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تحليل الضغط والازاحة لخطوط أنابيب النفط والغاز الهوائية: دراسة حالة مشروع النفق في لانتسانج

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الخلاصــة

مشروع النفق في لانتسانج يشمل على ثلاثة خطوط أنابيب متوازية من الغاز والنفط الخام والنفط المكرر ونظرا لحالة معقدة للنفق، وخصائص انحدار حاد للنفق ، وحقيقة أن المشروع يقع في منطقة زلزال خطرة، فإن المشروع ذو أهمية كبيرة لضمان سلامة العمليات. لذلك فإنه يتطلب تحليل الضغط والإزاحة على خطوط الأنابيب الثلاثة. وبواسطة التحليل بواسطة العناصر المحدودة، تم استخدام برنامج CAESAR II لإنشاء نموذج الإجهاد التحليلي لخطوط الأنابيب في النفق. وتم تحليل الضغط والإزاحة على خطوط الأنابيب الثلاثة تحت الظروف الطبيعية. وتم استخلاص الاستنتاجات التالية: (1) بعد دراسة شاملة لتوزيع الضغط في خطوط الأنابيب الثلاثة، وجد بأن إنحناء الأول والثاني كانت على الأجزاء الأكثر خطورة في الأنابيب، (2) ينبغي رصد الأزاحة لخط أنابيب الضغط العالي لا سيما من خلال المشروع، (3) الأزاحة المحورية هي مفتاح للمصادقة على تشريد خطوط أنابيب النفق.

Stress and displacement analysis of aerial oil & gas pipelines: A case study of Lantsang tunnel crossing project

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ABSTRACT

Lantsang tunnel crossing project involves three parallel pipelines of gas, crude oil and refined oil. Due to the complex condition of lagging in the tunnel, the characteristics of steep slope tunnel and the fact that the project is located at earthquake fault zone, it is of great significance to ensure the safety of operation. Therefore, stress and displacement analysis are required on the three pipelines. Based on beam element and finite element analysis, CAESAR II software was used to establish stress analytical model for the pipelines in Yanyingshan tunnel. Stress and displacement analysis of the three parallel pipelines under normal condition were conducted. The following conclusions were drawn: (1) after comprehensive consideration of the stress distribution of the three pipelines, it was determined that Bend 1 and Bend 2 were the most risky sections in Yanyingshan tunnel pipelines; (2) the displacement of high pressure pipeline should be particularly monitored during engineering project; (3) axial displacement is the key of displacement validation of pipelines penetrating the tunnel.

Keywords: Aerial; displacement; finite element method; oil & gas pipelines; stress; tunnel crossing project.

INTRODUCTION

Oil and gas pipelines fail in tunnels for a number of reasons. In addition to design errors, the quality of construction, pipeline corrosion and fatigue, and insufficient strength in bends of pipelines can all contribute to pipeline failure. Therefore, it is vital to carry out stress analysis of pipelines in appropriate settings before construction begins.

The study of pipe stress can be traced back to 1930s, when method of structural mechanics was used (Watkins & Anderson, 1999). With decades of development, elastic center method (Sokolnikoff & Specht, 1956; Yu & Lv, 2008), methods of statically indeterminate structure as well as matrix method of structural analysis were studied (Zhang, 1993; Peng, 1978). In recent years, with the fast development of computational techniques, commercial software is mostly used to conduct stress calculation and analysis in both research and engineering projects. Common software includes ANSYS and CAESAR II.

In 2012, Wu *et al.* conducted stress analysis on gas pipeline in operating tunnel. Analytical model of gas pipeline in inclined tunnel structure was proposed and stress distribution of pipeline in normal condition was acquired (Wu *et al.*, 2012). Huang *et al.* established stress analytical model of gas pipeline in typical mountain region (Huang *et al.*, 2012). In 2013, Wu *et al.* proposed stress analytical model of gas pipeline in shaft tunnel structure and stress distribution in pressure test condition was acquired (Wu *et al.*, 2013). Huang *et al.* conducted discussion on the support spacing of gas pipeline penetrating inclined tunnel (Huang *et al.*, 2013). In 2014, Wang *et al.* conducted impact analysis of pipeline in tunnel under the effect of pipe cleaning using ABAQUS software based on finite element method (Wang *et al.*, 2014).

