Research on Failure of Tee Pipe Based on AutoPIPE

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Abstract. During the construction of a tunnel beneath a buried oil pipeline, leakage occurred in the tee near the elbow due to accidental collision of construction equipment on the pipeline. In order to analyze the failure reason of tee near elbow, based on the interaction mechanism between ideal elastic-plastic soil and pipeline, the pipeline model was established by using the method of equivalent external load with uniform load, and the pipeline simulation and stress analysis were carried out by using AutoPIPE software. The results show that the allowable stress is not exceeded in the section directly subjected to external loads, but the actual stress value exceeds the allowable stress value due to the concentrated stress near the elbow, which is the main reason for the failure of the tee.

1. Introduction
Buried pipelines have the advantages of high efficiency and economy in transporting oil and gas. They have become an important mode of transportation for this medium, and the tee as a connecting pipe is an indispensable connecting piece. In the project, the three links will be affected by the external load, soil load and internal pressure of the pipeline. Once the leakage occurs, it will not only affect the production but also have serious safety hazards[1].Defining the stress characteristics of pipelines and tees is of great significance for maintaining pipeline safety[2].

Currently, the commonly used pipeline and tee force analysis software is AutoPIPE and CAESARII. The burial theory includes ALA (American Lifelines Alliance) theory[3] and LCPeng theory[4]. LCPeng theory is too simple to deal with soil parameters and its application has certain limitations, so it is only used in CAESARII. This theory is still applicable to the analysis of buried pipelines and tees in China, but ALA theory has gradually gained more recognition and application from engineers[5]. Because AutoPIPE software is more accurate and reasonable than soil parameter processing and analysis, it is more widely used in buried pipeline and flange stress analysis than CAESAR II.

In order to further analyze the stress characteristics and failure causes of pipelines and tees under external loads, the theory of pipe-soil interaction is further considered on the basis of literature [7], and combined with a domestic oil pipeline project as the engineering background, the value is established by using AutoPIPE software. The model is also added with fixed constraints. The soil parameters are set according to the actual situation on site and the uniform load is added to the pipe section to further analyze the influence of external loads on the pipe and the tee.

2. Tube soil interaction theory
Although the theory of pipe-soil interaction has been proved for many years, it is still not perfect. In the theory of pipe-soil interaction, the AutoPIPE software issued by Bently Software Company of the United States is an international general pipeline stress analysis software. For the pipe-soil interaction
problem, the software also uses the ideal elastic-plastic model (soil spring model), and uses two methods to calculate $K_1$ and $P_1$ (software set $K_2$ as a fixed minimum, tending to 0)) in four directions (horizontal, axial, upward and downward), that is the method in AutoPIPE software manual. And the methods defined in the Guidelines for the Design of Buried Steel Pipe published by the American Association of Civil Engineers (ASCE). After calculating the soil parameters, the software calculates the stress and deformation of the pipeline according to the finite element theory. As shown in Figure 1.

Figure 1. Schematic diagram of pipe-soil interaction

The soil load calculated by the ASCE specification is as follows:

1) Axial earth springs. The maximum soil reaction force acting on a pipe per unit length can be expressed by the following formula [6]:

$$ T_u = \pi \cdot D \cdot \alpha \cdot c + \pi \cdot D \cdot H \cdot \gamma \cdot \frac{-1 + K_u \cdot \tan \delta}{2} $$  

(1)

2) Horizontal transverse earth springs. The lateral soil reaction acting at the maximum level of the unit length of the pipe can be expressed as:

$$ P_u = N_{ch} \cdot c \cdot D + N_{qh} \cdot \gamma \cdot H \cdot D $$

(2)

3) Vertically up the soil spring. When the tube moves vertically downwards, the maximum soil reaction force acting on the tube of unit length can be expressed by the following formula:

$$ Q_u = N_{cv} \cdot c \cdot D + N_{qv} \cdot \gamma \cdot H \cdot D $$

(3)

4) Vertically down the soil spring. When the tube moves vertically upwards, the maximum soil reaction force acting on the tube of unit length can be expressed by the following formula:

$$ Q_u = N_{cv} \cdot c \cdot D + N_{qv} \cdot \gamma \cdot H \cdot D + N_{uv} \cdot \gamma \cdot \frac{D^2}{2} $$

(4)

3. Model establishment

3.1 Pipeline parameter settings

The calculation model is established by the AutoPIPE software and is calculated as a 32.6 meter pipeline. The anchor is fixed at both ends of the pipeline. A total of 30 pipeline nodes are set. The A00-A30 pipeline node is set for the first half and 32 nodes are set for the second half. The diameter of the three-way branch pipe is 150mm, and the pipe section is set to two pipe points of A21-B01. In the General Model Options interface before the model is built, the Piping Code selects B31.3Process, the version is 2012, the Material selects CHINAGB, the unit selects the metric system, and the rest is set to the default. The pipeline model is shown in Figure 2. The specific parameters of the pipeline are shown in Table 1.
3.2 Soil parameter settings

