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The Study and Application of Safety Assessment System for Town Gas Networks

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ABSTRACT

This study carefully reviews and compares the characteristics and diversities between Long Distance Gas Transmission Pipelines and Town Gas Networks on the ways of construction, administration , and raises that the traditional approach of applying to the safety assessment system for Long Distance Gas Transmission Pipelines does not meet the requirements on the infrastructures of Town Gas Networks in P.R. China, and it is time to establish a new comprehensive Safety Assessment Model and System in compliance with the needs and characteristics on safety for Town Gas Networks.

According to the principles of Safety Engineering, the grades of safety of Town Gas Networks in operation lie on two major factors: the probability of occurrence along with the degree of severity of the accidents or incidents. So the key to this study are to quantify the two essential factors, set the maximum acceptable limit, and then make rational decisions on the investing amount. Around above core ,mathematical model and fuzzy assessment method is employed to calculate and evaluate the probability of occurrence and the degree of severity of the accidents or incidents, so as to determine the Safety Grade for each section of the gas networks through a Risk Matrix according to the calculate results obtained. To apply the achievements of this study to daily operation, the Safety Assessment System for Town Gas Networks is installed and integrated onto the platform of Geographical Information System (GIS), and then all the statistical figures and results of calculation of the Safety Assessment System shall be dynamically displayed through the GIS interface.

The probability of occurrence and the degree of severity are taken into consideration comprehensively in this system, the results of evaluation could contribute to the safety administration and risk management either on strategically planning or for daily operation. In the past two years of trial run, we use the system data to guide our administration for each section of gas networks based on different safety grade, it has proved that the system is already playing an active and positive role in the safety management, daily maintenance, maintenance arrangement, and pipeline service life.

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1 INTRODUCTION

The Pipeline Risk Management Manual [1] presents the method of safety assessment for long distance gas transmission pipelines embedded underground. It gives the scores of the affecting ingredients and factors based on a large amount of complete and reliable pipeline operation data. We also tried to employ the method [2] and asked related experts to fill in a questionnaire to determine the scores of various affecting ingredients and factors through statistics. Experts who filled in the questionnaire were all from design, construction, supervision, operation, emergency maintenance and management departments. The result shows that the assessment conclusion largely differs from the actual situation [3]. The reasons are as follows: First, long distance gas transmission pipelines remarkably differ from town gas networks in the construction and management.

Long distance gas transmission pipelines	Town gas networks
Generally single-piece pipes, with few valves and reducers	Mostly mesh-type and branch systems, with a large number of valves, tees, condensate boots, and reducers
Generally a whole project is completed within the planned period, with the support of well furnished survey design, construction supervision and project completion acceptance procedures, which assure relative uniform quality with few defects	Formed gradually with the development of urban construction, and expanded continuously. Complicated investment sources, which usually result in spotty design, construction and acceptance quality and quality defects here and there
Usually constructed in the suburbs and countryside, where changes of surrounding environments are smooth changes, which are easy to control and little subject to influence of stray currents	Complicated surrounding environments, which sometimes change abruptly and are subject to widely existing and serious stray currents
A well designed management system is available. The daily management lays emphasis on cathode protection, and improvements are made when the potential is found abnormal.	The management is relatively weak, and the daily management lays emphasis on locating gas leakage points. Even if problems are found, problem handling involves many aspects of urban management and complicated procedures, so hidden dangers cannot be timely eliminated

Table 1 Differences between long distance gas transmission pipelines and town gas networks

Second, most affecting ingredients and factors of the model in the *Pipeline Risk Management Manual* are conceptual, and value assignments by experts are quite subjective, while a large amount of reliable historical and operation data is required for statistical value assignments. Third, the model assumes that all the technical parameters of newly constructed pipelines are completely in compliance with the design requirements. These conditions for model setup are feasible for long distance gas transmission pipelines, but it is quite difficult to meet these model setup conditions in the case of town gas networks. Therefore, a safety assessment modle should be set up according to the principle of typical pipeline safety assessment and based on the characteristics of town gas networks.