In recent two years, the analyzed objects of pipeline stress moved gradually to special conditions or special regions, such as: earthquake, landslip and swamp. In 2014, Chen *et al.* proposed stress analytical method of gas pipeline under the effect of transverse and vertical landslip (Chen *et al.*, 2014a). In the same year, stress analytical method of gas pipeline in swamp condition was proposed by the same researcher (Chen *et al.*, 2014b). In 2015, Wu *et al.* proposed stress analytical method of oil pipeline in mountain region under the effect of earthquake (Wu *et al.*, 2015). Lu *et al.* conducted case study and analysis on the positive displacement pump pipeline system in oil station (Lu *et al.*, 2015).

The China-Burma natural gas pipeline is one of the key projects during the “Eleventh Five-year” period. The total length of the main pipeline is 1726.8 km. There are 64 mountain tunnels along the China Burma gas pipeline in which gas and oil pipelines share 55 mountain tunnels. As the tunnel structure of China-Burma pipeline is different from typical tunnel structure, urgent repair is difficult when accident occurs. In order to reduce safety hazards, it is necessary to conduct stress and displacement analysis on the three pipelines in the tunnel. Although studies of stress analysis on gas pipeline penetrating tunnel have been conducted worldwide, stress analysis on three pipelines penetrating simultaneously is rare.

Lantsang bridge and tunnel crossing project is located at the boundary of Baoshan City and Dali City, Yunan Province. Yanyingshan tunnel of Lantsang tunnel crossing project was selected as an example in this study. Three-pipeline model was established to analyze the stress and displacement distribution of the three pipelines during normal operating condition. Relevant procedures were proposed accordingly.

THEORY AND METHOD

Tunnel structure

The basic form of a tunnel-laid pipeline follows the "inclined shaft-level-inclined shaft" structure, and can be divided into two parts: the pipeline in the tunnel and the pipeline outside the tunnel. The pipe piers and lines in a typical tunnel are laid out as shown in Figure 1, where fixed piers A and H are installed on both sides of the model. The pipeline at the entrance (L_1) and exit (L_5) of a tunnel is generally laid horizontally and covered by soil, and no buttresses are used. L_2 is the length of the western inclined shaft, with an angle of α, and anchor block C is installed in the middle. L_4 is the length of the eastern inclined shaft, with an angle of β, and anchor block F is installed at a distance from bend G. If α exceeds 20°, the tunnel is categorized as steep slope tunnel. Moreover, at section L_2, multiple dip angles exist and each segment is connected by bends.

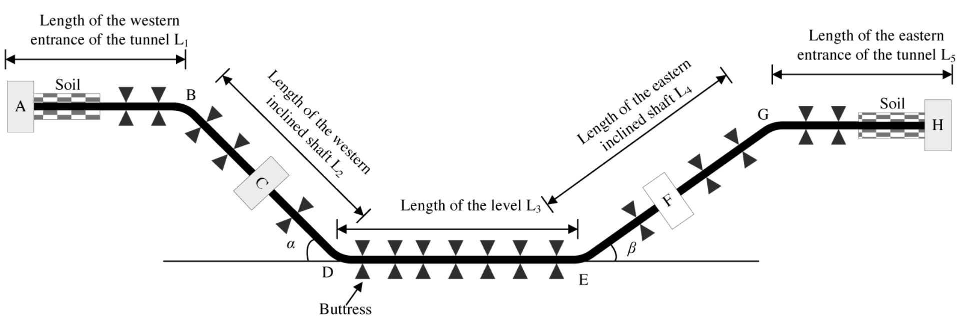


Fig. 1. Schematic diagram of tunnel structure.

