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Research Article

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Comprehensive Evaluation of Loess Collapsibility of Oil and Gas Pipeline Based on Cloud Theory

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Abstract

The comprehensive evaluation of pipeline loess collapsibility risk is a necessary means to grasp the safety risks of pipelines in the collapsible loess section, and it is also one of the key scientific basis for risk prevention, control and management. The comprehensive evaluation system of cloud theory consists of quantitative and qualitative indexes, and the evaluation system has the characteristics of randomness and fuzziness. Aiming at the problem that the common qualitative and semi-quantitative evaluation methods have strong subjectivity in dealing with the uncertainty problems such as randomness and fuzziness of the system, the cloud theory, which can effectively reflect the randomness and fuzziness of things at the same time, is introduced, and the state scale cloud and index importance weight cloud of pipeline loess collapse risk are constructed by golden section method. The uncertainty cloud reasoning process of the quantitative indexes and the expert scoring method of the qualitative indexes are proposed. The comprehensive evaluation model of loess collapsibility risk of oil and gas pipeline is established and the engineering example is analysed. The comprehensive evaluation results of 10 samples to be evaluated are basically

consistent with the results of semi-quantitative method, and are consistent with the actual situation. The evaluation process softens the hard division of index boundary, simplifies the index data pre-processing, realizes the organic integration of quantitative and qualitative, integrated decision-making, and improves the accuracy, rationality and visualization of the results.

Keywords

Oil and Gas Pipeline; Loess Collapsibility; Risk Assessment; Cloud Theory; Single Condition Single Rule Cloud Generator

1. Introduction

Oil and gas pipeline geological disasters Girgin et al. refer to the evolution process of geological processes or geological environment that threaten and endanger the safety and operation environment of oil and gas pipeline engineering[1]. Influenced by differences in geology, landform, meteorology and other environmental differences along the onshore long-distance pipeline, geological disasters mainly include landslides, water damage, loess collapsibility, frost heave and thaw settlement, wind erosion sand burial, salt expansion and swelling settlement, etc. Collapsible loess disaster of pipeline is a kind of geological disaster which is easy to occur and frequently occurs, and seriously affects the safe and green operation of the pipeline project laid in the collapsible loess stratum[2,3]. The loess plateau of China, where the collapsible loess strata is connected with each other in great thickness, is the place where the national gas (oil) is transported from the west to the east and the oil (gas) from the north to the south. At present, the total mileage of pipelines in service in this area is more than 5000 km, and more than 80% of the various geological disasters suffered by these lines are related to loess collapsibility. The risk of pipeline loess collapsibility is often used to characterize the possibility and degree of damage to the line. Scientific and reasonable analysis and evaluation of its status is a necessary means to grasp the safety risk of the line, and it is also the key scientific basis for disaster monitoring, governance and management [4-6].

At present, scholars at home and abroad have done a lot of research on pipeline geological disaster risk assessment. For example, Jamshidi et al. combined qualitative and quantitative assessment, established a pipeline comprehensive risk assessment model based on fuzzy logic and relative risk score[7]. Lozoya et al. proposed a method for multi-hazard risk assessment[8]. Fayaz et al. established a heuristic hierarchical fuzzy reasoning model for determining membership functions[9]. The method is applied to the hazard assessment of oil and gas pipeline disasters. However, the research on loess collapsibility of pipeline is generally less, and more attention is paid to the numerical simulation and experimental analysis of stress and strain of suspended pipeline, as well as the type of possible water damage, influencing factors, development and Developmental mechanism and so on, such as; Chen et al. established the contribution rate model, which comprehensively analyzed and sorted the sensitivity of influencing factors of pipeline water damage[10]. Jiao et al. established a finite element model and analyzed the stress of the pipeline under different conditions[11]. It provides a reference for the safe operation of oil and gas pipeline through the landslide; Zhong et al. analyzed the hazard forms of typical geological disasters on oil and gas pipelines, and established the risk assessment system of geological disasters on oil and gas pipelines[12]. Based on the investigation of geological hazards of oil and gas pipelines. Yu et al . evaluated the risk of loess collapse hazards by using the method of fuzzy mathematical comprehensive evaluation[13]. The existing research results Zhang et al. and others have little specific evaluation for loess collapse risk, and the relevant evaluation of geological hazard comprehensive risk is weak in the selection of indicators, and the guidance for risk prevention and control of a specific type of pipeline geological hazard is poor[14-16]. At the same time, the evaluation methods used in data acquisition and processing are cumbersome and time-consuming, and the processing of quantitative continuous and qualitative discrete data fusion and evaluation is subjective. It may affect the consistency between the evaluation results and the actual situation.

Loess collapse risk of pipeline is a system which is unified by the pipeline vulnerability and the pipeline vulnerability, affected by many factors, its evaluation organization has the characteristics of multi-attribute, multi-level, multi-index, and both quantitative and qualitative indicators. It is the key to the success of the evaluation and the accuracy of the results that how to make these uncertain indexes with randomness, fuzziness, different magnitudes and dimensions merge organically and participate in the risk assessment. Cloud theory. Li et al. is a powerful mathematical tool used to describe the transformation of uncertainty relationship between qualitative and quantitative, which integrates the advantages of fuzzy mathematics and probability statistics, and can effectively reflect the randomness and fuzziness of things attributes at the same time, and constitute the mutual mapping between qualitative and quantitative, making the transformation between qualitative concepts and quantitative values clear, concrete and controllable17. In the past 20 years, the theory and method have been widely used in system evaluation and control, data mining, group decision-making and other fields[18,19]. In this paper, the loess collapsibility of oil and gas pipeline is taken as the research object, and a comprehensive evaluation model of loess collapsibility of oil and gas pipeline based on cloud theory is proposed. The pre-treatment process of quantitative data is simplified, and the cloud method and results of qualitative score are optimized. The cloud results are compared with the results of semi-quantitative method to test the validity and rationality of the model, which provides a reference for the study of geological disasters of oil-gas pipeline.

2. Cloud Theory

2.1 Basic Concept

Given quantitative universe of discourse U, X ∈ X, U, T are qualitative concepts in U space. If the membership degree CT (X) ∈ [0,1] of quantitative numerical value X (X ∈ X) to T is a kind of random number with stable tendency, as in (1), then the distribution of the mapping of concept T from universe U to interval [0,1] in the number domain space is called cloud "Fu et al(2017)", and each X is a cloud droplet.

$$C_T(x): \forall x \in X \left(X \subseteq U \right) x \to C_T(x) \qquad (1)$$

In general, the expectation Ex, entropy En and excess entropy He are used to reflect the whole "skeleton" of clouds, that is, the numerical characteristics of clouds, abbreviated as C (Ex, En, He). Where Ex is the representative value of the qualitative concept and the central value of the universe; En is the range of cloud droplet distribution that can be accepted by the qualitative concept in the universe space (that is, the fuzzy degree of the concept); Excess entropy He is the entropy of En, which is determined by the randomness and fuzziness of entropy, and reflects the aggregation degree of cloud droplets in the universe.

2.2 Basic Algorithm

One-dimensional normal cloud generator is a powerful tool for the conversion between qualitative concepts and quantitative data, which has universal applicability[20], including forward cloud, reverse cloud, X-conditional cloud and Y-conditional cloud.

1. Forward cloud algorithm:

(1) generating a normal random number taking En as expectation and He as standard deviation, wherein norm is a function generating random numbers which obey normal distribution; $y_i = norm\left(En, He^2\right)$

(2) generating a normal random number with Ex as an expected value and Y^2 as a variance; $x_i = norm\left(Ex, y^2\right)$

(3) Calculating the certainty of random number

$$\mu_i = e^{-(x_i - Ex)2/(2y_i^2)} \qquad (2)$$

(4) output a cloud droplet; (x_i, μ_i)

And (5) repeating the steps (1) to (4) until the required N cloud droplets are generated, and the N cloud droplets form a cloud to realize the uncertainty cloudification of the concept.

2. Reverse cloud algorithm:

(1) Sample mean calculated from cloud droplets Xi (cloud expectation)

$$Ex = \overline{X} = \frac{1}{n}\sum_{i=1}^{n} x_i \qquad (3)$$

(2) Calculating the Entropy of Cloud Droplet

$$En = \sqrt{\frac{\pi}{2}} \times \frac{1}{n}\sum_{i=1}^{n}\left|x_i - Ex\right| \qquad (4)$$

(3) Calculating the Excess Entropy of Cloud Droplet

$$He = \sqrt{\left|\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{X})^2 - En^2\right|} \qquad (5)$$

3. X-conditional cloud algorithm:

(1) the numerical characteristics (Ex, En, He) and the quantized value x of the concept are known, and a normal random number En' is generated by taking En as an expected value and He as a mean square deviation;

(2) Calculate the degree of certainty y that the quantitative value X belongs to a certain concept, namely:

$$y = e^{\frac{-(x-Ex)^2}{2(En')^2}} \qquad (6)$$

4. Y-conditional cloud algorithm:

(1) Given the numerical characteristics (Ex, En, He) of the concept and the certainty y, y ∈ [0,1], a normal random number En′ is generated with En as the expected value and He as the mean square deviation;

(2) calculating a quantitative value X satisfying the certainty y, namely:

$$x = Ex \pm En' \times \sqrt{-2\ln y} \qquad (7)$$

2.3 Four Arithmetic Operations

For two clouds C_1 (Ex_1, En_1, He_1) and C_2 (Ex_1, En_1, He_1) in the same domain, there is an algorithm in Table 1 Can be generalize to n clouds.

