows the uncertainty by integrating fuzziness and randomness of an element belonging to set U.

Normal clouds are most useful in linguistic terms of vague concepts because normal distribution has been supported by the results in every branch of both social sciences and natural sciences. A normal cloud is defined with three digital characteristics, expected value *Ex*, entropy *En,* and hyperentropy *He* (Figure 1) [25].

The expected value *Ex* is the position at U corresponding to the center of gravity of the cloud. The entropy *En* is a measure of the coverage of the concept within the universe of discourse and is described by the bandwidth of the mathematical expected curve (MEC) of the normal cloud showing how many elements in the universe of discourse could be accepted to the linguistic term. The MEC of the normal cloud to a linguistic term may be estimated as its membership function from the fuzzy set theory point of view. The hyperentropy is the entropy of the entropy *En*. It is used to measure dispersion of the cloud drops [26].

A set containing three dimensions U1= $\{x_1, x_2, x_3\}$ is called a domain. For the fuzzy sets of the three-dimensional universe, U1 is A= $(\mu_A(x_1),\ \mu_A(x_2), \mu_A(x_3))$, in which $\mu_A(x_1),\ \mu_A(x_2), \mu_A(x_3)$ for every arbitrary elements x_1, x_2, x_3 to the fuzzy set A generated a stable tendency of the random number. Therefore, it will be referred to as the elements to the membership degree of fuzzy set A. If each element is provided three dimensionally in the expected domain, entropy, and excess entropy, subsequently each element can be generated in a cloud model, and the three one-dimension cloud models are combined to form a three-dimensional cloud [27].

Algorithm. Input: The digital characteristic of each cloud model (Ex, Ey, Ez), (Enx, Eny, Enz), (Hex, Hey, Hez), the number of cloud droplets N.

Output: Drop (x_i, y_i, z_i, μ_i).

(1) Use the (Enx, Eny, Enz) as the expected value, $((Hex)^2, (Hey)^2, (Hez)^2)$ as the standard deviation, creating a three-dimensional random number $(Enxi', Enyi', Enzi')$.

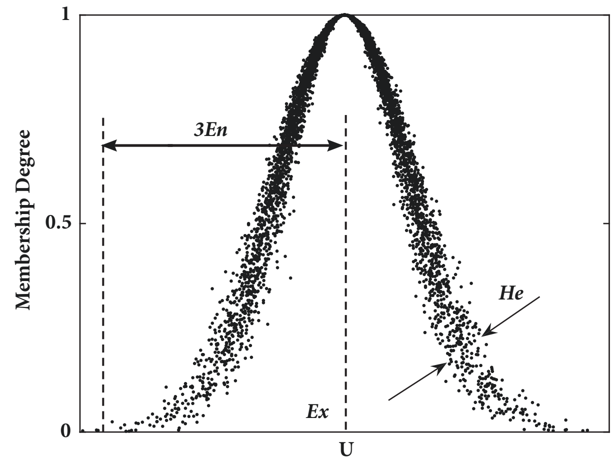

Figure 1: Illustration of the three digital characteristics of a normal cloud.

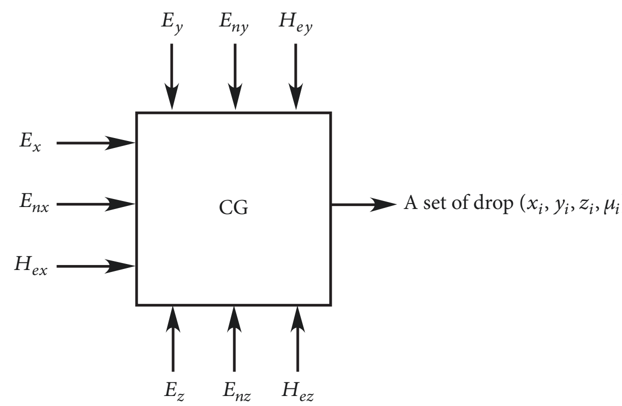

Figure 2: Three-dimensional positive cloud generator.

(2) Use the (Ex, Ey, Ez) as the expected value, $(Enxi', Enyi', Enzi')$ as the standard deviation, creating a three-dimensional random number (x_i, y_i, z_i).

(3) $\mu_i = \exp[-((x_i - (Ex)^2)/2(Enxi')^2 + (y_i - (Ey)^2)/2(Enyi')^2 + (z_i - (Ez)^2)/2(Enzi')^2)]$

(4) (x_i, y_i, z_i, μ_i) is a cloud droplet, it is a concrete implementation of the cloud model.

(5) Repeat steps (1) to (4), until N cloud droplets are generated.

In Figure 2, CG is the abbreviation for cloud generator. After introducing the cloud model, we will discuss the new prediction method of highway distress in permafrost in permafrost regions.