For pipelines in Yanyingshan tunnel, in the direction of flow, crude oil pipeline is located at the left part of the tunnel, gas pipeline at the right part and refined oil pipeline d2 m above the crude oil pipeline. The clear spacing between gas pipeline and crude oil pipeline was 1.2 m. According to the terrain of the tunnel portal and elevation of pipeline in the tunnel, the connection of pipelines inside and outside the tunnel was achieved by bend and the burial depth of the top of external pipeline was larger than 1.2 m. With consideration of the fact that the slope of the tunnel is large and the requirement of compensation of span section pipeline, the pipelines in the tunnel were lagged as overhead on the piers (Figure 2).

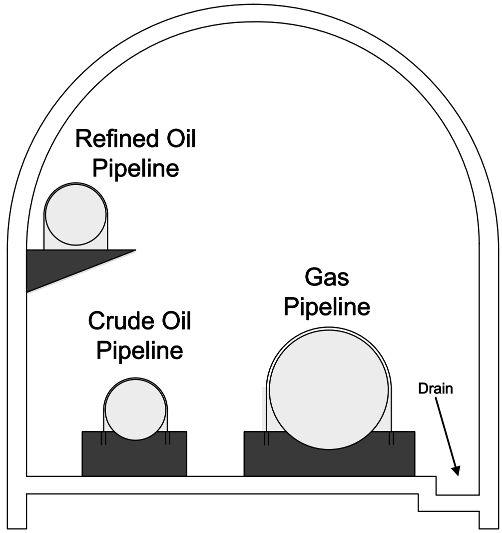


Fig. 2. Vertical section of the pipelines in the tunnel.

Finite element model of the pipelines

For pipeline of long distance, beam model is often used for stress analysis. In beam model, the specific assumptions are listed in (Wu *et al.*, 2015). ANSYS and CAESAR II are both based on finite element method. Different from ANSYS, meshing in CAESAR II is achieved according to the nodes of the pipeline. The gravity force of pipeline between the two nodes is sustained by the two nodes and calculation of stress and displacement is achieved by the nodes (Wu *et al.*, 2015; Jiang *et al.*, 2013; Sreejith *et al.*, 2004). In order to ensure the accuracy and simplicity of calculation, the length of a section of pipeline should be smaller than 20 times the pipe diameter, if the pipe diameter is larger than 304.8 mm; and it should be smaller than 30 times the pipe diameter if the pipe diameter is smaller than 304.8 mm.

Beam model is used for both bend pipe and straight pipe. For bend pipe, oblateness is produced due to bending and thus stress strengthening coefficient is introduced, which can be calculated as discussed in (ASME 2012a). Furthermore, when establishing finite element model of bend pipe, hot-bended bend pipe and cold-bended bend pipe should be distinguished. The degree of bending of cold-bended bend pipe is small and can be achieved by the flexibility of the pipe. The radius of curvature is taken as R=40D. For hot-bended bend pipe, the degree of bending is large and cannot be achieved by gravity and flexibility of itself. The degree of curvature is taken as R=6D.

Boundary condition

In order to prevent bending caused by the weight of the entire pipeline system, fixed piers are installed to eliminate the effects of the pipeline outside the tunnel on the pipeline inside the tunnel. In practical applications, fixed piers are mitered, and deviate from adjacent joints of the pipeline system. Therefore, fixed piers are constrained from displacing and bearing axial forces, but they can bear bending moments and shear forces.

Standards for stress and displacement of pipelines

CAESAR II is capable of choosing different stress validation standard according to different conditions. ASME B31.8 *Gas Transportation and Distribution Piping Systems* (ASME 2012c) is normally used for gas pipeline while ASME B31.4 *Pipeline Transportation Systems for Liquids and Slurries* (ASME 2012b) is used for oil pipeline. For the validation of displacement (GB 50251; GB 50316), GB 50251 *Code for design of gas transmission pipeline engineering* is used for transverse displacement validation and GB 50316-2008 *Design code for industrial metallic piping* is used for axial displacement and angular displacement.