Table 1 The algorithm of cloud theory

Rule	*Ex*	*En*	*He*
+	$Ex_1 + Ex_2$	$\sqrt{En_1^2 + En_2^2}$	$\sqrt{He_1^2 + He_2^2}$
-	$Ex_1 - Ex_2$	$\sqrt{En_1^2 + En_2^2}$	$\sqrt{He_1^2 + He_2^2}$
×	$Ex_1 \times Ex_2$	$\left|Ex_1Ex_2\right|\sqrt{\left(\frac{En_1}{Ex_1}\right)^2 + \left(\frac{En_2}{Ex_2}\right)^2}$	$\left|Ex_1Ex_2\right|\sqrt{\left(\frac{He_1}{Ex_1}\right)^2 + \left(\frac{He_2}{Ex_2}\right)^2}$
÷	$Ex_1 \div Ex_2$	$\left|\frac{Ex_1}{Ex_2}\right|\sqrt{\left(\frac{En_1}{Ex_1}\right)^2 + \left(\frac{En_2}{Ex_2}\right)^2}$	$\left|\frac{Ex_1}{Ex_2}\right|\sqrt{\left(\frac{He_1}{Ex_1}\right)^2 + \left(\frac{He_2}{Ex_2}\right)^2}$

3 . Model Construction of Collapse Risk Assessment of Pipeline Loess Based on Cloud Theory

3.1 Basic ideas and evaluation process

If the language description of the collapsible dangerous state of the pipeline loess can be correspondingly mapped into a cloud with a specific distribution range and a specific law, and the certainty that the evaluation index belongs to each state also obeys the cloud distribution, the evaluation idea is as follows: firstly, a comment standard set and a corresponding cloud digital characteristic C_{scale} are determined, and the scale cloud is generated by a forward cloud generator; Secondly, the quantitative indicators and qualitative indicators of the samples to be evaluated are transformed according to the cloud reasoning process to realize their own cloud digital feature $C_{evaluation}$. And calculate that C_{weight} of the digital feature of the weight cloud through the comment set of the relative importance of the expert group to the index; Then the clouds of different levels and different indexes are fused through the weight cloud by using the cloud four arithmetic operation, and the result cloud TC_{result} of the sample is jumped to step by step; And finally, visually analyse that shape similarity and the closeness between the result cloud and the scale cloud, and determining the dangerous state of the evaluation sample. The evaluation process is shown in Fig 1, and the derivation operation and the driving of the cloud generator are realized by MATLAB software.

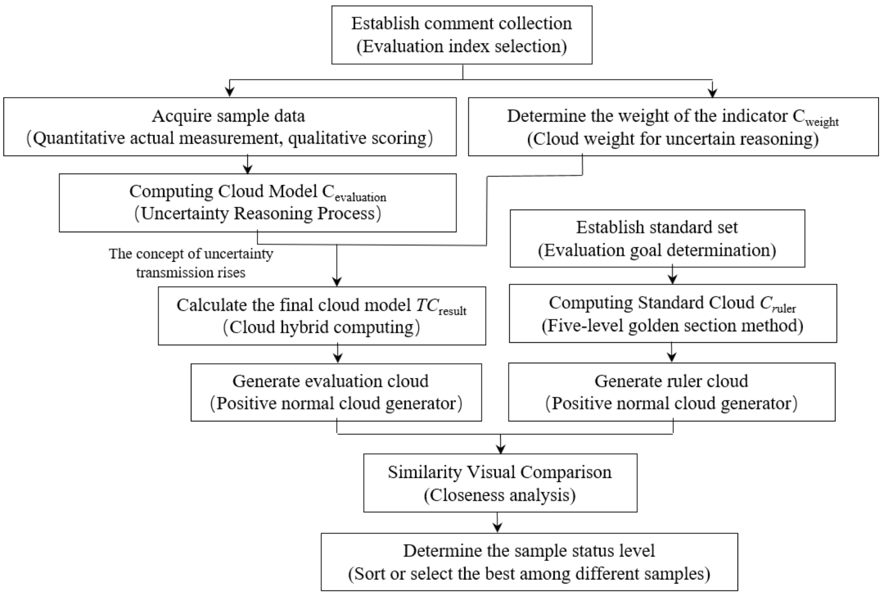

Figure 1. Risk assessment process based on cloud theory

3.2 Evaluation Index System and Cloud Transformation

3.2.1 Establish rating indicators and their rating standard

The loess collapse disaster of oil and gas pipeline is a geological disaster system, which takes the loess collapse (including historical and potential) as the disaster body and the pipeline engineering itself as the bearing body. Hazard-causing body is evolved and formed under certain engineering geological conditions (topography, tectonic activity, hydrogeology, strata lithology, etc.) And induced conditions (irrigation, precipitation, human activities, etc.), and a series of prevention and control measures in pipeline maintenance (excavation, backfilling and tamping, replacement, hydraulic measures, etc. The easily-occurring factors together constitute the risk assessment; The hazard-affected body is the pipeline engineering body including the steel pipeline, the anticorrosive coating, the station valve chamber and other facilities. The pipeline laying (location, mode, buried depth and so on) in the loess influence scope, as well as the pipe trench soil improvement and tamping, hydraulic protection and so on directly affect the bearing mode and bearing capacity of the pipeline. These complex factors together constitute the vulnerability factors of risk assessment.

Starting from the principles of systematicness, comprehensiveness, hierarchy and practicability of evaluation index construction, referring to previous achievements and combining with work practice, this paper optimizes and proposes a multi-level comprehensive evaluation index system consisting of 4 first-level indexes and 16 second-level indexes, as shown in Fig 2. Among the 16 secondary indicators, there are 8 quantitative indicators and 8 qualitative indicators, and these indicators are different in dimension, magnitude and attribute, so how to integrate these complex indicators organically and participate in model operation is the focus of evaluation research.

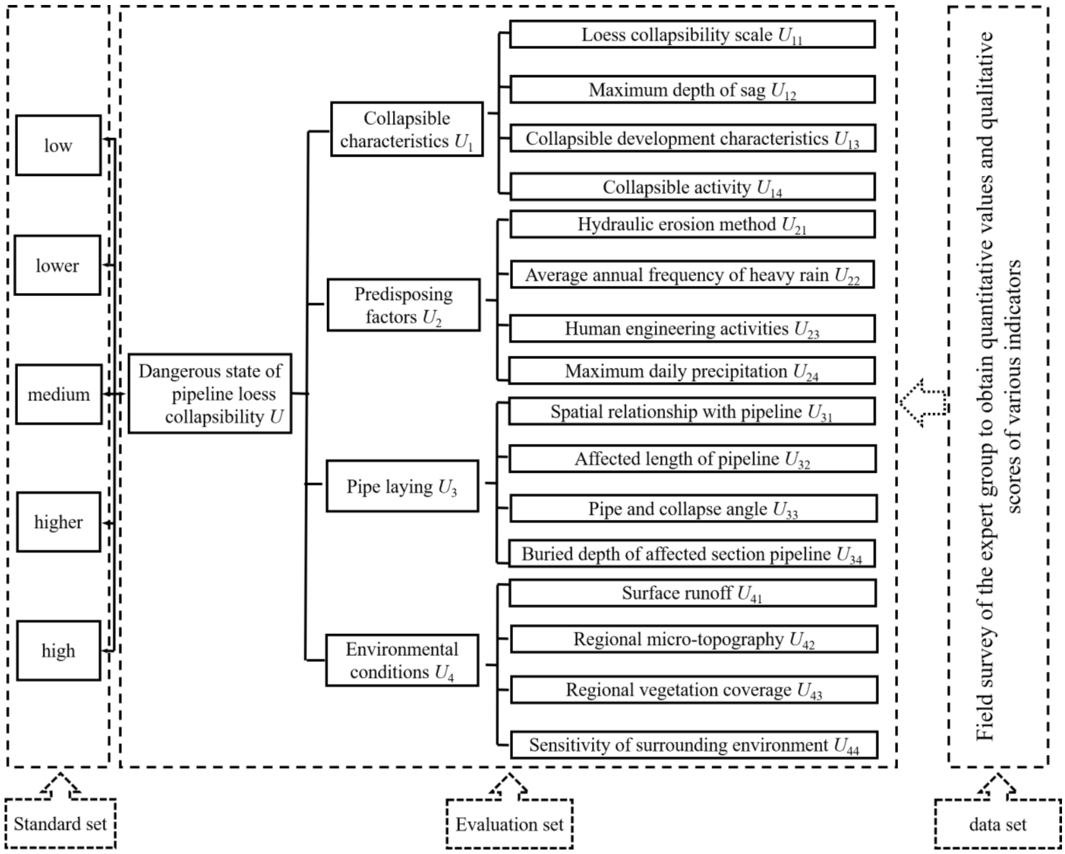

Figure 2. Diagram of the organization system of pipeline loess collapse risk assessment

In order to correspond to the results of the standard recommendation method, this paper uses five grades of comments, namely high, higher, medium, lower and low, to scale the state of loess collapse hazard of pipeline, as shown in Fig 2. And use the golden ratio method to divide it into 5 grades on the domain [0,1], the cloud number characteristics and distribution of each grade language are shown in Table 2 and Fig 3;Similarly, the results of the 5-grade rating scale for the secondary indicators are listed in Table 3.The 8 quantitative indexes in Table 3 are approximately divided by bilateral constraints; Eight qualitative indicators are graded according to experts' on-site scoring, and then cloud aggregation is carried out according to the cloud parameters of the corresponding levels in Table 2.