3. Prediction Method of Highway Distresses in Permafrost Regions Based on Three-Dimensional Multirules

3.1. Analysis of Influence Factors of Highway Distresses in Permafrost Regions. The highway distresses in permafrost regions are a complicated process affected by many factors, such as the environment, projects, and human behavior. It is hard to describe the relationship between these factors and the severity of highway distresses in permafrost regions using a model. Therefore, the cloud model is utilized to handle the randomness and fuzziness in the process of highway distresses prediction, which can reflect the actual situation. According to the relevant research results and literature data, the higher annual average ground temperature in permafrost regions is the primary cause of subsoil ice melting and thaw slumping, as well as the subgrade uneven deformation and subgrade settlement [28]. With the increase in the annual average ground temperature in permafrost regions, the stability of frozen soil becomes worse, and the highway distress degree increases. The fundamental reason for the formation of pavement distress in permafrost regions is the high ice content. The higher the ice content is, the more severe the highway distress will be [29]. The construction and maintenance of a highway are complicated in regions where thick underground ice is widely distributed, resulting in waves, upheaval, and other distress. Some studies have proven that the annual average ground temperature, ice content, and frozen-heave factors are the decisive factors of highway distresses in permafrost regions based on the distresses data of a certain section of the Qinghai-Tibet highway [10]. Therefore, the annual average ground temperature, ice content, and frozen-heave factor are the primary factors affecting highway distresses in permafrost regions. We selected the annual average ground temperature, ice content, and frozen-heave factor as our evaluation parameters. This paper does not consider the impact of engineering factor and other factors on highway distress. Combined with the experimental sections, a new method to predict highway distress in permafrost regions is presented based on the cloud model theory. The data of annual average ground temperature, ice content, and frozen-heave factor are easy to get. The data used in this paper come from the in situ measurement of CCCC First Highway Consultants Company. The climate is changing each year, but the characteristics of frozen soil are relatively stable in a certain period. This paper does not consider the changes of frozen soil.

3.2. Cloud Models of Evaluation Parameters and Highway Distress Degree. Refer to the classification of frozen soil by other experts [10, 30]. Consider the relationship between distress and evaluation parameters comprehensively. According to the expert's language evaluation value, the classification and range of evaluation parameters and distress degree were obtained. The annual average ground temperature is divided into three language description levels: lower, medium, and higher. The ice content and frozen-heave factor are, respectively, divided into the same three language description levels as well. This paper uses the highway distress degree to reflect the severity of highway distress. The highway distress degree corresponds to the disease rate. Distress rate is the probability of various highway distress. When the distress rate is 100%, the distress degree is 1; when the distress rate is 0, the distress degree is 0. A linear interpolation method was used to calculate the corresponding distress degree of another distress rate. The highway distress degree is divided into seven language description levels: very small, small, relatively small, medium, relatively big, big, and very big. The specific classification and value ranges are shown in Tables 1 and 2.

In Table 1, T, W, and X are the abbreviations of the annual average ground temperature, ice content, and frozen-heave factor. Language labels represent the language description levels. L, M, and H are the abbreviations of the three language description levels: lower, medium, and higher.

In Table 2, D is the abbreviation of the distress degree. Language labels represent the language description levels. VS, S, RS, M, RB, B, and VB are the abbreviations of the seven language description levels: very small, small, relatively small, medium, relatively big, big, and very big.

The evaluation cloud model is a bilaterally constrained comment $[C_{\min}, C_{\max}]$. The digital characteristics of the evaluation cloud model can be determined by formulas (2) and (3).

$$Ex = \frac{C_{\min} + C_{\max}}{2} \tag{2}$$

$$En = \frac{C_{\max} - C_{\min}}{6} \tag{3}$$

He=k, k is a constant and can be adjusted according to the degree of fuzziness of the evaluation sets.

Let He=0.01. According to formulas (2) and (3), the digital characteristics of the cloud model that are used to describe the evaluation parameters and highway distress degree can be obtained, as showed in Tables 3 and 4. For example, the range of "L" of the annual average ground temperature is [-6, -3]. According to formulas (2) and (3), $E_x = ((-6)+(-3))/2 = -4.5$; $E_n = ((-3) - (-6))/6 = 0.5$.

According to the digital characteristic in Tables 3 and 4, cloud models of evaluation parameters and distress degree can be obtained by using positive cloud generator. When the annual average ground temperature is -6°C – -4.5°C and -1°C – 0°C, the ice content is 0–10% and 36–50%, respectively; the frozen-heave factor is 0–2.5% and 10–14%, respectively; the membership degree of the cloud model is 1, which belongs to the trapezoidal cloud model. This article maps the vague comments as different cloud droplets with subtle variations. Figures 3–6 are, respectively, the annual average ground temperature cloud model, ice content cloud model, frozen-heave factor cloud model, and distress degree cloud model.

As showed in Figure 3, the three qualitative concepts describing the annual average ground temperature can be expressed as formulas (4) and (6):

$$\text{"Lower"} = \begin{cases} 1 & x \in [-6, -4.5] \\ C(-4.5, 0.5, 0.01) & \text{Else} \end{cases} \tag{4}$$

$$\text{"Medium"} = C(-2.5, 0.5, 0.01) \tag{5}$$

$$\text{"Higher"} = \begin{cases} C(-1.0, 0.33, 0.01) & \text{Else} \\ 1 & x \in [-1, 0] \end{cases} \tag{6}$$

C (Ex, En, He) in the inequality above represents a cloud model. The other parameters are similar.

Table 1: Evaluation parameters and its range.

