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Research article

Innovation design of long-distance pipelines buried under high-filling planned roads

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Abstract

If a long-distance gas pipeline is unavoidably buried under a planned high-filling road, the high fill subgrade setting will result in the change of the pipe's mechanical shape and the local stress concentration on the pipe, which will pose threats to the safe operation of the pipeline. Protection culverts are generally adopted to solve this issue, but the construction of protection culverts are difficult and high in cost and usually unable to meet the requirements of construction schedule of the planned road project by the local government. For this reason, the stress on pipelines in high fill subgrade was analyzed and a rectification measure was proposed and its safety and rationality was also calculated. The results show that increasing pipe thickness is a feasible rectification measure. Thus, we analyzed the stability of and stress on the pipe caused by the uneven high fill setting by using the ABAQUS finite element software package, in which the pipe was simulated as the beam element, the backfill above the pipe as the stress load, and the elastic foundation underneath the pipe as the evenly-distributed spring. From the stress cloud charts, we can see the stress concentration on the pipe where a sudden change occurs in high fill setting. Without proper measures, accidents would be inevitable in the end. The analysis results from the ABAQUS also show that the scheme of increasing the pipe thickness will be the most cost-effective and practical way to deal with the stress resulted from the uneven high fill setting above the pipe. But it is pointed out that the pipeline laying route should avoid planned high filling roads as far as possible to ensure its safe operation.

Keywords: Buried pipeline; High filling; Planned road; Subsidence; Stress analysis; ABAQUS finite element; Increase of pipe wall thickness; Protection culvert

As economic construction advances, in long-distance natural gas pipeline routing, not only the needs of pipeline transportation customers but also the safety risks that local economic development poses on pipelines should both be taken into consideration. The 22 Nov. 2013 crude oil pipeline explosion accident in Qingdao gave us a bitter lesson in that pipeline design must comply with local planning and pipeline routes should be as far away from the planned areas as possible. However, pipelines sometimes have to be connected with the planned urban gas supply inlet stations and have to cross planned areas. For example, due to planning and construction term, a section of a gas transportation pipeline in Hunan was laid underneath a planned urban road. With the development of local economy, the local government needs to build the planned road, consequently, the maximum thickness of backfill above the pipeline is 34 m because of the significantly undulating hilly topography along the pipeline route in the planned area. Safe operation of the pipeline is severely threatened due to stress concentration on the pipeline as a result of settlement of its foundation following such high filling [1]. Uneven settlement is one of the major reasons for buried pipeline damage [2]. In view of this problem, rectification measures were proposed and their safety rationality was calculated through an analysis of stresses on the high filled section of pipelines.

1. Project overview

For a long-distance X65 steel gas pipeline crossing Class III areas, with pipe diameter of 508 mm, wall thickness of

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7.9 mm, and designed pressure of 6.3 MPa, its 500 m section is laid underneath a planned road. Due to adjustment of road elevation, the thickness of required backfill above the pipe is up to 34 m at maximum, exceeding the maximum buried depth allowed. Furthermore, the pipeline would face settlement cracking and rupturing risks because of the backfilling and rolling compaction during the construction of roads above this section of the pipeline.

2. Rectification principles

Generally, all long-distance oil and gas pipelines are laid underground with surrounding soil as support and protection. The pipe-soil interaction element model is often used to simulate the soil movement and the interaction between the pipe and its surrounding soil. Simulation of the contact surface between the pipe and soil body is suitable for the issue of interaction between the deeply buried pipeline and its surrounding soil, which simplifies the simulation of pipe-soil contact [3].

For a buried pipeline, the surrounding soil can be regarded as elastic soil with a certain compressive stiffness coefficient, and the action of the soil on the pipe is in the form of active earth pressure and passive earth pressure. The backfill above the pipe is regarded as load and the soil underneath it as the elastic foundation [4]. The interaction between the pipe and soil is taken as the process of an elastic spring applying force and the pipe's reaction as an elastic foundation beam. This method is suitable for cases with small to medium ground deformation [5].

The safety rationality of our rectification scheme was judged by performing stress analysis of the rectification scheme for the pipeline laid underneath a high filling planned road using the ABAQUS finite element software, in which beam elements were used to simulate the pipe, the backfill above the pipe was regarded as load, and the elastic foundation underneath the pipe was simulated as an evenly-distributed spring.

3. Case study

3.1. Innovation design

The wall thickness of this section of pipeline is 7.9 mm; according to Section 5.1.4 in GB50251-2003 “Code for Design of Gas Transmission Pipeline Engineering” [6], when a pipeline's buried depth is large or the external load is high, its stability should be checked assuming there is no internal pressure. For the evaluation of a pipeline's radial stability according to the Code, the pipe deformation is calculated by using the IOWA formula, where the ΔX calculated should not exceed 3% of the pipe's outer diameter [7].

$$\Delta X \le 0.03D \tag{1}$$

$$\Delta X = \frac{ZKWD_{\mathrm{m}}^3}{8EI + 0.061E_{\mathrm{s}}D_{\mathrm{m}}^3} \tag{2}$$

$$\mathrm{W} = \mathrm{W}_1 + \mathrm{W}_2 \tag{3}$$

$$I = \frac{\delta_n^3}{12} \tag{4}$$

Where, D is the steel pipe's outer diameter, m; ΔX is the steel pipe's maximum horizontal deformation, m; D_{m} is the steel pipe's average diameter, m; W is the total vertical load acting on unit pipe length, N/m; W_1 is the vertical permanent load on unit pipe length, N/m; W_2 is the portion of ground variable load transferred onto the pipe, N/m; Z is the steel pipe's deformation lag coefficient, which is 1.5 in this case; K is the base coefficient; E is the pipe's elastic modulus, MPa; I is the cross-sectional moment of inertia of unit pipe length, m^4/m; δ_{n} is the steel pipe's wall thickness, m; E_{s} is the deformation modulus of backfill, MPa.

As was calculated by using the IOWA formula, the minimum wall thickness of the pipe required when the backfill above the pipe is 34.2 m thick should be 14.07 mm. Therefore, the pipe's current wall thickness can not meet the radial stability requirement. The calculation results are shown in Table 1.

Currently, long-distance pipelines in high filling planned areas are mostly protected by culverts. A protection culvert usually uses 4 m-span reinforced concrete covered culvert, and its pile foundation has a headroom of approximately 2 m. To prevent the damage caused by natural gas leakage, sand is generally backfilled into the protection culvert. Because the pipeline in this project is laid underneath a planned road with big elevation change, part of the pipeline ditch is at high steep slope, making piling very difficult; besides, a large working face is required for pipe culvert construction; the construction of the culvert is long in cycle; and the cost is high; it's difficult to meet the local government's requirement on road construction schedule. Compared with the protection culvert scheme, the scheme of increasing the pipe thickness has the advantages of shorter construction cycle, reduced impact on road construction and a lower cost. For this reason, the scheme of increasing the pipe thickness to 14.2 mm was chosen as our rectification scheme.

3.2. Foundation settlement calculation

This section of the pipeline passes through an area of denudated hill of weathered denudation with large overall topographic undulation at an altitude of 111.35–148.38 m. The soil at this pipeline section mainly consists of plain fill, silty clay and pebble soil, and the lower bedrock is Cretaceous glutenite and sandstone. In foundation settlement calculation,

Table 1
Radial stability checklist.

Wall thickness/mm	Buried depth/m	Total load/(kN·m)	ΔX/m	ΔX/D	Check result
7.90	34	328.6	0.071 6	14.1%	Unqualified
14.07	34	328.6	0.015 2	3.0%	Qualified