Table 2. Evaluation criteria and numerical characteristics of weight cloud

Numeric Feature	Scale grade C scale/standard				
	Low (Not important)	Lower (Less important)	Medium (General)	Higher (More important)	High (Very important)
Ex	0	0.309	0.5	0.691	1.0

En	0.1031	0.0640	0.0390	0.0640	0.1031
He	0.0130	0.0080	0.0050	0.0080	0.0130

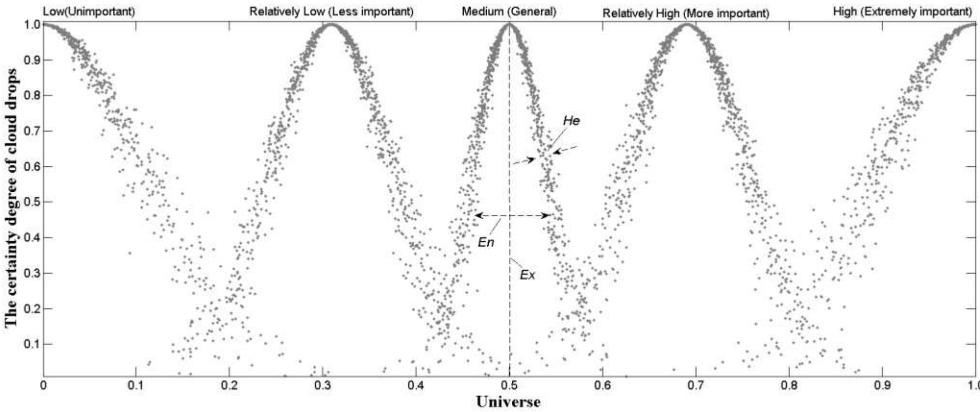

Figure 3. Cloud chart of comment criteria and weight

Table 3. Standard classification of evaluation index grades

	Index Factor	Low	Lower	Medium	Higher	High
Collapsible characteristic U_1	Collapse influence area U_{11}	0 ~ 10 (5.000,4.246,0.010)	10 ~ 20 (15.000,4.246,0.010)	20 ~ 40 (30.000,8.493,0.010)	40 ~ 80 (60.000,16.985,0.010)	80 ~ 100 (90.000,8.493,0.010)
	Maximum collapse depth U_{12}	0 ~ 0.4 (0.200,0.170,0.010)	0.4 ~ 0.7 (0.550,0.127,0.010)	0.7 ~ 1.0 (0.850,0.127,0.010)	1.0 ~ 1.5 (1.250,0.212,0.010)	1.5 ~ 3.0 (2.250,0.637,0.010)
	Characteristics of collapsible development U_{13}	0 ~ 0.1 (0.050,0.042,0.010)	0.1 ~ 0.3 (0.200,0.085,0.010)	0.3 ~ 0.5 (0.400,0.085,0.010)	0.5 ~ 0.7 (0.600,0.085,0.010)	0.7 ~ 1 (0.850,0.127,0.010)
	Collapse activity U_{14}	0 ~ 0.1 (0.050,0.042,0.010)	0.1 ~ 0.3 (0.200,0.085,0.010)	0.3 ~ 0.5 (0.400,0.085,0.010)	0.5 ~ 0.7 (0.600,0.085,0.010)	0.7 ~ 1 (0.850,0.127,0.010)
Inducing factor U_2	Water erosion mode U_{21}	0 ~ 0.1 (0.050,0.042,0.010)	0.1 ~ 0.3 (0.200,0.085,0.010)	0.3 ~ 0.5 (0.400,0.085,0.010)	0.5 ~ 0.7 (0.600,0.085,0.010)	0.7 ~ 1 (0.850,0.127,0.010)
	Rainstorm frequency U_{22}	0 ~ 3 (1.500,1.274,0.010)	3 ~ 6 (4.500,1.274,0.010)	6 ~ 9 (7.500,1.274,0.010)	9 ~ 12 (10.500,1.274,0.010)	12 ~ 15 (13.500,1.274,0.010)
	Human Engineering Activity U_{23}	0 ~ 0.1 (0.050,0.042,0.010)	0.1 ~ 0.3 (0.200,0.085,0.010)	0.3 ~ 0.5 (0.400,0.085,0.010)	0.5 ~ 0.7 (0.600,0.085,0.010)	0.7 ~ 1 (0.850,0.127,0.010)
	Multi-year maximum daily rainfall U_{24}	0 ~ 10 (5.000,4.246,0.010)	10 ~ 30 (20.000,8.493,0.010)	30 ~ 50 (40.000,8.493,0.010)	50 ~ 70 (60.000,8.493,0.010)	70 ~ 100 (85.000,12.739,0.010)
Piping U_3	Affected length of pipe U_{31}	0 ~ 5 (2.500,2.123,0.010)	5 ~ 10 (7.500,2.123,0.010)	10 ~ 20 (15.000,4.246,0.010)	20 ~ 40 (30.000,8.493,0.010)	40 ~ 80 (60.000,16.985,0.010)
	Spatial Relationship to Piping U_{32}	0 ~ 0.1 (0.050,0.042,0.010)	0.1 ~ 0.3 (0.200,0.085,0.010)	0.3 ~ 0.5 (0.400,0.085,0.010)	0.5 ~ 0.7 (0.600,0.085,0.010)	0.7 ~ 1 (0.850,0.127,0.010)

	Pipe Collapse Angle U_{33}	0 ~ 20 (10.000,8.493 ,0.010)	20 ~ 40 (30.000,8.493 ,0.010)	40 ~ 60 (50.000,8.493 ,0.010)	60 ~ 80 (70.000,8.493, 0.010)	80 ~ 90 (85.000,4.246, 0.010)
	Buried depth of pipeline U_{34}	0 ~ 0.8 (0.400,0.340, 0.010)	0.8 ~ 1.4 (1.100,0.255, 0.010)	1.4 ~ 2.0 (1.700,0.255, 0.010)	2.0 ~ 2.5 (2.250,0.212,0 .010)	2.5 ~ 6.0 (4.250,1.486,0 .010)
Ambient conditions U_4	Surface Runoff U_{41}	0 ~ 0.1 (0.050,0.042, 0.010)	0.1 ~ 0.3 (0.200,0.085, 0.010)	0.3 ~ 0.5 (0.400,0.085, 0.010)	0.5 ~ 0.7 (0.600,0.085,0 .010)	0.7 ~ 1 (0.850,0.127,0 .010)
	Microgeomorphology U_{42}	0 ~ 1 (0.500,0.425, 0.010)	1 ~ 3 (2.000,0.849, 0.010)	3 ~ 5 (4.000,0.849, 0.010)	5 ~ 7 (6.000,0.849,0 .010)	7 ~ 15 (11.000,3.397, 0.010)
	Vegetation coverage U_{43}	0 ~ 0.1 (0.050,0.042, 0.010)	0.1 ~ 0.3 (0.200,0.085, 0.010)	0.3 ~ 0.5 (0.400,0.085, 0.010)	0.5 ~ 0.7 (0.600,0.085,0 .010)	0.7 ~ 1 (0.850,0.127,0 .010)
	Environmental Sensitivity U_{44}	0 ~ 1 (0.500,0.425, 0.010)	1 ~ 3 (2.000,0.849, 0.010)	3 ~ 5 (4.000,0.849, 0.010)	5 ~ 7 (6.000,0.849,0 .010)	7 ~ 15 (11.000,3.397, 0.010)

3.2.2Uncertainty Cloud Transformation of Two Types of Comment Indicator

(1) Quantitative index cloudification

For the eight quantitative indicators U_{11}, U_{12}, U_{22}, U_{24}, U_{31}, U_{33}, U_{34} and U_{43} in Table 3, if there are comment levels with the sum of the upper and lower boundary values, the normal cloud digital characteristics can be expressed as:

x_{ij}^1 x_{ij}^2

$$Ex_{ij} = \frac{\left|x_{ij}^1 + x_{ij}^2\right|}{2} \tag{8}$$

Because the boundary value is based on the existing research and expert advice, according to certain standards and experience, the index of continuous quantitative description is artificially hard divided, but in essence, it has certain fuzziness. Therefore, it is necessary to soften the boundary so that the membership degrees of the boundary values to the adjacent two state levels are equal. $\exp\left[-\frac{\left(x_{ij}^1 - x_{ij}^2\right)^2}{8\left(En_{ij}\right)^2}\right] \approx 0.5$

$$En_{ij} = \frac{\left|x_{ij}^1 - x_{ij}^2\right|}{2.355} \tag{9}$$

From the cloud atomization ambiguity CD = 3 He_{ij}/En, He_{ij} generally takes the number between 0 ~ En/3 to satisfy the Gaussian cloud distribution. In general, the larger the He_{ij} is, the thicker the normal cloud is, and vice versa, the thinner it is (Fig 3).