Checking stress

According to different load sustained by the pipeline, the stress of pipeline in normal condition can be categorised as: primary stress, secondary stress, and peak stress (Song, 2011). The primary stress represents the effect of internal pressure and gravity on the stress, secondary stress represents the effect of difference in temperature on the stress and peak stress is the combination of primary stress and secondary stress. The general equation of stress validation is:

$$\sigma \leq F\sigma_s$$

which σ represents stress; F is the design coefficient of which the values are listed in Table 1; σ_s is the minimum yield strength of the pipeline material.

Primary stress is calculated as follows:

$$\sigma_L = \frac{F_{ax}}{A} + \frac{PD}{4S} + \frac{M}{W} \tag{1}$$

where σ_L is primary stress, MPa; F_{ax} is additional axial force which is caused by pressure, N; A is pipe cross-sectional area, mm^2; P is pressure, MPa; D is pipeline diameter, mm; S is pipeline thickness, mm; M is synthetic bending moment, N·mm; W is bending section modulus, mm^3.

Secondary stress is calculated as follows:

$$\sigma_E = \frac{M_E}{W} \tag{2}$$

where σ_E is secondary stress, MPa; M_E is bending moment of thermal expansion, N·mm; W is bending section modulus, mm^3.

Table 1. Values of the design coefficient (F)

Stress type	Gas pipeline	Oil pipeline
Peak stress	0.90	0.90
Primary stress	0.75	0.72
Secondary stress	0.72	0.90

Checking displacement

Displacement validation focuses on transverse and axial displacement. GB 50251 *Code for design of gas transmission pipeline engineering* requires that transverse displacement does not exceed 0.03 times of the diameter of the pipeline. GB 50316-2008 *Design code for industrial metallic piping* requires that axial displacement does not exceed 0.4 time of the length of pipeline support. The angular displacement of a horizontal pipeline is generally required to be no greater than 4°.

CASE STUDY

Pipeline project profile

The total length of Yanyingshan tunnel was 1.9 km. Three pipelines were lagged as overhead on the piers with a spacing of piers of 10 m. The coefficient of friction between the pier and pipeline was 0.6. The exit and entry of the tunnel were sealed by cement and fixed pier 1 and fixed pier 2 were constructed to cut off the influence of pipeline outside the tunnel. In the direction of flow, there was a horizontal pipeline with a length of 15 m at the entry of the tunnel, followed by a steep slope pipeline in the tunnel with a dip angle of 23°. Finally, there was a pipeline with small dip angle at both ends. The length of the pipeline was 540 m and 585 m and the dip angle was 7.43° and 6.17°, respectively. The direction of pipelines are shown in Figure 3.

The piers of gas pipeline and crude oil pipeline were located and lagged at the same surface with a clear spacing of 1.2 m. The refined oil pipeline was located 2 m above the crude oil pipeline. X80 steel pipe was used for gas pipeline with a transportation temperature of 38°C and operating pressure of 10MPa; X70 steel pipe was used for crude oil pipeline with a transportation temperature of 28°C and operating pressure of 15MPa, but no insulation was provided; X52 steel pipe was used for refined oil pipeline with a transportation temperature of 15°C and operating pressure of 12MPa. Specific pipeline parameters are given in Table 2 and the parameters of bends are given in Table 3.

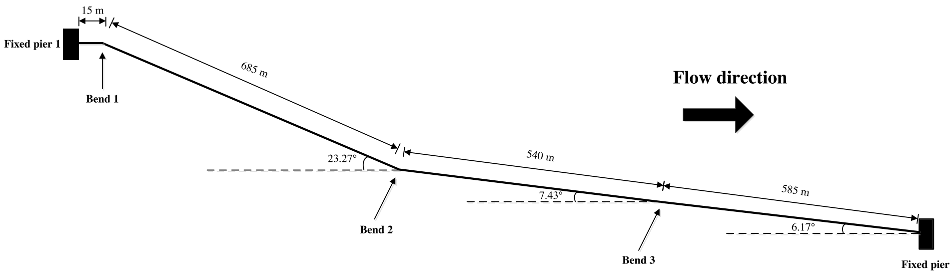


Fig. 3. Schematic diagram of pipeline directions in the tunnel.

