STABILITY ANALYSIS OF CROSS-SECTION OF DOUBLE-ROW LARGE-DIAMETER PIPELINE BASED ON BIM TECHNOLOGY

Fengtian Hao[1], Yueyue Zhang[2]
[1]*School of Construction Management, Jiangsu Vocational Institute of Architectural Technology, Xuzhou, Jiangsu, 221116, China*
[2]*Zheng Zhou Railway Vocational & Technical College, Zhengzhou, Henan, 450000, China*
E-mail:Haofengtian12@163.com

ABSTRACT*: For X80 pipeline with 1219mm diameter as the representative, an analysis method of the pipeline cross-section stability based on BIM technology is proposed in this paper. The general theory related to the internal force and deformation under the pressure of overburden mound load of the pipeline is described. The displacement field and stress characteristics of ground under the pressure of ground load are analyzed. The soil pressure around the cross-section of the pipeline under the pressure of ground load is calculated. The instability law of pipeline cross-section for the case of vertical load is summarized. According to the basic theory of pipeline cross-section stability, the influence factors of pipeline cross-section instability are analyzed. According to the requirement of the stability check, the criterion for the stability of the cross-section of the double-row large-diameter pipeline under the pressure of external load is determined. The dynamic response and deformation law of the cross-section of the double-row large-diameter pipeline under the impact of rockfall are analyzed by ABAQUS software and BIM Technology. The stress-strain response of the cross-section is obtained. The reasons of the pipeline cross-section instability have been clarified, which provide some reference for the pipeline construction and protection.*

KEYWORDS*: BIM technology; double-row; large-diameter pipeline; cross-section; stability*

1 INTRODUCTION

With the acceleration of urbanization, land has become a scarce resource. The use of underground space will inevitably become an important direction in the development of buildings. The development of the underground pipeline transportation system will help to alleviate the problem of congestion in the city and save a lot of land. Construction of foundation pit excavation, static pressure pile, pipe jacking, and precipitation can cause an inevitable disturbance to the surrounding environment. The uplift, settlement and lateral displacement of the surrounding soil will appear. The pipeline is a shallow buried infrastructure, which is sensitive to the displacement of the surrounding soil, and easily disturbed by the construction of the engineering. In the process of urban construction, the construction of ground buildings causes the pipeline to overload the ground.

The safety of the operation of buried pipeline is directly related to the stability of people’s normal life and social stability. Because of the imperfect management system, a large number of illegal buildings are built near the buried pipelines, and some are even directly placed above the buried pipeline. The effect of the overlying soil on the buried pipeline and the lateral displacement of the ground or soil will cause longitudinal bending, breaking, and rupture of the pipeline when these loads are too large to exceed their bearing range. Ignoring the ground loading will bring the hidden danger to the buried pipeline. A safety accident caused by a large number of loads on and around the buried pipeline and even more than the stability requirements of the pipeline will happen from time to time.

2 STABILITY ANALYSIS OF CROSS-SECTION OF DOUBLE-ROW LARGE-DIAMETER PIPELINE BASED ON BIM TECHNOLOGY

2.1 Stress analysis of double-row large-diameter pipeline under load

First, the double-row large-diameter pipeline model and the soil model are built by using BIM technology. The displacement field and stress characteristics of ground foundation under the pressure of ground load are analyzed. Then the calculation method of soil pressure of double-row large-diameter pipeline under the pressure of ground load is introduced (Huang,2015).

(I) Calculation of vertical stress of ground soil under local load

(1) Geostatic pressure of ground soil

Assume the natural foundation is a horizontal homogeneous isotropic semi-infinite body. The interface of each soil layer is horizontal. There is no shear stress on an arbitrary vertical plane. The total stress σ_z produced by the weight of soil at the depth z is given by

$$\sigma_{oz} = \sum_{i=1}^{n} \gamma_i h_i n i \quad (1)$$

where n is the number of soil layers from the ground to the depth z, h_i is the thickness of the i th soil layer, and γ_i is the bulk density of the i th soil layer.

(2) Calculation of vertical stress of ground soil under concentrated load

According to Boussinesq solution, the vertical stress and vertical displacement of the ground soil at any point are given by

$$\sigma_z = \frac{3P}{2\pi}\frac{z^3}{R^5} \quad (2)$$

$$\delta_z = \frac{P}{4\pi G}\left[\frac{z^2}{R^3} + \frac{2(1-\mu)}{R}\right] \quad (3)$$

where G is the shear modulus of soil, P is the elastic modulus of soil, μ is the Poisson's ratio of soil, R is the distance from the calculated point to load acting point.