The grade standardized cloud parameters of the eight quantitative indexes are determined by the method of (8), (4) and multiple tests, see Table 3. Then, the cloud conversion process of the measured value xa of the quantitative index is realized by constructing a single condition and single rule cloud generator[21]. The single condition and single rule cloud generator is shown in Fig 4. According to the formula (6) and (6), a normal random number En_a ′ is generated first with Ena as the expected value and Hea as the mean square error, and the certainty y = exp [-$(x_A-Ex_A)^2/2(En_A')^2$]; Then, a normal random number En_B 'is generated with En_B as the expected value and He_B as the mean square error. If the leading edge $x_A \leq Ex_A$ or $x_A > Ex_A$ is activated, the trailing edge $x_B = Ex_B-En_B' \times (-2\ln y)^{0.5}$ or $x_B = Ex_B + En_B' \times (-2\ln y)^{0.5}$ is also activated. The outputs of X-conditional cloud and Y-conditional cloud in the regular cloud generator are obtained by random process, so for the same input, the output values obtained by the cloud reasoning method each time have uncertain characteristics, but all the output values fluctuate up and down within a reasonable range, and have a stable tendency on the whole and follow Gaussian distribution[22]. On the one hand, it softens the artificial hard division of grade boundary; On the other hand, different dimensions and orders of x_A are calculated by the X、Y-conditional cloud generator, which realizes the dimensionless and normalization of data, thus simplifying the pre-processing program. This method ensures the effective transmission and inheritance of uncertainty in the evaluation process, and is obviously superior to other quantitative evaluation theories.

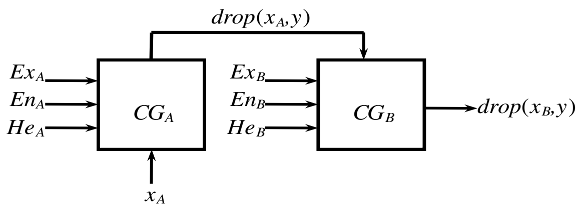

Figure 4. Single condition and single rule generator

(2) Qualitative index cloudification

For the eight qualitative indicators U_{13}, U_{14}, U_{21}, U_{23}, U_{32}, U_{41}, U_{42} and U_{44} in Table 3, it is actually impossible to use quantitative values to accurately characterize the attributes, according to the average value method after experts scoring, 10 experts were invited to conduct on-site investigation, and the eight qualitative indicators were scored and evaluated one by one. After obtaining the corresponding values, they are processed according to the quantitative index cloud and participate in the evaluation system.

3.3 Weighting of evaluation index system

The weight not only reflects the relative importance and contribution rate of each factor at all levels of the evaluation system to the target, but also is the key "hub" for the continuous transmission and leap of cloud theory. The evaluation indexes of loess collapsibility of oil and gas pipeline are mostly qualitative indexes, so it is difficult to get the weight value of each index through the objective weighting process such as entropy method, variation coefficient method, grey correlation method and so on; At the same time, in order to avoid the shortcomings of strong human arbitrariness in subjective empowerment such as AHP. In this paper, experts in conjunction with the pipeline company's main technical personnel to form an empowerment expert group, the relative importance of the indicators to participate in the evaluation language to describe the unimportant, less important, general, more important and extremely important five-level statue, based on the golden section rate driving method of index weight in the universe [0,1] for five-level scale empowerment, the corresponding cloud digital characteristics and cloud see Table 2 and Fig 3. This not only conforms to the law of people's scientific understanding of things, At the same time, the qualitative language is transformed into weight value for operation, which fully reflects the fuzziness, randomness and complexity of the evaluation process.

3.4 Comprehensive Judgement

Based on the evaluation index system and cloud weight determination process of text cloud transformation, according to the four operational rules of cloud in Table 1, the bottom evaluation results in the comment set are transferred to the upper layer by using the weighted average method, and then analogized to the target layer in turn, that is, the risk result cloud of the evaluation object, which can be used for visibility analysis and decision-making with the scale cloud.

$$TC = \sum_{i=1}^{n} \omega_i C_i / \sum_{i=1}^{n} \omega_i \tag{10}$$

In the formula, TC is the comprehensive cloud of the evaluation target, C_i and ω_i are the i index cloud and weight cloud respectively, and $\omega_i C_i$ is the multiplication of two clouds. This process not only conveys uncertainty reasoning, but also makes the concept of cloud theory constantly jump.

4. Engineering Illustration Analysis

Nearly 40% of the mileage of Lanzhou-Chengdu crude oil pipeline, a representative project of China's oil transportation from north to south, is laid in Longxi basin area, which is a typical collapsible loess area. This area is located in the southwest of the Loess Plateau, belonging to the humid climate area of the northern subtropical zone, with large temperature difference and small rainfall, annual average temperature of 4 ~ 14 ℃, annual precipitation from July to September accounting for 50 ~ 70% of the whole year, and is also a period of frequent geological disasters. Most of the area is agricultural cultivated land, the main vegetation is mainly crops and cash crops, and the vegetation coverage is generally low.

4.1 Data sources

According to the survey data of geological disasters in 2020, there are 109 geological disasters in Long-xi basin section of Lanzhou-Chengdu pipeline, of which 54 are loess collapse, accounting for 49. 54% of the total number of disasters, showing that loess collapse hazards are densely developed, prone to occur and high incidence characteristics. In this paper, 10 samples are randomly selected from 54 collapsible loess pipelines as the example samples for risk assessment. The specific locations are K7 + 110, K27 + 780, K32 + 720, K43 + 460, K43 + 920, K47 + 940, K57 + 900, K87 + 440, K168 + 850 and K257 +733 (numbered LC 1 to LC 10 in turn). The basic characteristics of loess collapsibility hazards are shown in Table 4. The initial data of 8 quantitative indicators of 10 samples to be evaluated are obtained from the existing meteorological, geographical and geological data by consulting and on-site measurement, and the results are listed in Table 5;Qualitative indicators invite experts to conduct on-site evaluation, record the score values of each expert for different indicators of loess collapse, and calculate the average value as the evaluation data .In order to simplify the length, Table 6 only lists the scores of 10 experts in U_{14} of the sample indicators to be evaluated, and the parameters of the remaining 7 indicators can be obtained in the same way.

Table 4. Environmental conditions and loess collapsibility development of the samples to be evaluated

No.	Collapsible area (m2)	Collapse Shape	Collapsible depth (m)	Vegetation Situation	Catchment Condition	Microgeomorphology	Spatial relationship with pipes	Type of water damage	Influence length (m)	Harmful degree of pipelines	Buried depth of pipeline (m)	Human Engineering Activities
LC 1	70	Stripe	1.3	Apple	Dispersion	Flat Ground	Oblique Cross	Irrigation	40	Low	1.8	More
LC 2	44	Multilateral	1.9	Lily	Dispersion	Flat Bottom	Oblique Cross	Rainfall	10	Lower	1.4	More
LC 3	33	Stripe	1.2	Corn	Catchment	Flat Ground	Vertical	Rainfall	3	Lower	1.2	Moderate
LC 4	6	Stripe	2.5	Weed	Catchment	Flat Ground	Oblique Cross	Rainfall	12	Medium	1.5	More
LC 5	45	Stripe	0.4	Corn	Dispersion	Flat Ground	Oblique Cross	Irrigation	30	Lower	1.5	Less
LC 6	50	Semicircle	1.7	Weed	Catchment	Scarp	Oblique Cross	Rainfall	10	High	2.2	More
LC 7	32	Ellipse	1.5	Wasteland	Dispersion	Flat Ground	Oblique Cross	Irrigation	10	Lower	1.4	More
LC 8	50	Stripe	2.0	Potato	Catchment	Flat Ground	Oblique Cross	Irrigation	40	Medium	1.2	More
LC 9	6.3	Circle	2.5	Potato	Catchment	Slope	Oblique Cross	Rainfall	5	High	3.2	More
LC 10	14	Multila	0.2	Road	Catch	Slope	Obliqu	Rainf	5	Lowe	1.6	More

teral	ment	e Cross	all	r

Table 5. Initial data table of eight quantitative indicators

Indicator Name	LC 1	LC 2	LC 3	LC 4	LC 5	LC 6	LC 7	LC 8	LC 9	LC 10
Collapse influence area U_{11} (m2)	70	44	33	6	45	50	32	50	6.3	14
Maximum collapsible depth U_{12} (m)	1.3	1.9	1.2	2.5	0.4	1.7	1.5	2.0	2.5	0.2
Rainstorm frequency/year U_{22}	10	9	9	10	10	13	9	10	8	13
Maximum average daily rainfall for many years U_{24} (mm)	75	72	75	80	70	80	80	72	70	80
Duct influence length U_{31} (m)	40	10	3	12	30	10	10	40	5	5
Pipe and Collapse Angle U_{33} (°)	12	16	86	12	81	72	21	15	45	72
Buried depth of pipeline U_{34} (m)	1.8	1.4	1.2	1.5	1.5	2.2	1.4	1.2	3.2	1.6
Vegetation coverage U_{43} (%)	0.95	0.43	0.12	0.33	0.47	0.18	0.06	0.34	0.21	0.02