Table 2. Parameters of pipelines

Pipeline	Material	Diameter (mm)	Wall thickness of straight pipe (mm)	Wall thickness of Pipe bend (mm)	Temperature (°C)	Pressure (MPa)	Fluid density (kg/ m^3)	Minimum yield stress (MPa)
Gas	X80	1016	22.9	26.4	38	10	0.784	551
Crude oil	X70	813	28.6	31.8	28	15	866.6	482
Refined oil	X52	219.1	8.7	9.5	15	12	725	360

Table 3. Parameters of bends

Bend	Type	Remark
Bend 1	Hot-bending bend	R=6D
Bend 2	Hot-bending bend	R=6D
Bend 3	Cold-bending bend	R=40D

Numerical simulation

Basic model

A pipeline model was established according to the actual strike of the pipeline, and mainly consisted of straight pipes and bends.

Simplification of constraints

According to the actual conditions of the pipeline in a tunnel, constraints were simplified and loaded to the pipelines. There were two constraint models in total:

(I) Fixed pier model: It was capable of bearing bending moments and shear forces, but could not displace or bear axial forces;

(II) Buttress: Buttress constraint includes pipe pier and pipe strap locate at the bottom of the pipeline, which constrain movement of pipeline other than axial movement. In CAESAR II, two-directional vertical constraints (+Y and -Y) and two-directional transverse constraints (+Z and -Z) are used for buttress. Besides, coefficient of friction between the pipe strap and the pipeline needs to be defined.

Operating conditions

The loads applied to pipelines from production to operation differ. Therefore, on the basis of analytical needs, different operating conditions were established. In order to analyze whether the primary stress, secondary stress, and peak stress of the pipelines met the standards, different operating conditions were established in CAESAR II software according to the characteristics of the various types of stress, as shown in Table 4.

Table 4. Load cases.

Operating conditions	Representation in CAESAR II	Remark
Operating conditions for the calculation of peak stress	*W+T+P*	A combination of primary stress and secondary stress
Operating conditions for the calculation of primary stress	*W+P*	A result of gravity and pressure
Operating conditions for the calculation of secondary stress	*T*	A result of the difference in temperature

RESULTS

Stress checking

In normal conditions, the validation of peak stress, primary stress and secondary stress of the three pipelines in Yanyingshan tunnel is listed in Table 5. It is evident that the stress of the three pipelines in normal condition met the standard of validation of ASME B31.8.

It is clear from Figure 4 that:

(I) For gas pipeline, the peak stress was the highest, followed by primary stress and the secondary stress was the smallest, which demonstrates that difference in temperature has the least effect on the stress of gas pipeline. The highest stress occurred at Bend No.2 which shows that Bend No.2 was the most risky section of the gas pipeline, being at the bottom of the steep slope tunnel.

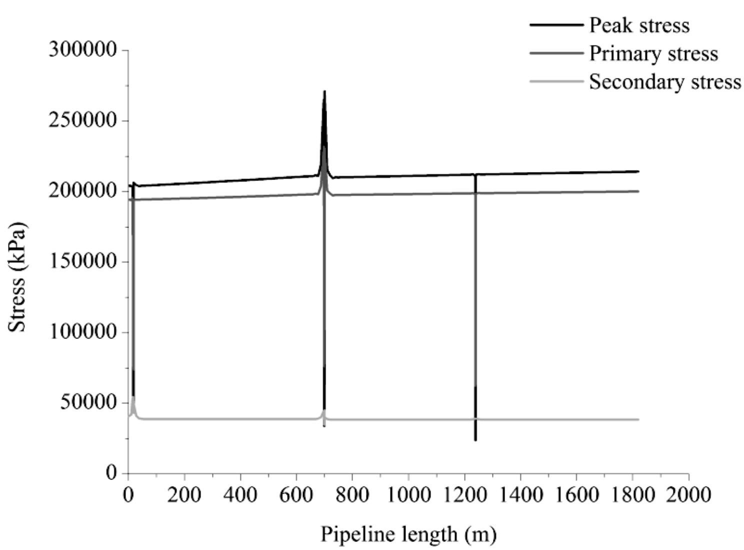
(II) For crude oil pipeline, the primary stress was the highest, followed by peak stress and the primary stress was very small, which demonstrates that crude oil pipeline penetrating the tunnel is affected significantly by pipeline pressure. The maximum stress occurred at Bend No.2 suggesting that Bend No.2 was the most risky section of the crude oil pipeline.