(3) Calculation of vertical stress of ground soil under uniform distributed load

A uniform distributed load is acted on the surface of a semi-infinite elastic body. Assume the density of the load is ρ, and it is uniformly distributed along the y axis and extended indefinitely. The stress and strain in the ground are not changed in the direction of y axis, and the strain component is 0 , which belongs to the problem of plane strain. It can be obtained by integral of stress in ground under concentrated load, given by

$$\sigma_z = \int_{-\infty}^{+\infty} \frac{3z^3}{2\pi(x^2+y^2+z^2)^{\frac{5}{2}}} p\,dy = \frac{2Pz^3}{\pi(x^2+z^2)^2} \quad (4)$$

(4) Calculation of vertical stress of ground soil under strip uniform distributed load

When the ground is a semi-infinite elastic body and the surface is acted by the strip uniform distribution load, stress distribution can be obtained by solving the stress of ground soil under strip uniform distributed load. The width of the load distribution is $2b$, stress component in ground is obtained by integral, which is given by

$$\sigma_z = \frac{P}{\pi}\left(arctg\frac{b-x}{z} + arctg\frac{b+x}{z}\right) - \frac{Pb(x^2-z^2-b^2)}{\pi\left[(x^2+z^2-b^2)^2+4b^2z^2\right]} \quad (5)$$

(5) Calculation of vertical stress of ground soil under rectangular uniform distributed load

Range of action of uniform rectangular load is $B \times L(2b \times 2l)$, where b is the short side length of rectangular area and l is the long side length of rectangular area. Assume the density of load is p, and center point of rectangular load is O. Vertical stress component in ground is given by

$$\sigma_z = \frac{3pz^3}{\pi}\int_{-l}^{l}\int_{-b}^{b}\frac{1}{\left[(x-\xi)^2+(y-\eta)^2+z^2\right]^{5/2}}d\xi\, d\eta \quad (6)$$

where ξ is the shear coefficient of soil and η is the elastic coefficient of soil.

At the arbitrary depth below the center point of the rectangular load, the vertical stress component of the double-row large-diameter pipeline at the coordinates of $(0,0,z)$ is expressed as

$$\sigma_{z0} = \frac{2p}{\pi}\left[arctg\frac{bl}{z(l^2+b^2+z^2)^{1/2}} + \frac{blz(l^2+b^2+z^2)}{(l^2+b^2)(b^2+z^2)(l^2+b^2+z^2)^{1/2}}\right] \quad (7)$$

At the arbitrary depth below the coner point of the rectangular load, the vertical stress component at the coordinates of $(\pm b, \pm l, z)$ is expressed as

$$\sigma_{z0} = \frac{2p}{\pi}\left[arctg\frac{4bl}{z(4l^2+4b^2+z^2)^{1/2}} + \frac{4blz(l^2+b^2+z^2)}{(4l^2+4b^2)(4b^2+z^2)(4l^2+4b^2+z^2)^{1/2}}\right] \quad (8)$$

According to the superposition principle, the vertical stress component at any point in the ground under rectangular load can be calculated by using Eq. (8). If the point is below the load surface, the rectangular abcd can be divided into four new rectangles I, II, III, and IV with M point as the common point. The vertical stress component of M point produced by the rectangular abcd load can be superimposed by the vertical stress components of M point produced by the divided four rectangular loads, that is,

$$\sigma_{z,M} = (\sigma_z, M)_{\mathrm{I}} + (\sigma_z, M)_{\mathrm{II}} + (\sigma_z, M)_{\mathrm{III}} + (\sigma_z, M)_{\mathrm{IV}} \quad (9)$$

If M is outside of the rectangular load surface, the load surface can be expanded to $beMh$, and the load density is unchanged. The vertical stress component $\sigma_{z,M}$ of M point under rectangular load is given by

$$\sigma_{z,M} = (\sigma_z, M)_{M'ebh} + (\sigma_z, M)_{M'eah} + (\sigma_z, M)_{M'fch} + (\sigma_z, M)_{M'fdh} \tag{10}$$

(II) Calculation of lateral earth pressure on underground structure

Under the overburden mound load, the ground produces not only vertical deformation, but also lateral deformation. Especially, the elastic modulus of soft clay is very low, and the lateral deformation of the ground is more significant (Sun,2015).