2 THE STUDY CONTENTS AND TECHNICAL GUIDELINES

2.1 The Structure of the Safety Assessment System

The safety status of town gas networks depends on the risk coefficient of pipeline operation, namely the product of two quantified indexes: the probability of occurrence and the degree of severity of accidents or incidents.

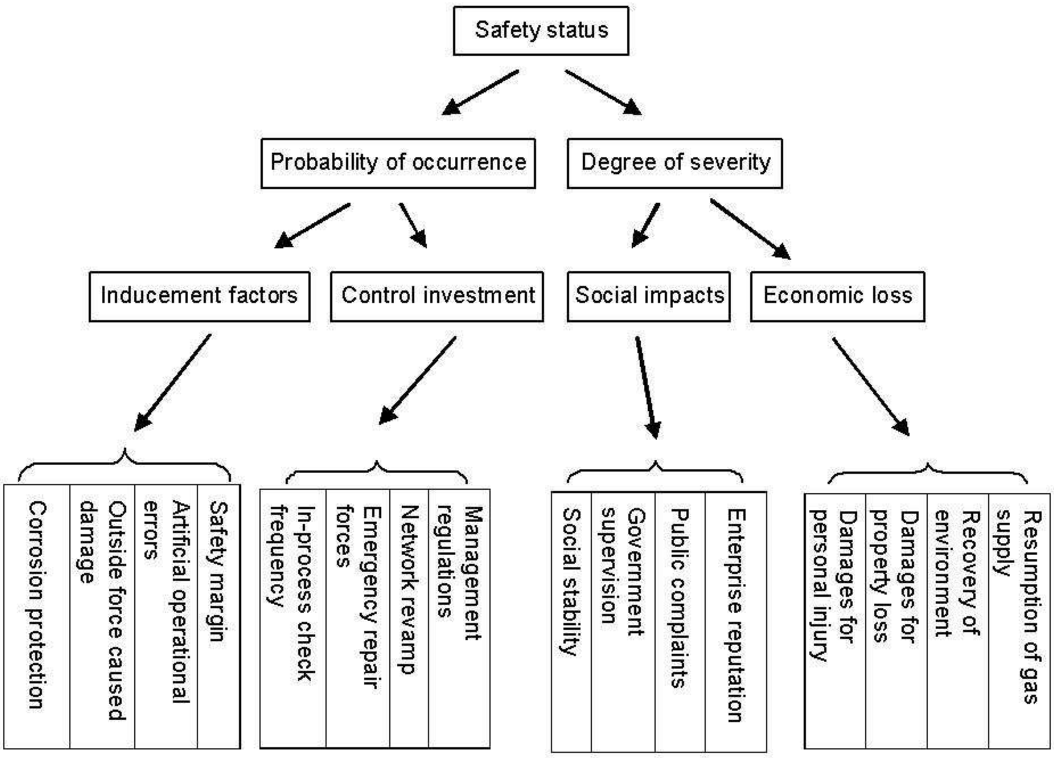

Figure 2 The structure of the safety assessment system

As shown above, the probability of occurrence depends on the interactions between inducement factors and control investments. The inducement factors are the major causes for failures of town gas networks, and are unfavorable to the safety status of the networks; the control investments are embodied in the safety management, favorable to the safety status of the networks, and are what we can do something about.

An accident in a section of a town gas network located down town, compared with an accident in a pipeline section located in the suburbs, may bring much more serious losses, and must be given more control investments. Therefore, for the same probability of accident occurrence to the above-mentioned two sections, the safety grades are different due to different degrees of severity. So, judgments simply based on the probability of occurrence cannot ensure the improvement of the overall safety performance of town gas networks.

2.2 The Assessment of the Probability of Occurrence

2.2.1 Corrosion protection status

2.2.1.1Analysis on affecting ingredients and factors

The corrosion protection status depends on many factors, including the condition of the anti-corrosion layer, the effectiveness of cathodic protection, the physico-chemical characteristics of soils, the distribution of stray currents, and so on. Any factor that affects the above-mentioned aspects may affect directly or indirectly the status of the corrosion protection of the pipelines. The influences of many factors on the corrosion protection status are non-linear, and different factors are associated with one another to different extents. It will take a long time and a huge amount of investment to measure all these factors, and duplicated information largely exists between different sets of data. This results in unnecessary increase of the dimensions of model variables. Therefore, dimension reduction preprocessing should be conducted based on the specific situation of the town gas networks.