T	Language label	L	M	H
	Range/°C	[-6, -3]	[-4, -1]	[-2, 0]
W	Language label	L	M	H
	Range/%	[0, 20]	[12, 25]	[22, 50]
X	Language label	L	M	H
	Range/%	[0, 5]	[2, 12]	[6, 14]

Table 2: Highway distresses degree and its range.

	Highway distresses degree(D)						
Language label	VS	S	RS	M	RB	B	VB
ranges	[0, 0.30]	[0, 0.40]	[0.25, 0.45]	[0.30, 0.70]	[0.55, 0.75]	[0.60, 1.00]	[0.70, 1.00]

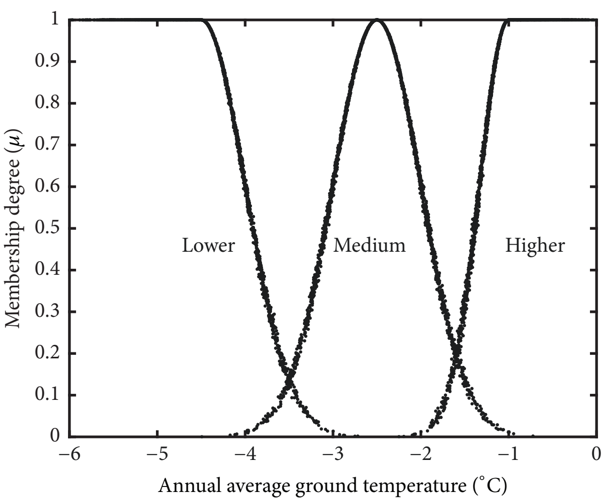

Figure 3: Average yearly ground temperature cloud model.

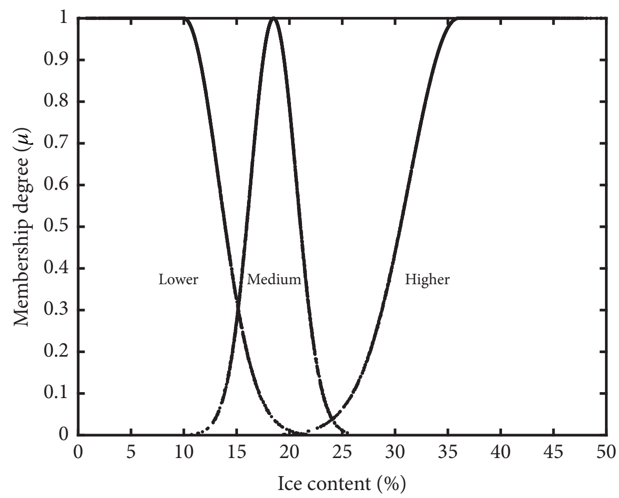

Figure 4: Ice content cloud model.

3.3. Inference Rules. Based on the clustering analysis of the existing data and the experts' experience, the inference rules between the evaluation parameters and distress degree are established. Three evaluation parameters exist; each evaluation parameter has three levels, and any evaluation parameter is arranged at any level, with a total of $3 \times 3 \times 3 = 27$ combinations. This article uses the rule of "and" to connect the evaluation parameters. Limited by the length of the paper, only some of the rules are showed. Table 5 displays the details of the inference rules.

The rules in Table 5 are primarily displayed as the fuzzy concept of the qualitative linguistic value; the highway distress degree of the characteristic parameters of the cloud object after treatment is shown in Table 6. Limited by the length of the paper, only some inference rules parameters are shown in Table 6.

3.4. Multidimensional and Multirules Qualitative Reasoning Algorithm. The cloud model rule generator was constructed based on the X-condition cloud model and Y-condition cloud model [31]. By providing the three digital characteristics of the cloud model and the specific values "x" in the domain, the X-condition cloud model is formed by the cloud droplets, as formulas (7) and (8).

$$P_i = R_1\left(E_n, H_e\right) \tag{7}$$

$$\mu_i = \exp\left(-\frac{1}{2}\left(\frac{x - E_x}{P_i}\right)^2\right) \tag{8}$$

When specific values "μ" are given, the cloud droplets form the Y-condition cloud model, as formulas (9) and (10).

$$P_i = R_1\left(E_n, H_e\right) \tag{9}$$

$$y_i = E_y \pm \sqrt{-2\ln\mu P_i} \tag{10}$$

A plurality of three-dimensional X-conditional cloud generators and a plurality of one-dimensional Y-conditional cloud generators form the highway distresses degree prediction generator, which was based on the multidimensional rules cloud model qualitative reasoning, as showed in Figure 7.

In Figure 7, $CG_{A1}, CG_{A2} \ldots CG_{An}$ are three-dimensional X-conditional cloud generators. $C_{A1}, C_{A2} \ldots C_{An}$ are three-dimensional cloud models. $CG_{B1}, CG_{B2} \ldots CG_{Bn}$ are one-dimensional Y-conditional clouds generators. $C_{B1}, C_{B2} \ldots C_{Bn}$

Table 3: Digital characteristic of evaluation parameters cloud model.