(1) Rankine earth pressure theory

Rankine earth pressure theory is often used to calculate the lateral earth pressure on the cross-section of double-row large-diameter pipeline under local overload. The calculation equation is given by

$$q_0 = K_h \gamma_i H_1 \tag{11}$$

$$K_h = \tan^2(45^\circ - \frac{\varphi}{2}) \tag{12}$$

where K_h is the lateral earth pressure coefficient, φ is the internal friction angle of soil, and H_1 is the height of the calculation point to the surface of the filled soil. Rankine earth pressure theory does not take into account the effect of the vertical load on the depth diffusion, and the value is larger.

(2) Boussinesq formula

Starting from Boussinesq solution, the calculation formula of the lateral pressure of ground soil under local load is derived. The formula is simple and convenient to calculate the lateral pressure on the underground structure.

(i) Lateral pressure under concentrated load

Boussinesq solution is spatial solution and its horizontal stress formula is given by

$$\sigma_x = \frac{3\Psi}{2\pi}\left\{\frac{x^2 z}{R^2} + \frac{1-\mu}{3}\left[\frac{R^2 - Rz - z^2}{R^3(R+z)} - \frac{x^2(2R+z)}{R^3(R+z)^2}\right]\right\} \tag{13}$$

where Ψ is the concentrated force acting on the coordinates of the origin and vertical to the ground.

(ii) Lateral pressure at the middle point of the long side of rectangular area

The uniformly distributed load q is acted on the rectangular area $l \times b$. To calculate the lateral pressure Φ_x at M point below the middle point O of the long side l of rectangular area, the unit area $dA = dxdy$ is taken in the rectangular area. The concentrated force acting on the unit area is $d\Psi = qdxdy$. Then the lateral pressure Φ_x is obtained by using

$$\Phi_x = \int_{y=-\frac{b}{2}}^{y=\frac{b}{2}} \int_{z=0}^{z=l} \frac{3x^2 zq}{\pi R^5} dxdy = \frac{3zq}{\pi} \int_{y=-\frac{b}{2}}^{y=\frac{b}{2}} \int_{z=0}^{z=l} \frac{x^2}{(x^2+y^2+z^2)^{5/2}} dxdy$$
$$= \frac{2}{\pi}\left[\arcsin\frac{\sin(\arctan\frac{b}{2z})}{\sqrt{\frac{z^2+l^2}{l^2}}} - \frac{lbz}{(l^2+z^2)\sqrt{b^2+4z^2+4l^2)}}\right]q \tag{14}$$

2.2 Analysis of ground deformation characteristics under load

(I) Calculation of settlement of soil layer under load

When the ground is overloaded, the change of effective stress is the cause of the settlement of the ground. When the load is applied, the additional total stress $p(z)$ at any point in the ground is borne by the porewater in the soil. After the time t, the porewater pressure dissipates and the additional stress changes into $u(z,t)$ and effective stress is increased by $u(z,t) - p(z)$. Then for the soil layer with the depth z and the thickness dz, the settlement after the time t is given by

$$dS(z) = m_v(z)[p(z)u(z,t)]dz \tag{15}$$

where $m_v(z)$ is the volume compression coefficient.

Under the load, $p(z)$ has little change along the depth of the soil, and is within the range of the soil compression layer. The change of $m_v(z)$ is small. Then Eq. (9) can be simplified as

$$dS(z,t) = m_v(z)[p - u(z,t)]dz \tag{16}$$

By using Terzaghi’s one-dimensional consolidation theory, the value of excess porewater pressure in the ground under load is given by

$$u(z,t) = \frac{4}{\pi} p \sum_{m=1}^{\infty} \sin\frac{m\pi z}{2H} e^{\frac{m^2\pi^2}{4}T_v} \tag{17}$$

$$T_v = C_v / H^2 \tag{18}$$

where C_v is the consolidation coefficient of soil and H is the thickness of soil compression layer.

2.3 Criterion for determining the cross-section stability of large-diameter buried pipeline

For the elliptical instability problem of the cross-section of double-row large-diameter pipeline, the instability criterion of the pipeline cross-section should be applied for limiting the critical instability state. When it is beyond the requirement of the instability criterion, it is considered that the cross-section generates elliptical instability.

Gresnigt proposed that the maximum value of the roundness O_r of the control pipe is 0.15, that is, 15%. O_r is calculated by using

$$O_r = \frac{(D - D_s)}{D} \quad (19)$$

where D is the original outer diameter of the pipeline, and D_s is the minimum outer diameter of the pipeline with elliptical deformation.