First, a correlation analysis and a clustering analysis are on the factors that affect the corrosion protection status based on the detection data and excavation of six municipal pipelines and six residential community pipeline sections. The result shows that 44 factors that affect the corrosion protection status obviously cluster into eight categories when the correlation coefficient is greater than 0.5. To find out a characteristic factor from each category, a principal component analysis is carried out on such factors, with the contribution rate as the basis for choosing the characteristic factors. At the same time, a principal component analysis is also carried out directly on the 44 factors so as to avoid possible overlooked items in clustering analysis. Finally, an analysis with the SPSS software shows that the characteristic contribution rate of the 8 principal factors reaches 95.1%.

2.2.1.2 Division of assessment units

The assessment procedure is divided into the following two steps:

1)Performing a preliminary assessment of the atomic level pipeline sections by leveraging all the basic factors and combined factors;

2)Categorizing adjacent pipeline sections of which the preliminary assessment result is the same, and then correcting the preliminary assessment result by using the combined correction factor to get the final assessment result.

2.2.1.3 Assessment model establishment

Due to shortage of historical data of town gas networks, we have established an assessment model for the corrosion protection status by using the BP neural network mainly based on the survey data of the current conditions of the town gas networks, with the operation log data as supplement.

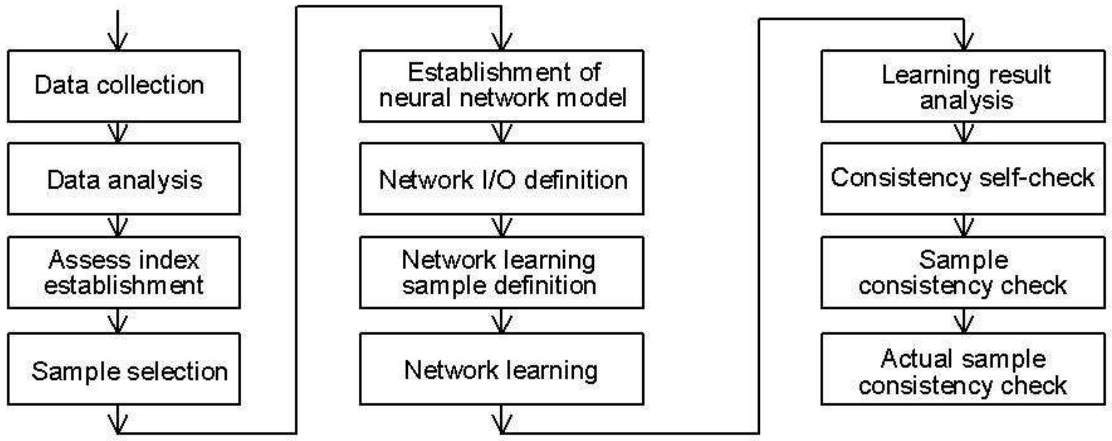

Figure 3 Assessment module for corrosion protection status

This module has the following features:

1) The model is mainly based on the measured data of the current conditions of the pipelines, with historic data as reference;

2) The module well embodies the nonlinear mapping among various affecting ingredients and factors by means of intermediate layer design;

3) The module takes the interactions among different ingredients and factors into full consideration;

4) It has powerful auto-learning and auto-correction functions. Established first based on a limited number of samples, the module is capable of continuous auto-learning along with the accumulation of measurement data so as to give assessment results that are closer to the actual conditions.

2.2.2 Outside force caused damage

2.2.2.1 Analysis on ingredients and factors

Outside force caused damage mainly refers to damage to the pipelines due to activities of third parties or changes of the natural environment, resulting in breakage of the pipelines and gas leakage. Outside force caused damage takes a very proportion in accidents of town gas networks.

The factors that affect outside force caused damage to town gas networks include the buried depth of the pipelines, human activities around the pipelines, the conditions of auxiliary facilities around the pipelines, other municipal facilities around the pipelines, construction activities around the pipelines, the legibility of signs along the pipelines, the maintenance level of the pipelines, the geologic and geomorphologic changes, and foundation settlement.