Digital characteristic	T/°C			W/%			X/%		
	L	M	H	L	M	H	L	M	H
E_x	-4.50	-2.50	-1.00	10.00	18.50	36.00	2.50	7.00	10.00
E_n	0.50	0.50	0.33	3.33	2.17	4.67	0.83	1.67	1.33
H_e	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01

Table 4: Digital characteristic of highway distresses degree cloud model.

Digital characteristic	Distresses degree (D)						
	VS	S	RS	M	RB	B	VB
E_x	0.150	0.200	0.350	0.500	0.650	0.800	0.850
E_n	0.050	0.067	0.033	0.067	0.033	0.067	0.050
H_e	0.001	0.001	0.001	0.001	0.001	0.001	0.001

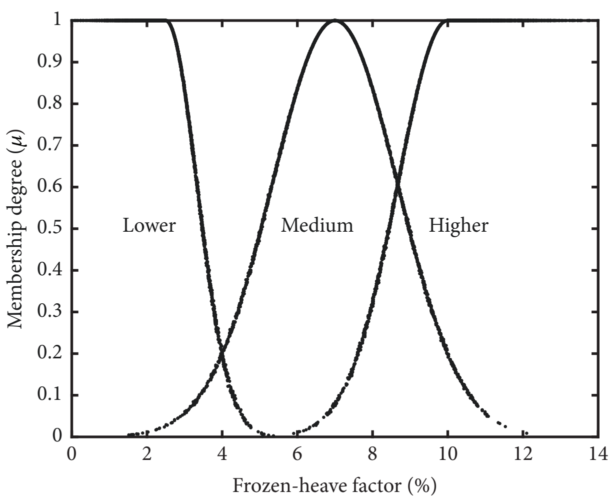

Figure 5: Frozen-heave factor cloud model.

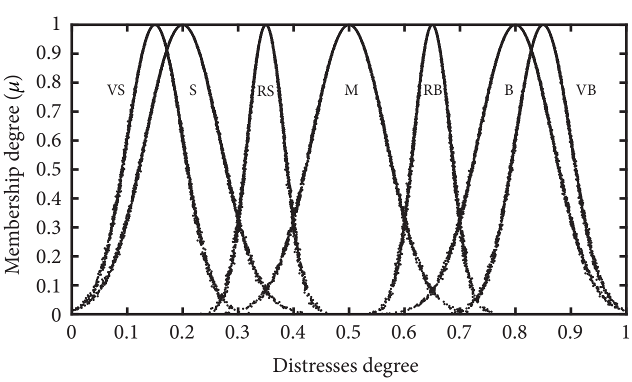

Figure 6: Distresses degree cloud model.

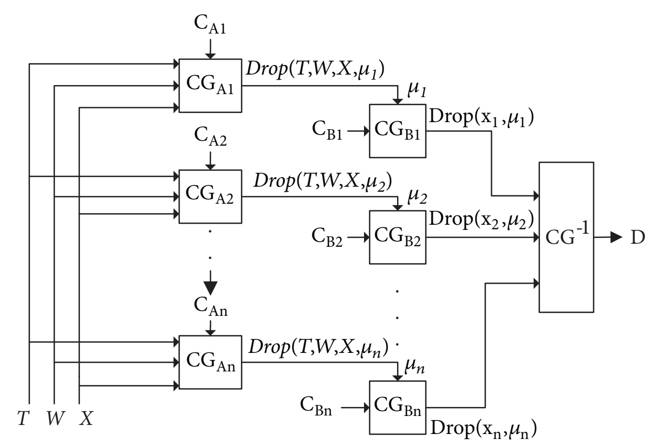

Figure 7: 3D and multirules for uncertainty reasoning generator.

are one-dimensional cloud models. CG^{-1} represents the method of generating output values; it is described in step (6) of the subsequent reasoning process.

It can predict the highway distress degree under the given conditions, according to the rules extracted from the data. The specific multidimensional cloud model based on the regulations of qualitative reasoning process is as follows:

(1) Provide the digital characteristics of each evaluation parameter of the cloud model and the highway distress degree cloud model with different conditions.

(2) For every single rule, use the $(En_{A1i}, En_{A2j}, En_{A3k})$ as the expected value, $(He_{A1i}, He_{A2j}, He_{A3k})$ as the standard deviation, generating a three-dimensional random number $(Enn_{A1i}, Enn_{A2j}, Enn_{A3k})$ that complies with the three-dimensional normal distribution.

(3) According to the given specific value (T, W, X), obtain the activation degree of every single rule, as formula (11).

$$\mu_i = e^{-((T-Ex_{A1i})^2/2Enn_{A1i}{}^2+(W-Ex_{A2j})^2/2Enn_{A2j}{}^2+(X-Ex_{A3k})^2/2Enn_{A3k}{}^2)} \tag{11}$$

(4) Take the maximum μ in μ_i, the corresponding individual laws, according to the given digital characteristic (Ex_b, En_b, He_b) of the postcondition of the relevant rules. Subsequently, use En_b as the expected value, He_b as the standard deviation, generating a one-dimensional standard random value Enn_b.

Table 5: Inference rules table.