Table 6. Summary of expert scores for qualitative indicator U14

Expert Serial Number	LC 1	LC 2	LC 3	LC 4	LC 5	LC 6	LC 7	LC 8	LC 9	LC 10
1	0.45	0.88	0.83	0.42	0.23	0.84	0.92	0.56	0.21	0.54
2	0.84	0.69	0.45	0.65	0.31	0.77	0.66	0.35	0.35	0.53
3	0.62	0.53	0.68	0.72	0.33	0.76	0.74	0.32	0.45	0.41
4	0.65	0.67	0.77	0.42	0.62	0.66	0.68	0.42	0.48	0.35
5	0.77	0.78	0.46	0.33	0.54	0.68	0.77	0.57	0.38	0.32
6	0.60	0.62	0.70	0.55	0.45	0.72	0.72	0.38	0.46	0.28
7	0.64	0.89	0.68	0.63	0.67	0.83	0.62	0.39	0.28	0.26
8	0.55	0.92	0.72	0.65	0.46	0.91	0.63	0.46	0.34	0.64
9	0.80	0.95	0.66	0.64	0.34	0.66	0.88	0.45	0.22	0.54
10	0.82	0.82	0.73	0.51	0.24	0.82	0.69	0.33	0.25	0.24
Average value	0.67	0.78	0.66	0.55	0.42	0.77	0.73	0.42	0.34	0.41

4.2 Calculation of result

First, the cloud digital eigenvalues of 16 indexes of No.1 to No.10 loess collapsibility are calculated in turn by using the single-condition and single-rule cloud reasoning (MATLAB generator circulates for 1000 times) algorithm, as listed in Table 7. Then, the algorithm in Table 1 is used to evaluate the index cloud C and the weight cloud C in Table 7. According to the formula

(10), the second-level index U_{ij} is uploaded to the first-level index U_i, and then transferred to the target layer U of the comment set, so as to obtain the result cloud TC results of each loess collapsibility hazard, which are TC1 (0.6210, 0.0670,0.0073),TC2(0.6552,0.0679,0.0075),TC3(0.5646,0.0572,0.0068),TC4(0.5733,0.0665,0.0067),TC5(0.5394,0.0568,0.0060),TC6(0.7517,0.0797,0.0085),TC7(0.5648,0.0589,0.0065),TC8(0.6473,0.0679,0.0076),TC9(0.5220,0.0539,0.0067),TC10(0.4708,0.0551,0.0058). After that, the TC results are generated according to the forward cloud algorithm steps, as shown in fig 5, and the pipeline loess collapse risk cloud is superimposed with the pre-determined scale cloud.

Table 7. Cloud parameters of evaluation indexes and weights of samples to be evaluated

Evaluation Index and Cloud Weight		Engineering Samples and Cloud Eigenvalues				
		LC 1	LC 2	LC 3	LC 4	LC 5
Collapsible characteristic U_1 (1,0.1031,0.013)	Collapse influence area U_{11} (1,0.1031,0.013)	(0.7286,0.0046,0.0007)	(0.5648,0.0086,0.0003)	(0.5138,0.0018,0.0002)	(0.0243,0.0031,0.0004)	(0.6345,0.0067,0.0008)
	Maximum collapse depth U_{12} (1,0.1031,0.013)	(0.7061,0.002,0.0002)	(0.9429,0.0072,0.0007)	(0.6758,0.0019,0.0001)	(1.0405,0.0051,0.0009)	(0.233,0.0106,0.0006)
	Characteristics of collapsible development U_{13} (0.5,0.309,0.005)	(0.7446,0.0094,0.001)	(0.9428,0.0086,0.0009)	(0.737,0.008,0.0016)	(0.6529,0.0064,0.0011)	(0.5093,0.0016,0.0002)
	Collapse activity U_{14} (0.309,0.064,0.008)	(0.5235,0.0041,0.001)	(0.6757,0.0025,0.0002)	(0.3242,0.0026,0.0003)	(0.7142,0.0041,0.0007)	(0.5189,0.0034,0.0001)
Inducing factor U_2 (0.691,0.064,0.008)	Water erosion mode U_{21} (0.5,0.309,0.005)	(0.691,0.064,0.0001)	(0.7139,0.0041,0.0009)	(0.3696,0.0104,0.0009)	(0.5326,0.0058,0.0003)	(0.3695,0.0099,0.0024)
	Rainstorm frequency U_{22} (0.691,0.064,0.008)	(0.6658,0.003,0.0003)	(0.5459,0.0058,0.0005)	(0.5461,0.0062,0.0004)	(0.6658,0.0031,0.0001)	(0.6661,0.0033,0.0005)
	Human Engineering Activity U_{23} (0.691,0.064,0.008)	(0.7292,0.0063,0.0017)	(0.6756,0.0027,0.0005)	(0.486,0.0024,0.0003)	(0.9592,0.0061,0.0004)	(0.3776,0.0124,0.0011)
	Maximum daily rainfall U_{24} (1,0.1031,0.013)	(0.9185,0.0101,0.0014)	(0.7814,0.0106,0.0005)	(0.9196,0.0101,0.0004)	(0.9593,0.0051,0.0005)	(0.7664,0.0093,0.0006)
Piping U_3 (0.5,0.309,0.005)	Duct Influence Length U_{31} (0.691,0.064,0.008	(0.7662,0.0097,0.0003)	(0.384,0.0094,0.0015)	(0.0242,0.0031,0.0002)	(0.4725,0.0036,0.0002)	(0.691,0.0001,0.0001)

	)					
	Spatial Relationship to Piping U_{32} (1,0.1031,0.013)	(0.3469,0.0064,0.0009)	(0.9589,0.0062,0.0004)	(0.9755,0.0035,0.0005)	(0.3397,0.0051,0.0005)	(0.6604,0.0051,0.0005)
	Pipe Collapse Angle U_{33} (0.309,0.064,0.008)	(0.0242,0.003,0.0004)	(0.0727,0.0087,0.001)	(1.0244,0.0031,0.0004)	(0.0244,0.003,0.0003)	(0.9029,0.0121,0.0022)
	Buried depth of pipeline U_{34} (0.691,0.064,0.008)	(0.5152,0.0021,0.0003)	(0.3847,0.0099,0.0008)	(0.3342,0.0032,0.0002)	(0.4694,0.0042,0.0006)	(0.4692,0.0043,0.0003)
Ambient conditions U_4 (0.309,0.064,0.008)	Surface Runoff U_{41} (0.691,0.064,0.008)	(0.4628,0.0065,0.001)	(0.6604,0.0055,0.0012)	(0.5138,0.0024,0.0002)	(0.3243,0.0027,0.0001)	(0.2863,0.0037,0.0009)
	Microgeomorphology U_{42} (0.309,0.064,0.008)	(0.039,0.0048,0.0004)	(0.3467,0.0046,0.0004)	(0.4723,0.0035,0.0005)	(0.6759,0.0019,0.0002)	(0.3544,0.0059,0.0002)
	Vegetation coverage U_{43} (0.309,0.064,0.008)	(1.0819,0.0118,0.0013)	(0.514,0.0024,0.0005)	(0.1825,0.0553,0.026)	(0.4675,0.0057,0.0006)	(0.5327,0.0057,0.001)
	Environmental Sensitivity U_{44} (0.5,0.309,0.005)	(0.4771,0.0031,0.0002)	(0.4863,0.0017,0.0002)	(0.4815,0.0024,0.0004)	(0.9331,0.0084,0.0006)	(0.7514,0.0078,0.001)