2.2.2.2 Division of assessment units

The principle of dividing assessment units are as follows:

5) Pipe size and pressure grading is the major segmentation factor;

6) Ground pedestrian movement and building situation is the second segmentation factor;

7) Valves and condensate boots form the third factor.

Based on the above-mentioned principle, we divide a 200-km tested pipeline into 188 assessment units and complete the field collection of the assessment data.

2.2.2.3 Assessment model establishment

According to the characteristics of the ingredients and factors for outside force caused damage, a mathematical model integrating the fault tree analysis method and fuzzy assessment method [4] is employed. A Boolean algebra model is established through Fault Tree Analysis (FTA) to get the minimum cut set (path set), find out various basic events that affect outside force caused damage and their degrees of importance, and then get the probability of outside force caused damage based on the fuzzy set theory.

2.2.3 Artificial operational errors

2.2.3.1 Analysis on ingredients and factors

There are mainly two factors that affect artificial operational errors. One is the quality of people, namely the technical and moral quality of the personnel engaged in network design, construction, operation and maintenance; the other is supervision on the work of the personnel engaged in network design, construction, operation and maintenance.

It is very difficult to quantify or precisely assess artificial operational errors. The qualitative method, scoring method and/or fuzzy assessment method are usually used. In addition, many factors should be taken into account during the assessment, mainly including “design errors”, “construction errors”, “operation errors” and “maintenance errors”.

2.2.3.2 Data collection and assessment

In order to collect the data of various affecting ingredients and factors mentioned above and facilitate summarization and arrangement of the data and materials, we have designed a *Data Collection Form for Artificial Error Factors*.

2.2.4 Safety margin status

2.2.4.1 Analysis on ingredients and factors

With respect to the safety margin, many factors should be taken into consideration. Among these factors, the wall thickness of steel pipes used in the network, the selection of design pressure and the difference between the design pressure and the working pressure, the nature of load in the design, the required hydraulic test, the allowed over-pressure condition, the considerations of geologic situations for the gas network, etc. all have influence on the operation safety of the town gas network.

2.2.4.2 Data collection and assessment

In order to collect the data of various affecting ingredients and factors mentioned above and facilitate summarization and arrangement of the data and materials, we have designed a *Safety Margin Data Collection Form*.

2.2.5 Comprehensive assessment of probability of occurrence

2.2.5.1 Factor set establishment

A hierarchical evaluation is carried out respectively on the above-mentioned four sub-models, namely “corrosion protection”, “outside force caused damage”, “artificial operational errors” and “safety margin”, and the methods of fuzzy mathematics assessment were employed for the assessment of the influence of these four factors on the probability of occurrence of accidents or incidents, to obtain the grade of probability of occurrence.

2.2.5.2 Data preparation

1) Establishment of assessment set

The probability of occurrence is divided into five level, which is expressed in the fuzzy language to establish an assessment set:

V ={very small, small, normal, big, very big}

2) Establishment of weights set

The above-mentioned four factors affect the probability of accident occurrence differently, and the differences among them are embodied through a weights set. The weights set, which is $\tilde{A}$, is obtained through the AHP analysis.

2.2.5.3 Fuzzy assessment

1) Level 1 fuzzy assessment is to determine the influence of each factor on the probability of occurrence, where $\tilde{R}$ is the membership matrix. Then, $\tilde{B}_i = \tilde{A}_i \circ \tilde{R}$

2) Level 2 fuzzy assessment is to determine the grade of probability of occurrence by summarizing the influence of all the factors on the probability of occurrence and based on the grade of membership correlation principle. The level 2 fuzzy assessment set $\tilde{C}$ is calculated as follows: $\tilde{C} = \tilde{A} \circ \tilde{B}$

3) The assessment determines the grade of the synthetic probability of occurrence based on the maximum membership grade principle.

2.3 The Evaluation of the Degree of Severity

The degree of severity refers to the possible range and extent of the consequence when an accident or incident occurs to the gas network, including personal casualty, property loss, damage to the surrounding facilities and environment pollution, impacts on social stability, interruption of gas supply, economic investment made for emergency repairs, etc.