Rule	T	W	X	D	Rule	T	W	X	D	Rule	T	W	X	D
1	L	L	L	VS	10	M	L	L	VS	19	H	L	L	VS
2	L	M	L	VS	11	M	M	L	S	20	H	M	L	M
3	L	H	L	VS	12	M	H	L	RS	21	H	H	L	RB
4	L	L	M	VS	13	M	L	M	RS	22	H	L	M	S
5	L	M	M	S	14	M	M	M	M	23	H	M	M	B
6	L	H	M	S	15	M	H	M	M	24	H	H	M	VB
7	L	L	H	S	16	M	L	H	RS	25	H	L	H	M
8	L	M	H	S	17	M	M	H	M	26	H	M	H	B
9	L	H	H	RS	18	M	H	H	RB	27	H	H	H	VB

(5) According to the formula $\mu = e^{-((D-Ex_b)^2/2Enn_b{}^2)}$, $D = Ex_b \pm Enn_b \times \sqrt{-2\ln\mu}$ is obtained.

(6) Because the given specific amount (T, W, X) may activate the rising edge or falling edge of each cloud model, three output cases exist.

(a) If T, W, and X are all activating the rising edge, i.e., $T \le Ex_{A1}$, $W \le Ex_{A2}$, $X \le Ex_{A3}$, subsequently, $D = Ex_b - Enn_b \times \sqrt{-2\ln\mu}$.

(b) If T, W, and X are all activating the falling edge, i.e., $T > Ex_{A1}$, $W > Ex_{A2}$, $X > Ex_{A3}$, subsequently, $D = Ex_b + Enn_b \times \sqrt{-2\ln\mu}$.

(c) If T, W, and X are activating both the falling edge and the rising edge, a total of six cases are included: ($T > Ex_{A1}$, $W > Ex_{A2}$, $X \le Ex_{A3}$), ($T > Ex_{A1}$,$W \le Ex_{A2}$,$X \le Ex_{A3}$), ($T > Ex_{A1}$,$W \le Ex_{A2}$,$X > Ex_{A3}$), ($T \le Ex_{A1}$,$W \le Ex_{A2}$,$X > Ex_{A3}$), ($T \le Ex_{A1}$,$W > Ex_{A2}$,$X \le Ex_{A3}$), and ($T \le Ex_{A1}$,$W > Ex_{A2}$,$X > Ex_{A3}$).

Use the ($T > Ex_{A1}$,$W > Ex_{A2}$,$X \le Ex_{A3}$) as examples, similar to others. If $T > Ex_{A1}$,$W > Ex_{A2}$,$X \le Ex_{A3}$, subsequently calculate according to formulas (12)–(18).

$$\mu_1 = e^{-(T-Ex_{A1})^2/2(Enn_{A1})^2} \tag{12}$$

$$D_1 = Ex_b + Enn_b \times \sqrt{-2\ln\mu_1} \tag{13}$$

$$\mu_2 = e^{-(W-Ex_{A2})^2/2(Enn_{A2})^2} \tag{14}$$

$$D_2 = Ex_b + Enn_b \times \sqrt{-2\ln\mu_2} \tag{15}$$

$$\mu_3 = e^{-(X-Ex_{A3})^2/2(Enn_{A3})^2} \tag{16}$$

$$D_3 = Ex_b - Enn_b \times \sqrt{-2\ln\mu_3} \tag{17}$$

$$D = \frac{D_1\mu_1 + D_2\mu_2 + D_3\mu_3}{\mu_1 + \mu_2 + \mu_3} \tag{18}$$

Use D as the output. The process goes back to step (2), looped several times, and the average of all the cloud droplets is used. This is the predicted value of highway distress degree in permafrost regions.

4. Case Verification

We use the example of the K3030+000–K3080+000 section of the Qinghai-Tibet highway with common frozen soil distress as the experimental highway section, as showed in Figure 8. Total road mileage is 50km with an extensive amount permafrost covering this area, and the terrain condition is better overall. The average annual ground temperature along the experimental highway section is between -5°C and 0°C, and the permafrost types are dominated by ice-rich soil. The characteristic of the frozen soil in the permafrost regions changes, obviously. Some typical highway distresses such as subgrade settlement, net-shaped cracks, wave, and rutting had occurred. The experimental highway section shows an active representation.

The experimental highway section is divided into 10 equidistant sections; the number is one to ten. The statistics were supplied by the CCCC First Highway Consultants Company. The original data of each evaluation parameter were adequately collected and matched with the measured data of highway distress. The detailed data are presented in Table 7.

Distress degree of highway sections in Table 7 is predicted using the method proposed herein. For example, in highway section 8 in Table 7, the inputs T=-3, W=15.9, X=5.3 were used in the three-dimensional and multirules cloud model for the qualitative reasoning generator; the qualitative rule of maximum activation intensity was rule 14; the activation strength was 0.17. According to step (3) of the reasoning process above, two cloud droplets $P1$ and $P2$ can be obtained, as showed in Figure 9. Because T, W, and X are all activating the rising edge, subsequently D= 0.376.

In Table 7, Y is the actual value of the distress degree. D is the result of the prediction. Figure 10 displays the comparison of the exact distress degree and the predicted distress degree.