Evaluation Index and Cloud Weight		Engineering Samples and Cloud Eigenvalues				
		LC 6	LC 7	LC 8	LC 9	LC 10
Collapsible characteristic U_1 (1,0.1031,0.013)	Collapse influence area U_{11} (1,0.1031,0.013)	(0.6532,0.0048,0.0006)	(0.5092,0.0011,0.0001)	(0.6533,0.0047,0.0008)	(0.0315,0.0037,0.0004)	(0.2939,0.0018,0.0002)
	Maximum collapse depth U_{12} (1,0.1031,0.013)	(0.8267,0.0177,0.0022)	(0.7663,0.01,0.0012)	(0.9595,0.0051,0.0008)	(1.0405,0.0053,0.0004)	(0,0.1031,0.013)
	Characteristics of collapsible development U_{13} (0.5,0.309,0.005)	(0.9344,0.0094,0.0015)	(0.9019,0.0152,0.0017)	(0.5092,0.0017,0.0005)	(0.4722,0.005,0.0007)	(0.5046,0.0008,0.0001)
	Status of disaster activities U_{14} (0.309,0.064,0.008)	(0.9019,0.0147,0.0005)	(0.3779,0.0116,0.0017)	(0.7369,0.0084,0.0014)	(0.7141,0.0041,0.0001)	(0.2861,0.0039,0.0006)
Inducing factor U_2 (0.691,0.064,0.008)	Water erosion mode U_{21} (0.5,0.309,0.005)	(0.9021,0.0146,0.0014)	(0.332,0.0041,0.0007)	(0.4674,0.0058,0.0015)	(0.3166,0.0013,0.0002)	(0.4675,0.0056,0.0005)

	Rainstorm frequency U_{22} (0.691,0.064,0.008)	(0.9597,0.0052,0.0009)	(0.5461,0.0058,0.0012)	(0.6657,0.0032,0.0005)	(0.5153,0.0019,0.0001)	(0.9595,0.0051,0.0003)
	Human Engineering Activity U_{23} (0.691,0.064,0.008)	(0.7292,0.0066,0.0004)	(0.7373,0.0084,0.002)	(0.6757,0.0025,0.0005)	(0.9022,0.015,0.0016)	(0.7521,0.0112,0.0021)
	Maximum daily rainfall U_{24} (1,0.1031,0.013)	(0.9597,0.0053,0.0009)	(0.9593,0.005,0.0006)	(0.782,0.011,0.0007)	(0.7658,0.0096,0.0004)	(0.9593,0.0051,0.0003)
Piping U_3 (0.5,0.309,0.005)	Duct Influence Length U_{31} (0.691,0.064,0.008)	(0.3844,0.0097,0.0017)	(0.3844,0.0093,0.0008)	(0.7664,0.0094,0.001)	(0.2333,0.0097,0.0011)	(0.2338,0.0094,0.001)
	Spatial Relationship to Piping U_{32} (1,0.1031,0.013)	(0.752,0.0099,0.0011)	(0.4815,0.0032,0.0006)	(0.7833,0.0159,0.0037)	(0.1836,0.0545,0.0294)	(0.5094,0.0017,0.0003)
	Pipe Collapse Angle U_{33} (0.309,0.064,0.008)	(0.7061,0.0018,0.0002)	(0.2414,0.0087,0.0003)	(0.0604,0.0076,0.0012)	(0.4771,0.003,0.0001)	(0.6925,0.0019,0.0001)
	Buried depth of pipeline U_{34} (0.691,0.064,0.008)	(0.6757,0.0021,0.0003)	(0.3844,0.0099,0.0005)	(0.3342,0.0032,0.0005)	(0.9791,0.0382,0.004)	(0.4847,0.0021,0.0002)
Ambient conditions U_4 (0.309,0.064,0.008)	Surface Runoff U_{41} (0.691,0.064,0.008)	(1.0163,0.0024,0.0002)	(0.7524,0.0108,0.0018)	(0.472,0.005,0.0012)	(0.5278,0.005,0.0006)	(0.4907,0.0016,0.0001)
	Microgeomorphology U_{42} (0.309,0.064,0.008)	(0.2939,0.0019,0.0001)	(0.2567,0.0069,0.001)	(0.4589,0.0054,0.001)	(0.6305,0.0074,0.0016)	(0.843,0.0193,0.0028)
	Vegetation coverage U_{43} (0.309,0.064,0.008)	(0.2937,0.0027,0.0005)	(0.0246,0.0079,0.0045)	(0.4718,0.0052,0.001)	(0.3166,0.0014,0.0002)	(0.0801,0.025,0.017)
	Environmental Sensitivity U_{44} (0.5,0.309,0.005)	(0.7136,0.0028,0.0002)	(0.4862,0.0018,0.0002)	(0.6685,0.003,0.0005)	(0.2563,0.0067,0.0008)	(0.5092,0.0012,0.0002)

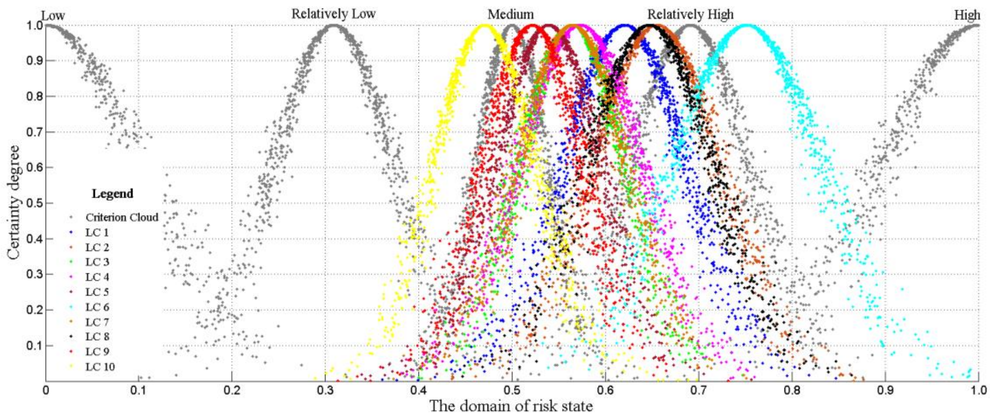

Figure 5. The dangerous state cloud of collapsibility of loess in pipelines

It can be seen from Fig 5 that the shape "skeleton" of the dangerous result cloud of collapsibility of loess No.1-10 is basically similar to the scale cloud, and there are distributions between "lower" and "high" cloud scales, and mainly concentrated between "medium" and "higher" cloud scales. Specifically, LC1 cloud is inclined to "higher cloud"; LC2 cloud is close to "higher cloud"; LC3 cloud is inclined to " medium cloud"; LC4 cloud is close to " medium cloud" and LC5 cloud is near " medium cloud"; LC6 cloud is adjacent to "higher cloud"; LC7 cloud is adjacent to " medium cloud"; LC8 is close to "higher cloud"; LC9 cloud is close to " medium cloud"; LC10 cloud is close to " medium cloud ". The hazard degree of loess collapse to oil and gas pipelines is in the order of LC6 > LC2 > LC8 > LC1 > LC4 > LC2 > LC3 > LC5 > LC9 > LC10.

4.3 Result Analysis

In order to test the applicability and effectiveness of cloud theory in loess collapsibility hazard evaluation of oil and gas pipeline, the risk probability of loess collapsibility from No.1 to No.10 is evaluated respectively with reference to the principle, method and grade standard of risk probability index evaluation of loess collapse disaster recommended by the specification, and the results are listed in Table 8. In addition, the hired expert group for scoring of qualitative indicators also made an empirical assessment on the field risk of sample points No.1 to No.10, and the results are shown in Table 8.The risk probability value obtained in the code recommendation method is based on the possibility index of pipeline failure under the threat of loess collapsibility, which has the same purpose as the comprehensive evaluation of cloud theory in this paper, that is, the risk probability value can indirectly reflect the dangerous state grade of loess collapsibility.

Table 8. Comparison table of evaluation results of collapsibility risk state of loess No. 1 ~ 10

Sample to be evaluated	Normative method result	Empirical method result	Results of this paper	Sample to be evaluated	Normative method result	Empirical method result	Results of this paper
LC 1	High (0.2127)	Medium	Medium ~ high, bias high	LC 6	Higher (0.1846)	Higher	Higher ~ high, next to higher
LC 2	Higher (0.1973)	Medium	Medium ~ high, bias high	LC 7	Medium (0.0926)	Medium	Medium ~ higher, near medium cloud
LC 3	Medium (0.677)	Higher	Medium ~ higher, incline to medium cloud	LC 8	Higher (0.1773)	Higher	Medium ~ Higher, next to Higher
LC 4	Lower (0.0472)	Low	Medium ~ higher, near medium cloud	LC 9	Medium (0.0635)	Lower	Medium ~ upper, next to medium cloud
LC 5	Medium (0.0513)	Higher	Medium ~ higher, near medium cloud	LC 10	Lower (0.0391)	Lower	Medium ~ higher, near medium cloud

Combined with Table 8 and Fig 5, it can be seen that the results of loess collapsibility hazard from No.1 to No.10 obtained by using the standard method are basically consistent with those obtained by the method proposed in this paper, which shows that the comprehensive evaluation method for loess collapsibility hazard of oil and gas pipeline based on cloud theory is effective and feasible, and the fuzziness and randomness of evaluation variables can be fully reflected in the evaluation process. It is more in line with the thinking mode and expression habits of people in understanding the development of loess collapsibility risk of pipelines, and also makes the expression of evaluation results intuitive. The cloud theory method, the standard recommendation method and the expert group experience judgment method are used to carry on the risk assessment separately to the 10 loess collapsibility. Through the contrast analysis of the results, it can be concluded that: (1) The consistence proportion of the cloud theory method and the standard method is 70%, and there is no higher or lower proportion of 30%;(2) The consistency of the results of the cloud theory method and the empirical method is 30%, the high proportion is 50%, and the low proportion is 20%;(3) that proportion of the consistency of the result of the standard method and the empirical method reaches 40%,The proportion is 40% higher and 20% lower.