Since most of ingredients of the degree of severity are quite difficult to be quantified accurately and vary as time elapses, fuzzy disposal is needed by means of the gray theory. A neural network model with multi-variable input and single-variable output can be built directly and optimized by means of genetic algorithms. By substituting related parameters into the model, we can get the degree of severity of each section.

2.3.1 Analysis on ingredients and factors

Factors that affect the evaluation of the degree of severity include: gas leakage speed, the population and building density where the gas network is located, vehicle traffic flow, importance of surrounding environment, personnel evacuation ability and pipeline maintainability in case of accidents, impacts caused by gas supply interruption, conditions of adjacent pipeline trenches and cable trenches, the connections of the adjacent pipeline trenches with the residential buildings, etc.

2.3.2 Assessment model establishment

A mathematical model integrating the Analytical Hierarchical Process (AHP) and fuzzy set theory is used for the assessment of degree of severity. A factor set and related assessment set are established based on the analysis of the collected or surveyed data and materials, with the ingredients and factors affecting the degree of severity as the fuzzy assessment factors. A fuzzy relation matrix and weights set of the assessment factors are built to obtain the result vector of the fuzzy assessment, set the fuzzy membership function, and obtain the fuzzy grade of the consequence of an accident or incident.

2.3.3 Division of ingredient and factor grades

In order to carry out statistics and analysis of the data obtained from survey, the above-mentioned ingredients and factors are classified into eight categories. Based on the specific survey data of each pipeline section or area, the grade of each factor can be determined against the factory grading table. Grade 1 is the grade that has the smallest influence on the consequences of accidents, and Grade V is the grade that has the biggest influence on the consequences of accidents.

2.3.4 Determining factor weights by AHP

The above-mentioned eight factors do not bring completely equal influences to the consequences of accidents. The extents of their influences are usually expressed with weights, and the factor weights set reflects the extent to which each factor affects the assessment object, as follows.

$$W = [W_1, \quad W_2, \quad W_3, \quad W_4, \quad W_5]$$

Presently, the AHP method is widely used to determine the weights set. The specific method is as follows:

1) First, establish a hierarchical structure of the assessed issues, and divide the elements of the assessed issues into several groups according to their attributes and the extents of their influences on the assessed issues, with different groups located in different levels. To establish such a hierarchical structure, it is necessary to carry out a comprehensive judgment, because the assessment of the importance degree of the membership indexes in the assessed issues is not completed by a single decision maker; it must be the product of synthesizing the assess results of all the assessment experts.

2) Build a judgment matrix of paired comparison of the assessed issues. Use the integers 1 through 9 as the scales of relative degree of importance for comparing one factor with another. The scales are defined as follows:
I) If the two factors are equally important, the scale is 1;
II) If one factor is slightly more important than the other, the scale is 3;
III) If one factor is remarkably more important than the other, the scale is 5;
IV) If one factor is strongly more important than the other, the scale is 7;

V) If one factor is extremely more important than the other, the scale is 9.

2, 4, 6 and 8 are the mean values of two adjacent judgment scales above.

If scale a_{ij} obtained from the comparison between factor i and factor j, then the result of the comparison between factor j and factor i is $1/a_{ij}$.

For an assessed issue composed of *n* factors, the following judgment matrix of paired comparison:

$$A = (a_{ij})_{n \times n}$$

After getting the judgment matrix, calculate the product of each line of elements in the matrix (M_i) and the n^{th} root of M_i .

$$\overline{W_i} = \sqrt[n]{M_i}$$

To verify the rationality of the characteristic vectors, the obtained judgment matrix must possess consistency. The process of verifying the consistency of the judgment matrix is as follows:

Calculate the maximum characteristic value of the judgment matrix:

$$\lambda_{\max} = \sum_{i=1}^{n} \frac{(A\overline{\omega})_i}{nW_i}$$

Define the consistency index (CI) and the random consistency index (RI):

$$CI = \frac{\lambda_{\max} - n}{n-1}$$

Define the consistency ratio (CR): $CR = \frac{CI}{RI}$

Generally, if CR < 0.1, the consistency of the judgment matrix is acceptable.