Using the regression analysis algorithm of SPSS, the relational model between the exact distress degree (Y) and the expected distress degree (D) is established, as formula (19). The exact distress degree (Y) is dependent variables; the expected distress degree (D) is independent variables.

$$\mathrm{Y} = 0.675\mathrm{D} + 0.233 \tag{19}$$

As showed from the relational model (Table 8), the regression analysis of the actual distress degree and the predicted distress

Table 6: Inference rules table.

Rules	$T/^{\circ}C$			$W/\%$			$X/\%$			D		
	E_x	E_n	H_e	E_x	E_n	H_e	E_x	E_n	H_e	E_x	E_n	H_e
1	-4.5	0.5	0.01	10	3.33	0.01	2.5	0.83	0.01	0.15	0.050	0.001
2	-4.5	0.5	0.01	18.5	2.17	0.01	2.5	0.83	0.01	0.15	0.050	0.001
3	-4.5	0.5	0.01	36	4.67	0.01	2.5	0.83	0.01	0.15	0.050	0.001
						......						
25	-1	0.33	0.01	10	3.33	0.01	10	1.33	0.01	0.50	0.067	0.001
26	-1	0.33	0.01	18.5	2.17	0.01	10	1.33	0.01	0.80	0.067	0.001
27	-1	0.33	0.01	36	4.67	0.01	10	1.33	0.01	0.85	0.050	0.001

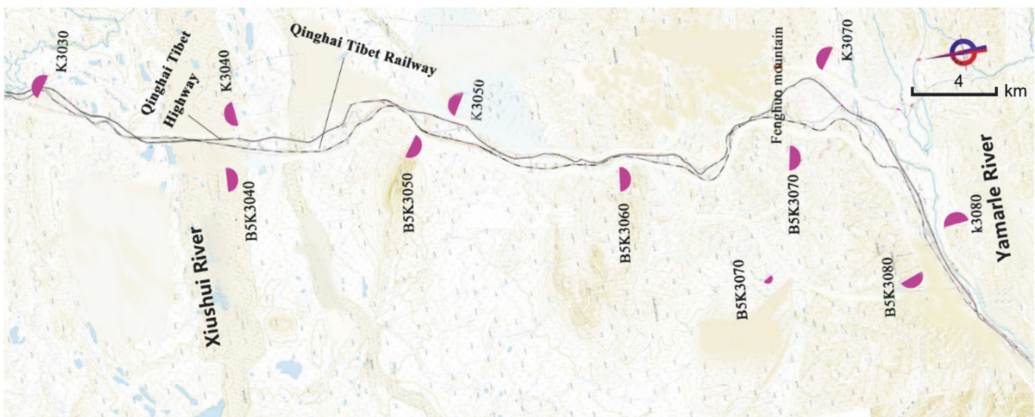

Figure 8: K3030+000~K3080+000 section of the Qinghai-Tibet highway.

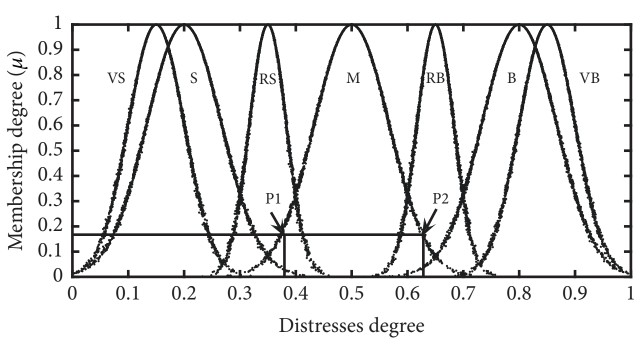

Figure 9: Schematic diagram of calculation.

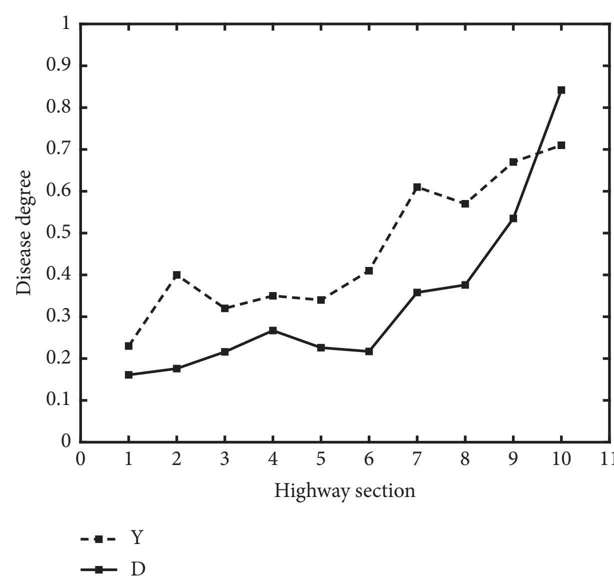

Figure 10: Relationship between actual distresses degree and predicted distresses degree.

degree is calculated by the method proposed herein, $R^2 = 0.738$; therefore, the error is permitted. It shows that the plan proposed herein can reflect the actual highway distress rate in permafrost regions and proves that this approach is feasible and practical.