To sum up, the evaluation results of cloud theory method and normative method have high consistency, but the results of cloud theory method and empirical method have poor consistency. The main reason is that both cloud theory and normative method quantify the comprehensive indicators, and carry out fusion operation through a certain mathematical model, which can weaken the subjective arbitrariness to a certain extent, and the evaluation process is systematic. However, the result of experience method is only judged by expert group according to individual experience, which is subjective and easy to be affected by different experts' personal preferences, professional background, awareness and other differences, and the accuracy of the result is poor.

5 . Conclusion

(1) The collapsible loess hazard evaluation system of oil and gas pipeline is composed of multi-level and multi-objective complex index system, and the commonly used evaluation theory and method can not deal with the fuzziness and randomness of the system at the same time. Based on the analysis of fuzziness, randomness, dimension and magnitude difference of the evaluation index of loess collapse hazard, a comprehensive evaluation model of single loess collapse hazard for oil and gas pipeline based on cloud theory is proposed. Through the risk assessment and verification analysis of 10 loess collapse disaster points in Lanzhou-Chengdu oil pipeline, the practicability and effectiveness of the method are proved.

(2) The quantitative data in the evaluation come from the actual measurement and background information, and the qualitative information comes from the scoring and assignment of experts, so the initial data source is objective and reliable; The index weight cloud is determined by the golden section ratio method of five-level scale, and the effective weight of quantitative and qualitative indexes is realized on the basis of the fuzziness and randomness of the transfer system.

(3) The single condition and single rule cloud transformation method is used for the quantitative indexes in the evaluation, which effectively transmits and inherits the fuzziness and randomness of the system, weakens the hard division of grade boundary and simplifies the pre-treatment of initial data; The single condition and single rule cloud transformation method is adopted after the average value assignment of the expert group scoring of the qualitative indexes, and the interference of subjective factors can be reduced to a certain extent by weakening the grade boundary division.

(4) The evaluation result is a cloud composed of three parameters of expected value, entropy and hyper entropy, which realizes the fusion of quantitative and qualitative in complex system, the evaluation process of integrated decision-making and the visualization of the final results, which provides scientific and technological support for loess collapse monitoring and control of oil and gas pipelines, and also provides an effective new method for related research.

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Competing interests. There are no conflicts to declare.