(III) For refined oil pipeline, the peak stress was the highest, followed by primary stress and the secondary stress was the smallest. The maximum stress occurred at Bend No.1 suggesting that Bend No.1 was the most risky section of the refined oil pipeline.

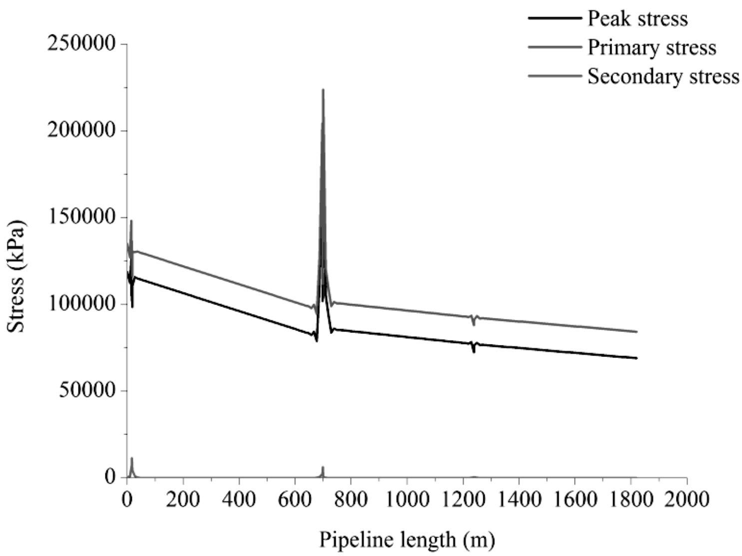
(IV) As the three pipelines were parallel lagged, the specific condition of the three pipelines should be considered overall during pipeline design. According to the results of stress validation, it is recommended that stress at Bend No.1 and No.2 be monitored and controlled specifically.

Table 5. Condition of stress validation of the three pipeline in normal conditions.

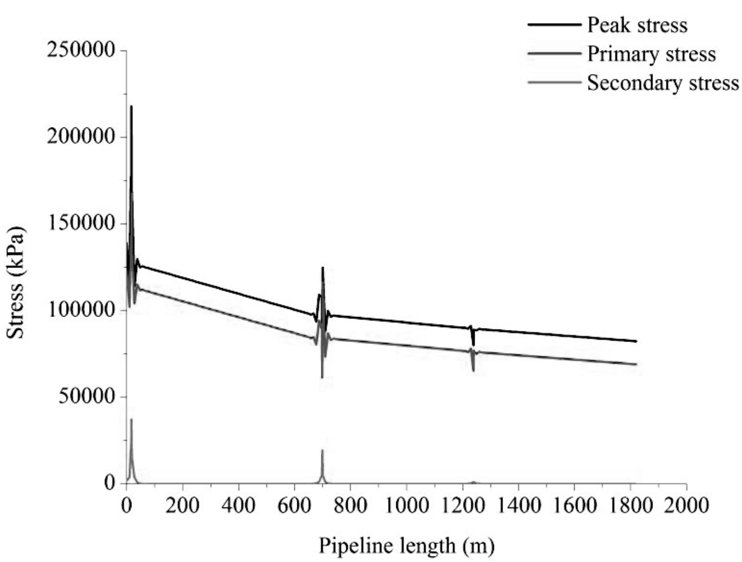
Pipeline	Peak stress		Primary stress		Secondary stress	
	Maximum value (MPa)	Requirement (MPa)	Maximum value (MPa)	Requirement (MPa)	Maximum value (MPa)	Requirement (MPa)
Gas pipeline	271.09	551×0.9=495.9	232.26	551×0.75=413.3	54.65	551×0.72=396.7
Crude oil pipeline	209.22	482×0.9=433.8	223.86	482×0.72=347.0	11.34	482×0.9=433.8
Refined oil pipeline	217.97	360×0.9=324.0	167.80	360×0.72=259.2	37.30	360×0.9=324.0