5. Discussion and Conclusion

The following conclusions are derived from this study:

(1) The study proposed a feasible and automatic way to predict the potential distress sections of the newly built highway on permafrost regions, based on the qualitative reasoning of multidimensional and multirules cloud model. The establishment of the cloud model considers both the fuzziness and randomness to overcome the inherent defects of the fuzzy set theory. Thereby we hope that the study would help policymakers in China and many other countries

Table 7: Sample sections prediction.

Highway Section	$T/^{\circ}C$	$W/\%$	$X/\%$	D	Y
1	-5	12.6	2.2	0.161	0.230
2	-5	19.0	4.8	0.176	0.400
3	-5	20.0	7.2	0.216	0.320
4	-4	17.2	4.9	0.267	0.350
5	-4	18.4	4.3	0.226	0.340
6	-3	21.5	3.9	0.217	0.410
7	-4	39.4	12.5	0.358	0.610
8	-3	15.9	5.3	0.376	0.570
9	-2	27.4	8.2	0.535	0.670
10	-1	31.8	7.3	0.842	0.710

Table 8: Analysis result of relational model.

R	R^2	Error
0.859	0.738	0.08986

to better plan their infrastructure project, so as to avoid environmentally vulnerable regions.

(2) The study established the inference rules between the evaluation parameters (annual average ground temperature, ice content, and frozen-heave factor) and distress degree in various modes, and formed positive cloud generator to establish the specific multidimensional cloud models for evaluation parameters and distress degree. We hope that the study offers a basis for exploring impacts of permafrost on roads.

(3) The study utilized the 10 equidistance sections of the Qinghai-Tibet highway as a case and predicted distress degrees using the multidimensional cloud models. Our results show that the distress degrees of the road sections are uneven in spatial distribution, and the relevance between the actual distress degree and the predicted distress degree is 0.738. Thus, more maintenance should be applied to potentially higher distress sections in road operation. In addition, we are now working on more parameters, aiming to improve the assessment accuracy and to provide better suggestions on the infrastructure construction and planning.

(4) The method proposed in this paper has a wide range of application which is suitable for multidimensional and multifactors. It could predict highway distress not only in permafrost regions, but also in areas where there is dense population, infrastructure construction. In addition, problems with quantitative expressions could be converted to quantitative analysis referring the cloud model adopted here. Further research is required to address the limitations of this prediction model considering more parameters and explore the application of cloud model.

Data Availability

The detailed information of measured section data and the assessment index in concept cloud data used to support the findings of this study are included within the article. The code data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

The authors appreciate the financial support from the Postdoctoral Fund of Ministry of Education of China (2016M590915), National Key R & D Project (2017YFC0803906), Special Fund Project for Basic Scientific Research Service of the Central University (310821172002 and 310821172201), Science and Technology Project of Shanxi Transportation and Transportation Department (20416-1-11), and Shanxi Natural Science Basic Research Project (S2017-ZRJJ-MS-0603).

References

[1] H. E. Ruixia, H. Jin, M. A Futing et al., "Recent progress in studying permafrost and cold regions' environment in the Hola basin of north Greater Khingan Mountains," *Journal of Glaciology Geocryology*, vol. 37, no. 1, pp. 109–117, 2015.

[2] C. Zhang, Q. L. Gong, Y. Y. Liu et al., "Computing a ground appropriateness index for route selection in permafrost regions," *Journal of Traffic and Transportation Engineering (English Edition)*, vol. 4, no. 5, pp. 436–450, 2017.

[3] H. Ming, S. J. Wang, J. Z. Zhang et al., "Experimental study on influences of water content and temperature on mechanical properties of ice-rich frozen soil," *Journal of Hydraulic Engineering*, vol. 39, no. 10, pp. 1165–1172, 2010.

[4] W. Zhi, S. Yu, M. A. Wei et al., "Ground temperature and deformation laws of highway embankments in degenerative permafrost regions," *Chinese Journal of Rock Mechanics & Engineering*, vol. 28, no. 7, pp. 1477–1483, 2009.

[5] C. Zhang, H. N. Wang, Z. P. You et al., "Sensitivity analysis of longitudinal cracking on asphalt pavement using MEPDG in permafrost region," *Journal of Traffic and Transportation*, vol. 2, no. 1, pp. 40–47, 2015.

[6] M. T. Chai, J. M. Zhang, Y. H. Mu et al., "Probability model for subgrade hazards susceptibility of qinghai-tibet highway in

permafrost regions," *Journal of Changan University*, vol. 37, no. 4, pp. 76–83, 2017.

[7] C. Zhang, K. Yang, S. J. Wang et al., "Highway intelligent route selection method in permafrost region of qinghai-tibet plateau," *Journal of Traffic &Transportation Engineering*, vol. 16, no. 4, pp. 14–25, 2016.

[8] X. U. Anhua, "Analysis of the sensitivity of highway diseases in permafrost regions to ground temperatures and ice contents," *Journal of Glaciology & Geocryology*, vol. 36, no. 3, pp. 622–625, 2014.

[9] M. Huo, J. B. Chen, D. P. Zhu et al., "Study of early warning on roadbed diseases of Qinghai-Tibet highway in permafrost regions," *Rock & Soil Mechanics*, vol. 31, no. 1, pp. 331–336, 2010.

