Test Analysis and Pipeline Risk Assessment of Oil and Gas Pipeline Laying in Typical Loess Area

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Abstract. In recent years, with the development of oil and gas storage and transportation technology, pipelines have been successfully laid and safely operated in areas with various geological and geographical characteristics. However, for pipelines in particular sections such as collapsible loess areas and landslide ones, oil and gas pipelines will be restricted by conditions. Different problems may even occur during laying and operation. On the basis of mechanical analysis and calculation, this paper establishes a mechanical model. Combined with similar simulation experiments, the influence of water flow erosion on oil and gas pipelines under different slope laying conditions is analyzed. At the same time, the risk assessment methods of special pipe sections in loess areas are established, which have certain guiding significance and reference value for pipeline laying in loess areas.

Key words: Oil and gas pipeline; Loess slope; Mechanical analysis; Similar simulation; Risk assessment.

1. Introduction
The pipeline project passes through typical collapsible loess areas such as Ningxia, Gansu and Shanxi Province, and the pipelines are mostly laid along the edges of loess ridges and hillocks, revetment and ditch banks. Due to the Collapsibility of loess and landslides, collapses, caves as well as other disasters caused by it, the pipelines are greatly threatened, which directly restrains the safe operation and economic benefits of the pipeline project.

Loess collapse is the subsidence deformation of collapsible loess caused by the destruction of the original soil structure soaked by water under a certain gravity pressure or external load. The loess collapse disaster points are generally distributed linearly along the pipeline, and many wet pits or butterfly lands with a length of tens to hundreds of meters are formed, which will cause problems such as exposed or suspending pipelines. Besides, the collapse of loess in the loess plateau areas at the top of steep slopes will make a large amount of surface water seep along the trenches to the slope areas, softening the soil of the slope, decreasing the stability of the slope, and causing loess landslide and collapse, thus causing greater harm and threat to the pipeline.
2. Basic physical and mechanical indexes and permeability analysis of loess

2.1. Project Overview
Sinopec Limited Coal-to-Gas Export Pipeline Project in Xinjiang (Xin Guangdong-Zhejiang Pipeline) is mainly located in Gansu section and Ningxia section in loess area. Gansu pipeline starts from Caofeng Town, Kongtong District, Pingliang City, passes through Chongxin County and Jingchuan County, and ends at Shaozai Town, Lingtai County, Pingliang City, with a length of 175 km. The trunk line crosses large and medium-sized rivers 49 times, medium-sized rivers 42 times, railway 8 times, highways 4 times, grade highway 40 times and mountain tunnels 7 times. There are 8 stations and 40 valve chambers in Gansu trunk line, including 29 monitoring valve chambers and 11 monitoring valve chambers.

2.2. Physical and mechanical properties of loess along the line
We carried out indoor tests on 163 samples taken along Gansu and Ningxia, including 7 loess clay samples, 153 loess silt samples and 3 silty sand ones. The test results show that the loess along the line is mainly silty loess, as shown in Table 1. Combined with the classification index of collapsible loess, it can be seen that the collapsible loess in the project area belongs to strong collapsible soil.

| Location       | Statistical soil moisture content /% | Natural proportion | Natural severe KN/m³ | Dry severe Ratio /% | Void Saturation /% | Liquid limit /% | Plastic limit /% | Plasticity coefficient | Self-weight collapsibility coefficient | Compression modulus MPa |
|----------------|-------------------------------------|--------------------|----------------------|---------------------|--------------------|-----------------|-----------------|------------------------|-------------------------------|---------------------|
| Ganpingliang section | 48 | 19 | 2.72 | 17.04 | 14.31 | 0.89 | 32.5 | 19.4 | 13.1 | 46.4 | 21.1 | 0.027 | 7.424 |
| Guyuang section | 28 | 13.9 | 2.71 | 14.29 | 12.58 | 1.13 | 68.9 | 29.2 | 17.8 | 11.5 | 29.5 | 21.1 | 0.1 | 2.63 |
| Zhongwei section | 30 | 13.7 | 2.72 | 14.32 | 12.15 | 1.01 | 67.5 | 30 | 18 | 12 | 31 | 22 | 0.1 | 3.6 |
| Jingchuan section | 32 | 14.2 | 2.72 | 14.28 | 12.35 | 1.11 | 65.9 | 30.2 | 18.5 | 11.7 | 30.2 | 21.7 | 0.1 | 3.57 |

2.3. Comparative experiment of loess infiltration
The horizontal and vertical permeability coefficients of undisturbed soil collected from each profile were measured, and the method of measuring the water flow in each profile horizontally and vertically for 6 times was adopted, and finally six groups of test data were obtained. The actually measured permeability coefficient decreases (for example, the vertical permeability of section I decreases from $3.95 \times 10^{-5}$ cm/s to $3.29 \times 10^{-5}$ cm/s), which is as a consequence the permeability coefficient is larger when the loess is soaked but has not yet reached saturation, and then it gradually decreases as the loess is gradually saturated.

The average values of the three profiles of vertical permeability measured by experiments are $3.70 \times 10^{-5}$, $3.28 \times 10^{-5}$ and $3.99 \times 10^{-5}$ respectively. The average values of three profiles of horizontal permeability are $3.69 \times 10^{-5}$, $3.22 \times 10^{-6}$ and $3.76 \times 10^{-6}$, respectively. By comparing the horizontal and vertical permeability coefficients, it can be found that the vertical permeability coefficient is larger than the horizontal counterpart, the former is about 10 times as much as the latter. For the reason that the permeability coefficient of loess decreases with the decrease of void ratio, on top of that there is a logarithmic function relationship between them. On account of the anisotropic structural properties of loess, vertical joints are far more developed than horizontal ones, so there are plenty vertical pores than horizontal pores, thus the vertical permeability coefficient is generally larger than horizontal permeability coefficient.
3. Similar simulation experiment and mechanical analysis

3.1. Similar simulation experiment of pipeline laying on the slopes

During laying the pipelines, unconventional terrain may occur like steep slopes and gullies, especially in loess areas, which will form great obstacles to the work. This experiment is aimed to find the target laying angle on which the influence of water flow erosion on the pipeline’s suspension.