2.4 The Assessment of Safety Status

2.4.1 The Division of safety grades

The risk matrix method is used to represent the grades of risks.

Probability of Occurrence					
V	C	C	C	D	D
IV	B	B	C	C	D
III	A	A	B	C	D
II	A	A	B	B	C
I	A	A	B	B	C
	I	II	III	IV	V
	Degree of Severity				

Figure 4 Risk grade matrix of safety status

The X-ordinate represents the degree of severity, which is divided into five levels: I, II, III, IV and V, where I represents the slightest influence on the consequences of accidents, and V the most significant influence on the consequences of accidents. The Y-ordinate represents the probability of occurrence, which is divided into five levels: I, II, III, IV and V, where I represents the lowest probability of occurrence, and V the highest probability of occurrence. In the figure, areas marked “A” are low risk areas, areas marked “B” are medium risk areas, areas marked “C” are medium-high risk areas, and areas marked “D” are high risk areas.

During pipeline assessment, represent the probability of occurrence and degree of severity of the accidents or incidents in points in the matrix. The area where a point falls in is the risk level of the pipeline.

2.4.2 Software structure and functions

The safety assessment system for town gas networks involves large amount of data and is closely related with the daily operation. To achieve visual display and analysis of the data, we build the assessment system on the Geographic Information System (GIS) platform in a manner of integrating the GIS technology and the database technology during the development of the safety assessment software. The pipeline status information database and the GIS share the data resources, and the calculation results are dynamically displayed and periodically refreshed through the interface with the GIS.