[10] S. J. Wang, L. Xiong, C. Zhang et al., "Fuzzy expert prediction method for highway diseases in permafrost region," *Journal of Traffic & Transportation Engineering*, vol. 16, no. 4, pp. 112–121, 2016.

[11] Q. Zhang, Y. Xiao, and Y. Xing, "The representation and processing of uncertain problems," *Procedia Engineering*, vol. 15, pp. 1958–1962, 2011.

[12] M. Effati, M. A. Rajabi, F. Samadzadegan et al., "Developing a Novel Method for Road Hazardous Segment Identification Based on Fuzzy Reasoning and GIS," *Journal of Transportation Technologies*, vol. 02, no. 01, pp. 32–40, 2012.

[13] O. Pellegrino, "Road context evaluated by means of fuzzy interval," *Cognition, Technology & Work*, vol. 13, no. 1, pp. 67–79, 2011.

[14] N.-F. Pan, "Fuzzy AHP approach for selecting the suitable bridge construction method," *Automation in Construction*, vol. 17, no. 8, pp. 958–965, 2008.

[15] G. Chai, M. M. Huang, J. Han et al., "Matching method for emergency plans of highway traffic based on fuzzy sets and rough sets," *Journal of Intelligent & Fuzzy Systems*, vol. 29, no. 6, pp. 2421–2427, 2015.

[16] D. Y. Li, L. Cy, Y. Du et al., "Artificial intelligence with uncertainty," *Journal of Software*, vol. 15, no. 11, pp. 1583–1594, 2004.

[17] S. Shi, X. Liu, K. Cao et al., "Study on cloud model of operating speed based on road alignment and sight distance," in *Proceedings of the International Conference on Transportation, Mechanical, and Electrical Engineering*, pp. 648–651, IEEE, 2012.

[18] J. C. Shen, D. U. Shu-Xin, Y. Luo et al., "Method and application research on fuzzy comprehensive evaluation based on cloud model," *Fuzzy Systems & Mathematics*, vol. 26, no. 6, pp. 115–123, 2012.

[19] S. B. Zhang, C. X. Xu, and Y. J An, "Study on the risk evaluation approach based on cloud model," *Chinese Journal of Computers*, vol. 42, no. 1, pp. 92–97+104, 2013.

[20] Q.-W. Zhang, Y.-Z. Zhang, and M. Zhong, "A cloud model based approach for multi-hierarchy fuzzy comprehensive evaluation of reservoir-induced seismic risk," *Journal of Hydraulic Engineering*, vol. 45, no. 1, pp. 87–95, 2014.

[21] X. Jia and X. U. Jinliang, "Cloud model-based seismic risk assessment of road in earthquake region," *Journal of Tongji University*, vol. 45, no. 1, pp. 1352–1358+1458, 2014.

[22] X. U. Zheng-Jie, Y. P. Zhang, and S. U. Hong-Sheng, "Application of risk assessment on fuzzy comprehensive evaluation method based on the cloud model," *Journal of Safety & Environment*, vol. 14, no. 2, pp. 69–72, 2014.

[23] G. Yang, D. W. Liu, F. J. Chu et al., "Evaluation on risk grade of tunnel collapse based on cloud model," *Journal of Safety Science & Technology*, vol. 11, no. 6, pp. 95–101, 2015.

[24] Y. Luo, L. K. Yao, and Y. Zhu, "Optimal model of scheme comparison for route selection of mountain railway based on deviation projection technology," *Railway Standard Design*, vol. 10, pp. 1–6, 2013.

[25] C. Zhang, H. Zhang, X. Y. Ma, M. Zhang, and S. W. Wang, "Driving risk assessment in work zones using cloud model," *Mathematical Problems in Engineering*, vol. 2018, Article ID 8759580, 9 pages, 2018.

[26] C. H. Dai, Y. F. Zhu, and W. R. Chen, "Adaptive Probabilities of Crossover and Mutation in Genetic Algorithms Based on Cloud Model," in *Proceedings of the IEEE*, vol. 24, pp. 710–713, 2006.

[27] Y. Yin and W. Ding, "A novel cloud model prediction for surface roughness based on multidimensional & multi-rules reasoning," *Journal of Mechanical Engineering*, vol. 52, no. 15, pp. 204–212, 2016.

[28] F. Yu, J. Qi, Y. Lai et al., "Typical embankment settlement/heave patterns of the qinghai–tibet highway in permafrost regions: Formation and evolution," *Engineering Geology*, vol. 214, pp. 147–156, 2016.

[29] S. U. Kai, J. M. Zhang, S. W. Liu et al., "Compressibility of warm and ice-rich frozen soil," *Journal of Glaciology & Geocryology*, vol. 35, no. 2, pp. 369–375, 2013.

[30] Z. T. Nan, S. X. Li, and Y. Z. Liu, "Mean annual ground temperature distribution on the Tibetan Plateau: permafrost distribution mapping and further application," *Journal of Glaciology and Geocryology*, vol. 24, no. 2, pp. 142–148, 2002.

[31] H. Chen and B. Li, "Cloud reasoning method and its application in prediction," *Computer Science*, vol. 38, no. 7, pp. 209–221+224, 2011.