Pipeline laying shall be excavated according to geometric similarity ratio, with laying angles of 15, 30, 45, 60 and 70 degrees respectively. After the pipeline laying is completed, the rain erosion is simulated. The simulated water flow added at regular intervals should permeate evenly from the top of the sample, so that the water flow cannot overflow to the slope to take away the sediment; Besides, observation for 6 times each hour is required. After that, collect and dry the sand flowing out from the bottom of the pipe and weigh it.

During the pipeline laying process, the soil loss around the pipeline is closely related to the pipeline laying angle. Generally speaking, when the pipeline is laid at 40 ~ 60 degrees, the soil loss around the pipeline is the most serious. According to the formula fitted by the average value of the three sand production rates, it is as follows:

\[ y = \sin(\pi \frac{x - 105.5754}{4.8053}) \]

According to the formula, it can be obtained that the laying angle reaches the peak value at about 50°, that is, when the laying angle of the pipeline is about 50°, the soil around the pipeline suffers the most damage after the rainwater infiltrates. Then as the angle gradually increases, the soil loss decreases gradually again, but it is still more serious than the counterpart of 10 to 40 degrees. (Note: The angle over 70° will not be considered, which does not match the construction conditions of the project).

![Fig. 1 Similarity simulation comparison of three experiments](image)

3.2. Mechanical analysis of damage to pipeline laying on loess slope

After laid down on the loess slope, the pipeline mainly suffers from destruction by surface precipitation such as hanging from ground collapse or exposure as a result of soil erosion. According to the experimental results, the pipeline is laid at different angles, and the level of soil destruction caused by precipitation verifies.

Due to excavation, the structure and stability of some soil around the pipeline have been greatly ruined, forming a weak zone within 1m around the pipeline, and leaving enough channels for rainwater
infiltration. In the process of water infiltration, the water content of the soil increases continuously, and the adsorption force between the soil decreases, resulting in a decrease in the strength. Under the influence of the soil of own weight, and with humidification, the strength of the soil is continuously reduced, and the cemented structure is gradually destroyed. At this time, the pore water replaces the soil skeleton to bear most of the pressure. Initiated to develop into a flow-slip movement, then coupled with the collapsibility of loess, the soil in the weak zone was destroyed firstly, and a large amount of soil was lost, causing the pipeline to hang and be exposed.

4. Risk assessment of pipeline laying in loess area
Combining with similar simulation and mechanical analysis, we can see that the risks of pipelines in the loess area mainly come from geological and hydrological conditions. Therefore, this article will proceed from these two aspects and consider the various risk factors of dangling and exposed pipelines, thereby forming a risk evaluation index system for pipelines in collapsible loess areas.

4.1. Risk assessment system of geological conditions for pipeline laying in loess area
Conditions like topography, stratum characteristics, geological structure, loess of own structural structure, surface vegetation and so on, constitute the influencing factors of the geological environment during the pipeline laying process in the loess area. According to the previous experimental data analysis, combined with the actual situations of gas pipeline laying in China, The environment and geological conditions can be summarized into five aspects: topography, loess structure characteristics, stratum characteristics, geological structure and surface vegetation function. (Table 2)

| Primary factor                  | Secondary factor        | Three-level factor          |
|--------------------------------|-------------------------|-----------------------------|
| Environmental and Geographical conditions | Topography and landform | Landform characteristics     |
|                                |                         | Slope height and slope angle |
|                                | loess structure         | Physical properties         |
|                                | characteristics         | Mechanical properties       |
|                                | stratum characteristics | Hydraulic properties        |
|                                | geological structure    | Geological age              |
|                                | surface vegetation      | Formation lithology         |
|                                | function                |                             |

4.2. Soil erosion risk assessment system for pipeline laying in loess areas
The bare dangling of the pipeline is largely caused by soil erosion around the pipeline. The structural joints of loess coupled with the excavation and laying of pipelines enable rainwater to seep down along the gap or even pour into it, increasing the weight of the rock, forming pore water pressure, reducing the strength of the soil, causing soil erosion around the pipeline and even collapse and landslides. This article mainly considers the effect of water on the pipeline.
5. Conclusion

(1) This article performed conventional mechanical and physical analysis of the loess along the pipeline, calculated its collapsibility coefficient and compression modulus, and provided a parameter basis for the installation and operation of the pipeline;

(2) This article conducted tests on the permeability of the loess along the line, analyzed and compared the difference between the horizontal and vertical permeability of the loess. According to the experimental results and comprehensively analyzed the structure of the loess, it is concluded that the vertical permeability of the loess is much greater than the horizontal permeability;

(3) The authors self-designed the pipeline laying on the loess slope, simulated the influence on the soil around the pipeline when laying at different angles under precipitation conditions, and combined the experimental data and mechanical analysis to get the soil around the pipeline the damage mode and it is concluded that the damage suffered is the most severe at about 50°;

(4) On the basis of summarizing a large amount of data, this article analyzed and discussed the influence of geological and hydrological conditions on pipelines, and comprehensively considered and analyzed the risk factors of pipeline safety in collapsible loess areas, and constructed corresponding applicable strong and completed risk evaluation index system.

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