(a)



(b)



(c)

Fig. 4. Stress distribution of (a) Gas pipeline; (b) Crude oil pipeline; (c) Refined oil pipeline.

Displacement validation

In normal condition, the axial displacement and vertical displacement of the three pipelines are shown in Figure 5 and Table 6 (the lateral displacement was 0). It is clear that:

(I) When the length of pier was 1.5 m, according to GB 50316-2008 *Design code for industrial metallic piping*, the axial displacement of the pipeline must not exceed 150 cm×0.4=60 cm. The maximum angular displacement of the pipeline was 0.26°, which was smaller than 4°, indicating that the section of parallel oil and gas pipelines met displacement requirements

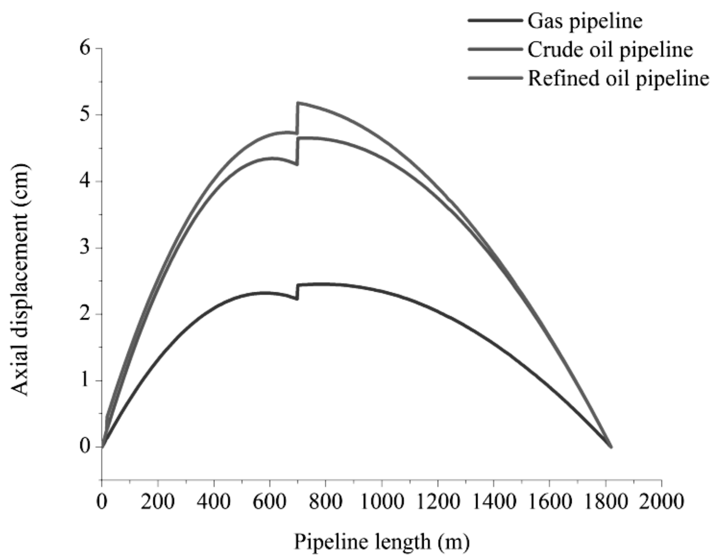
(II) The overall axial displacement of the pipelines was larger than vertical displacement, suggesting that axial displacement was the key of displacement validation of the pipeline.

(III) Judging from the axial and vertical displacement distribution of the pipelines, the axial displacement of refined oil pipeline was the largest, followed by crude oil pipeline and gas pipeline. The displacement of high pressure pipeline should be particularly monitored during practical engineering.

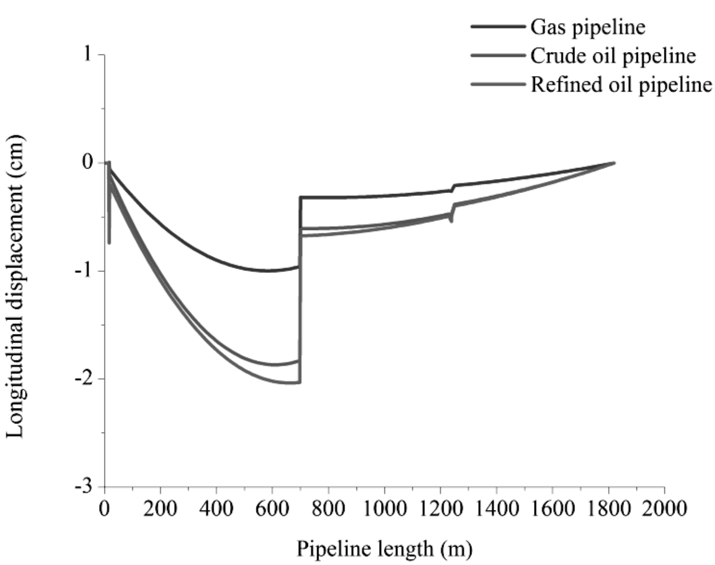
(IV) Sudden change of axial and vertical displacement was witnessed at Bend 2 due to the lack of support at Bend 2 and the high flexibility and deformability of the bend.