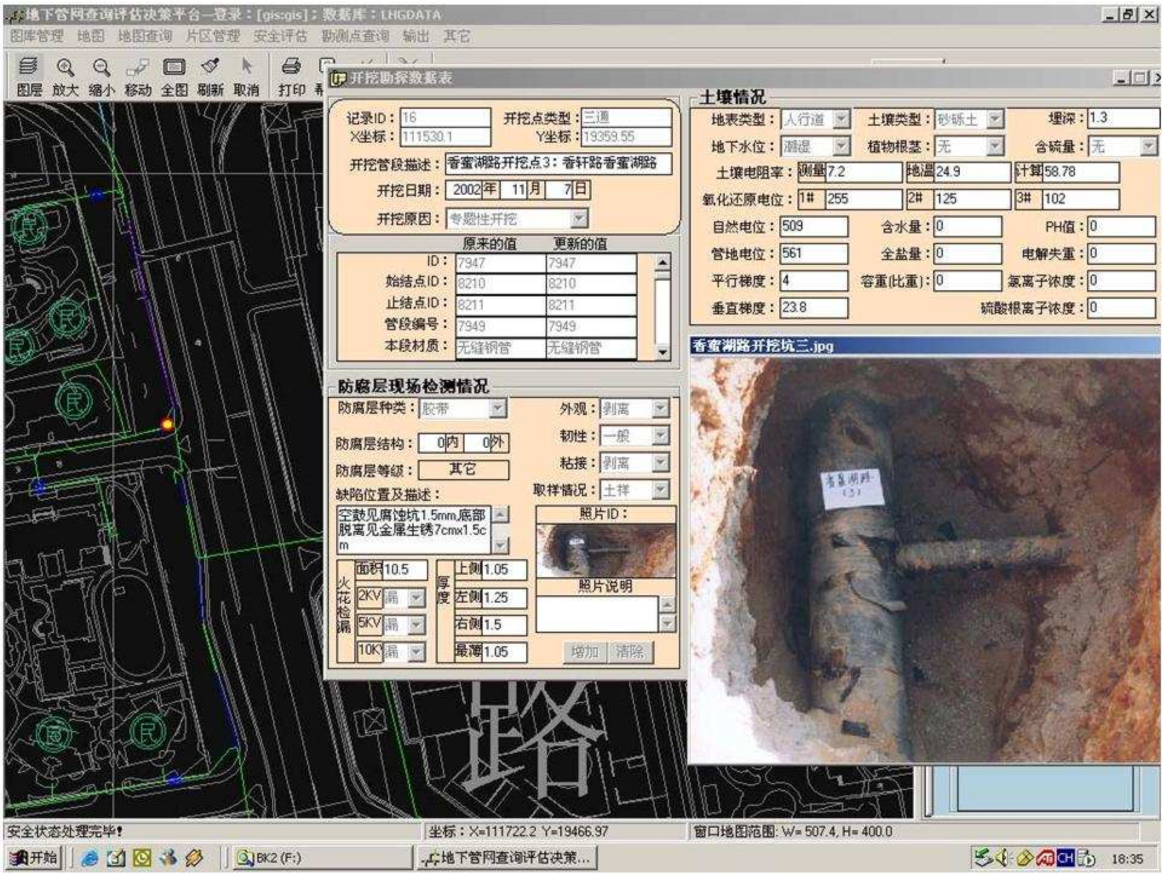

Figure 5 Visual display of the safety assessment result

The safety assessment software system supports the input and processing of the occurrence probability data, severity degree data, assessment parameters, etc., the online and automatic assessment process of the probability of occurrence, the degree of severity and the grades of safety, the statistical analysis of the assessment results, and system maintenance.

3 RESULTS

After the system passed its evaluation in January 2003, the assessment results given by this system have been used to guide the production while the system continues collecting data, implementing auto-learning and auto-correction. After two years of trial run, the system is already playing an active and positive role in the safety management, daily maintenance, maintenance arrangement, and pipeline service life.

3.1 Safety Management: from “Passive Emergency Repairs” to “Active Prevention”

Traditional gas network management lays emphasis on remedies after occurrence of gas leakage. A slight neglect may result in a serious accident. Safety assessments can greatly reduce the probability of pipeline leakage and prevent accidents from occurring, thus realizing the change of passive emergency repairs to active prevention.

3.2 Daily In-Process Checks: from “Average Investment” to “Investment by Necessity”

In the traditional in-process check mode, the man power and material resources are averagely distributed. Through safety assessments, different in-process check standards can be adopted for gas networks of different levels, so that more forces are put on the monitoring of important areas and pipeline sections, and gas concentration detection can be implemented for pipeline sections with low grades in the assessment result. After this system was put into service in 2003, through adjustment of the in-process check institution, the in-process checks have been enhanced for important areas and pipeline sections, and the mode of average distribution of in-process check forces has been replaced by distribution according to need. While the number of people has been decreased, the in-process personnel have found remarkably more network leakage points than in previous years.

3.3 Arrangement of Maintenances: from “Emergency Replacement” to “Schedule Maintenances”

In the traditional maintenance management mode, the decision of whether to repair or replace pipelines mostly based on the emergency repair situation. With the application of this system, pipelines above the “acceptable” grade in the assessment result can be maintained by means of excavation repairs at fixed points, supplement of sacrificial anodes, etc.; for pipeline sections on which improvements cannot be achieved through the above-mentioned measures or the above-mentioned measures are not economically advantageous in comparison with pipe replacement, a replacement plan can be made and implemented step by step.

3.4 Pipeline Life Expectancy: from “Scheduled Replacement” to “Replacement upon Necessity”

The operation expenses for pipelines that have reached their life expectancy will increase gradually. Through safety assessments, we can make economic comparisons to decide whether to continue using such pipelines or replacing them during an overhaul, and can take reasonable measures to prolong their service life.

4 CONCLUSION

4.1 Establishing Models based on the Characteristics of Town Gas Networks

For model establishment and parameter selection, this system makes use of the assessment methods for long distance gas transmission pipelines while taking into account the remarkable differences between town gas networks and long distance gas transmission pipelines. As an assessment system specific to town gas networks, this system features powerful auto-learning ability, high portability and good operation effect.

4.2 Shared Data Resource and Visual Display of Assessment Result

The database system and the production scheduling system share the data resources, and independent modules are used for data processing and display. This reduces the workload of data input and the probability of errors, and the assessment result is directly, visually displayed on the GIS.

4.3 Application of Assessment Result on Risk Management

The best advantage of all in this system is that it addresses valediction to the old days of rushing passively to deal with emergencies and starts a new age of active prevention of accidents and incidents in safety management for gas suppliers and distributors. This Safety Assessment System could contribute a great deal to the safety administration and risk management either on strategically planning or for daily operation.

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