In order to distinguish the characteristics of soils in different depths and under different conditions, six different soil models were set up with the numbers of S1-S6. The corresponding numbers in Figure 2 are A00-A01, A01-A02, A02-A12, A12-A24, A24-A38 and A27-B01. The horizontal pipeline and the vertical pipeline should use different soil identification symbols [7]. The buried depth parameters of the horizontal pipeline are the length from the surface of soil to the axis of the pipeline, and the vertical pipeline is the distance from the center point of the pipeline length to the surface of the soil.

| Pipeline parameters | Diameter (mm) | Wall thickness (mm) | Density (kg·m⁻³) | Poisson's ratio | Temperature (°C) | Pressure (Mpa) |
|---------------------|--------------|-------------------|------------------|----------------|------------------|--------------|
|                     | 610          | 9.5               | 7850             | 0.3            | 40               | 3.5          |

Table 1. Pipeline parameters

Figure 2. Pipeline model

In order to obtain a more accurate analysis of the stress and to simulate the interaction of the soil and the pipeline, the soil confinement spacing must be set very small, at the elbow and the tee. In the area away from the elbow and the tee, in order to obtain more accurate results, only the axial force of the pipe formed by the friction between the soil and the pipe is simulated, and the soil confinement interval can be set slightly larger. The soil stiffness was set to the default average and the soil type was selected as medium soil using the American Lifeline Alliance (ASCE 2001) calculation with the rest being the default. The specific parameter settings are shown in Table 2.

4. Calculation and analysis

The tunnel is directly below the pipeline. During the internal construction, the equipment accidentally bumped on the section A12-A14 of the pipe. The external load is simplified as 265000 N/m uniformly distributed load acting on A12-14 pipe section vertically. The combined working conditions of pipe self-weight and soil load are named U1. For ease of observation, a local enlarged picture of the pipeline under applied load is intercepted (Fig. 3). After calculation, the actual stress and allowable stress of each pipe point in the working condition are plotted as a curve (Fig. 4). By observing and comparing the actual stress of the tee pipe point A21 followed by A12 and A18 pipe points in the starting working condition. The actual stress of the tee is 158.93 N/mm², which exceeds the allowable stress of 148.36 N/mm².

| Soil parameters | Deep depth (mm) | Effective density (kg/m³) | Internal friction angle(°) | Static pressure coefficient |
|-----------------|-----------------|---------------------------|---------------------------|---------------------------|
| Soil layer S1   | 4700            | 1601.85                   | 35                        | 0.43                      |
| Soil layer S2   | 2980            | 1601.85                   | 35                        | 0.43                      |
| Soil layer S3   | 860             | 1601.85                   | 35                        | 0.43                      |
Although the load in the working condition does not directly act on the A21 tee section, because of the special structure of the tee and the buried pipeline with elbows, the bending moment of the tee is greatly affected. Because the elbow is close to the elbow, the axial force at one end of the elbow will produce transverse bending moment at the other end. A12 and A18 are just the elbows of the pipeline, so the actual stress values of tees and elbows are larger than those of other sections. In Figure 3, the bigger stress points are A21, A12 and A18.

| Soil layer | Stress | Elasticity | Diameter | Ultimate stress |
|------------|--------|------------|----------|-----------------|
| Soil layer S4 | 2980   | 1601.85    | 35       | 0.43            |
| Soil layer S5 | 4700   | 1601.85    | 35       | 0.43            |
| Soil layer S6 | 4045   | 1601.85    | 35       | 0.43            |

Figure 3. Pipeline force cloud map

Figure 4. Pipe point actual stress and allowable stress
5. Conclusions and recommendations

The external load in the working condition does not directly act on the tee, but because the tee is close to the elbow, the force is concentrated, which is the largest actual stress value of all the pipeline points, and the actual stress value exceeds the allowable stress value. The actual stress value of two elbow sections does not exceed the allowable stress value, but is obviously greater than that of other sections. In view of the above analysis, the following suggestions are put forward.

(1) In order to avoid the failure of the tee, the pipeline near the elbow should be protected to reduce the impact of external loads.

(2) The installation position of the tee should be away from the elbow. It is suggested that the elbow should be 6 meters away from the pipe point A24.

(3) When the tee is close to the elbow in the project, if there is external load acting on the pipeline near the elbow, even if the pipeline itself does not fail, the tee should be checked in time for failure.

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