Figures

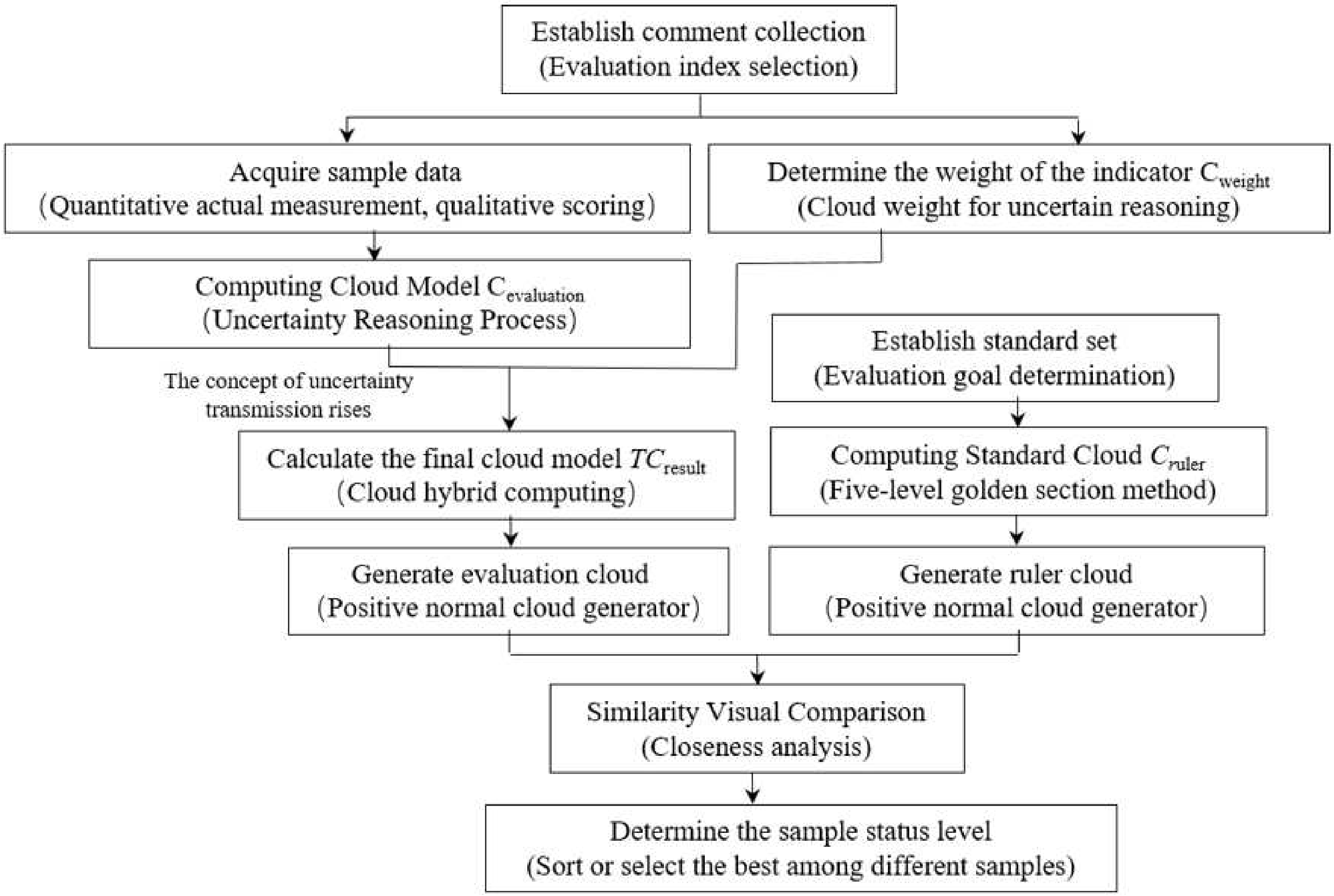

Figure 1

Risk assessment process based on cloud theory

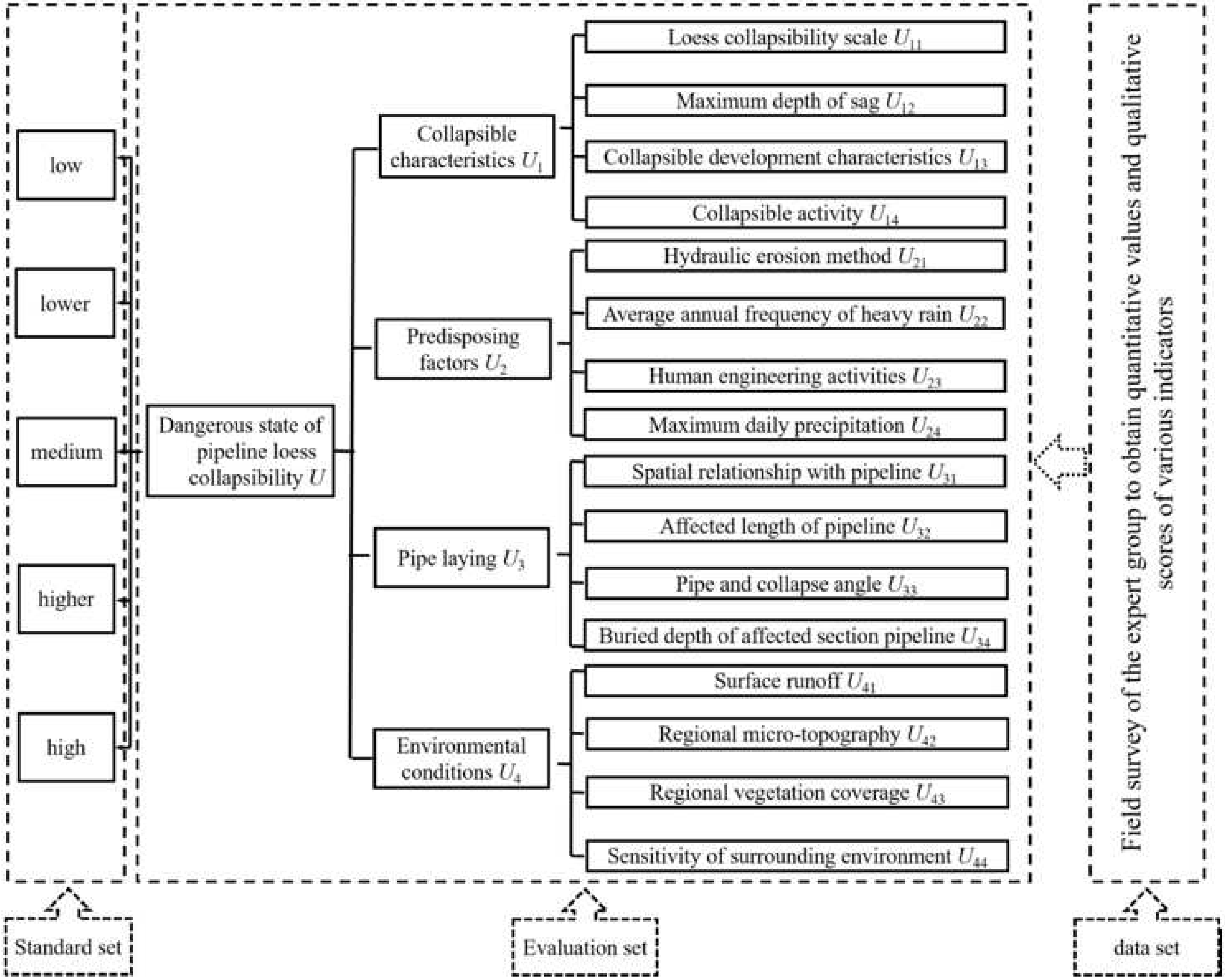

Figure 2

Diagram of the organization system of pipeline loess collapse risk assessment

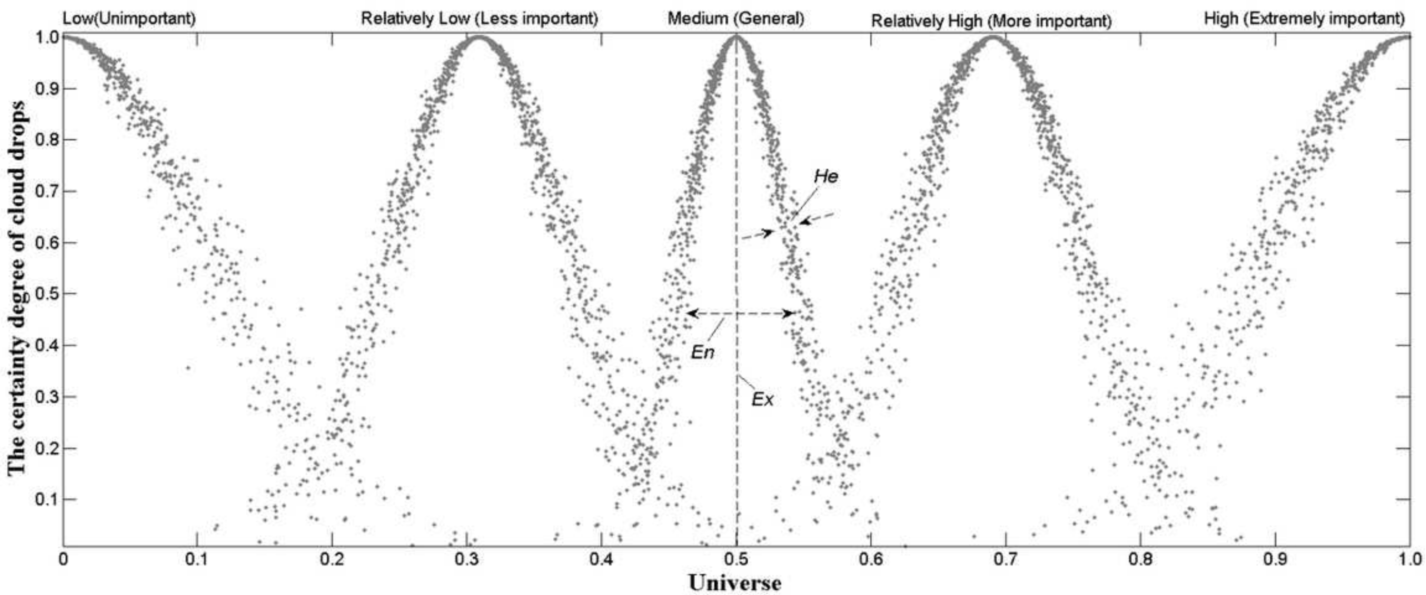

Figure 3

Cloud chart of comment criteria and weight

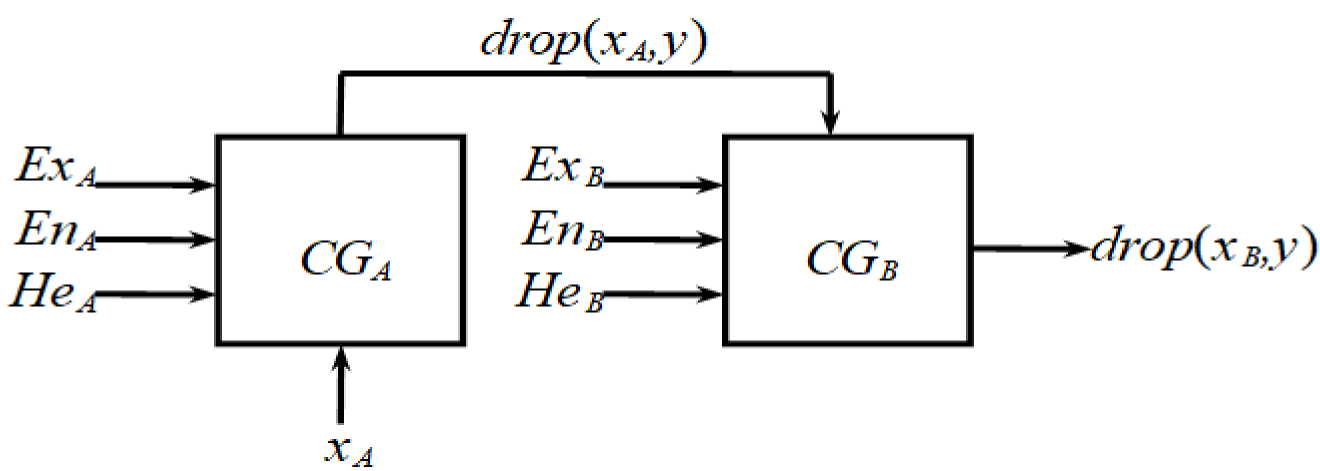

Figure 4

Single condition and single rule generator

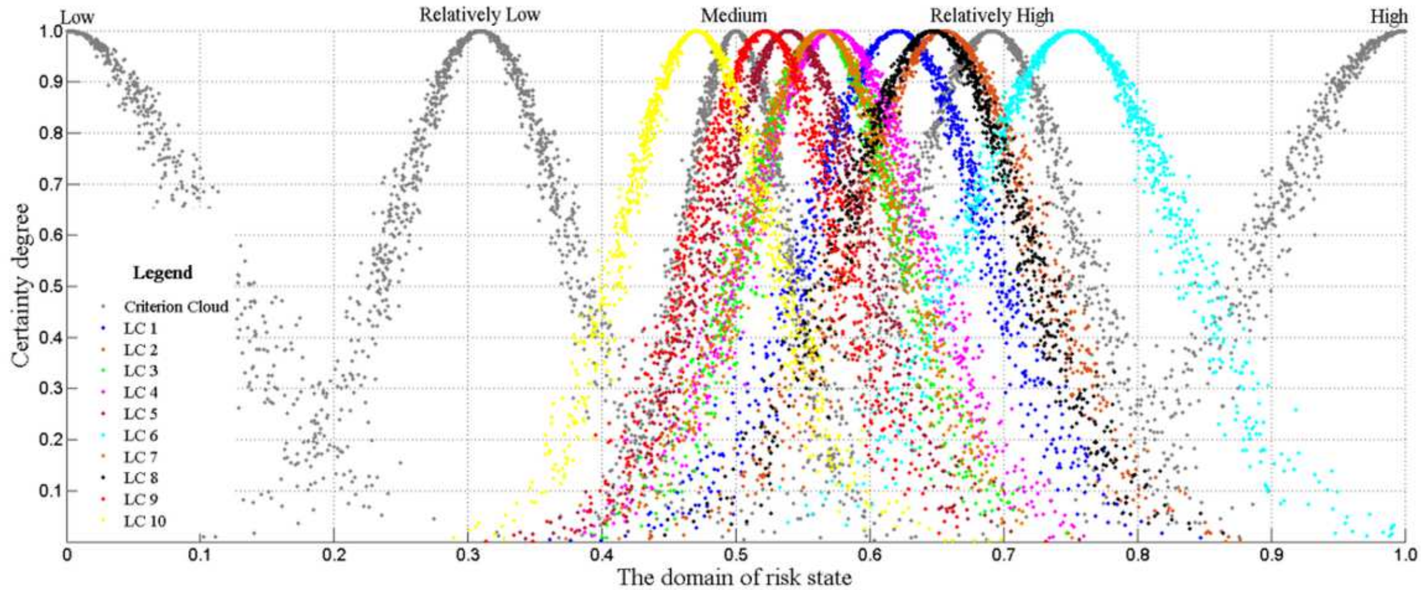

Figure 5

The dangerous state cloud of collapsibility of loess in pipelines