Table 6. Checking of the maximum displacement

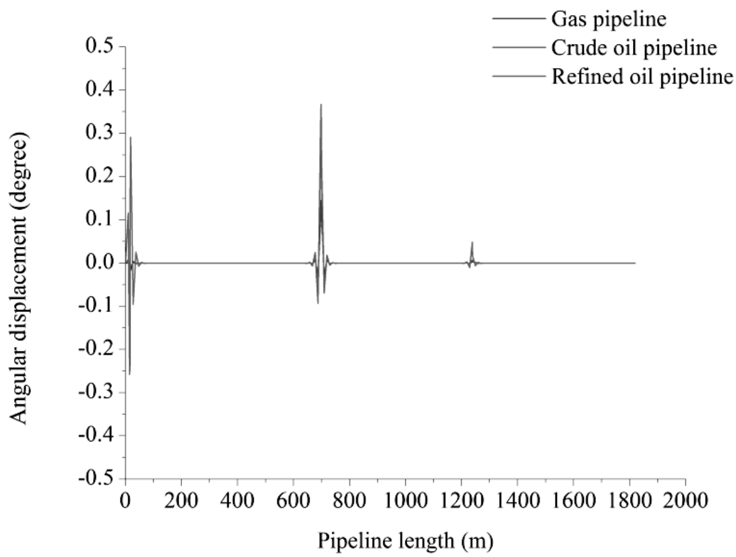
Pipeline	Maximum axial displacement		Maximum longitudinal displacement		Maximum angular displacement	
	Absolute value (mm)	Requirement (mm)	Absolute value (mm)	Requirement (mm)	Value (degree)	Requirement (degree)
Gas pipeline	24.56	600	9.97	-	0.03	4
Crude oil pipeline	46.56	600	18.68	-	0.06	4
Refined oil pipeline	51.83	600	20.36	-	0.26	4


Gas pipeline
Crude oil pipeline
Refined oil pipeline
Axial displacement (cm)
Pipeline length (m)
0
1
2
3
4
5
6
0
200
400
600
800
1000
1200
1400
1600
1800
2000

(a)


Gas pipeline
Crude oil pipeline
Refined oil pipeline
Longitudinal displacement (cm)
Pipeline length (m)
1
0
-1
-2
-3
0
200
400
600
800
1000
1200
1400
1600
1800
2000

(b)



(c)

Fig. 5. Displacement distribution of the pipelines (a) Axial displacement; (b) Longitudinal displacement; (c) Angular displacement.

CONCLUSION

With respect to a project, where three pipelines parallel penetrated inclined tunnel, the gas, crude oil and refined oil pipeline models were established based on beam model using finite element analysis. The constraints of actual project were simplified and stress and displacement analysis of the three pipelines under different conditions were conducted. Based on the analysis of pipelines under normal conditions, the locations of the critical sections and the main loads affecting stress of the gas, crude oil and refined oil pipelines running through a tunnel were obtained. It is concluded that: (1) after comprehensive consideration of the stress distribution of the three pipelines, it was determined that Bend No.1 and No.2 were the most risky sections in Yanyingshan tunnel pipelines; (2) axial displacement is the key of displacement validation of pipelines penetrating the tunnel; (3) the displacement of high pressure pipeline should be particularly monitored during engineering project.

This study fills the technological gap in stress analysis of parallel oil and gas pipelines that run through tunnels, provides designers with a knowledge base, and helps to ensure the safe operation of such pipelines.

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