GB50251-2003 Engineering design specification for gas transmission pipeline stipulates that the check of the radial stability of the cross-section of double-row large-diameter pipeline should meet the following expression requirement. When the buried depth of the double-row large-diameter pipeline is deeper or the external load is relatively large, the stability should be checked according to the pressure-free state.

$$\Delta x \leq 0.03D \quad (19)$$

where Δx is the maximum deformation of pipeline in horizontal direction.

$$\Delta x = \frac{ZKWD_m^3}{8EI + 0.06E_s D_m^3} \quad (20)$$

$$W = W_1 + W_2 \quad (21)$$

$$I = \delta_n^3 / 12 \quad (22)$$

where Z is the lag coefficient of pipeline deformation, K is the coefficient of pipeline bed, which is horizontal firing coefficient of pipeline ring under vertical load and related to the angle 2α of the bed, W is the total vertical load acting on pipeline with unit length, W_1 is the permanent vertical load acting on pipeline with unit length, W_2 is the load transferred by ground variable load acting on pipeline with unit length, D_m is the average diameter of pipeline, E is the elastic modulus of steel, I is the cross sectional moment of inertia, E_s is soil deformation modulus, and δ_n is the thickness of pipeline.

GB50251-2003 Engineering design specification for gas transmission pipeline stipulates that the stiffness of the double-row large-diameter pipeline should meet the requirements of transportation construction and operation. The ratio of the outer diameter of the steel tube to the wall thickness should not be greater than 140, that is, $D/t \leq 140$. The non-casing pipeline section and the deeply buried pipeline section should be checked according to the internal pressure free state. The deformation in the direction of the horizontal diameter should not be more than 3% of the outer diameter. The Iowa formula for calculating the radial deformation is also applicable here. The deformation modulus E_s of the backfilled soil and the value of the foundation bed coefficient are shown in Table 1.

Table 1.Design parameters of standard pipelaying condition

Pipelaying condition	Es(MPa)	Wrapping angle(deg)	Bed coefficient
The pipeline is laid on undisturbed soil, and the backfill is loose.	1.0	30	0.108
The pipeline is laid on undisturbed soil, and the soil below the middle line of the pipeline is gently compacted.	2.0	45	0.105
The pipeline is laid in the scarification soil cushion with the least thickness, and the backfill below the top of the pipeline is gently compacted.	2.8	60	0.103
The pipeline is laid in the gravel or gravel cushion. The top surface of the cushion should be at the 1/8 pipeline diameter above the pipe bottom, but at least 10cm, and the backfill below the top of the pipeline will be tamped. The compaction density is about 80% (standard Proctor density).	3.5	90	0.096
The middle line of the pipeline is laid in the compacted pellet material and the pellet material is backfilled below the top of the pipeline. The compaction density is about 90% (standard Proctor density).	4.8	150	0.085

In CECS19:50 design specification for pipeline structure of buried oil and gas transmission, it is required that when the pipeline stiffness and stability are checked, the stiffness check should be carried out for the pipeline with the ratio of diameter to thickness greater than 120 and low pressure gathering pipeline, which should also meet the Iowa formula. The expression is given by

$$\Delta x = \frac{D_l K W r^3}{E I_w + 0.061 E_s r^3} \times 10^{-4} \quad (23)$$

$$I_w = \delta_n^3 / 12 (m^4 / m) \quad (24)$$

where I_w is the cross sectional moment of inertia for unit pipeline length and D_l is deformation lag coefficient.

Under the condition of stiffness, the relationship between the maximum bending strain ε and the deflection Δx of the pipeline ring is given by

$$\varepsilon \approx 3 \cdot \frac{\tau}{D_m} \cdot \frac{\Delta x}{D_m} \quad (24)$$

where τ is the thickness of the pipeline.

According to the different type of pipeline load, the coefficient 3 in Eq. (24) can be replaced by 3~3.5, here is set to 3.2. In Eq. (24), $\Delta x / D = 0.03$.

When the ratio of diameter to thickness is 100, the maximum bending strain is 0.096%. Hooke law is observed in the phase of material elasticity.

$$\vartheta = E \varepsilon \quad (25)$$

The corresponding bending stress is about 200MPa. The yield limit of A3 steel (the minimum yield strength) is around 240MPa. The yield limit of X80 steel is around 555MPa (80000Psi).

In many specifications, the maximum value of the diameter to thickness ratio D/τ or the minimum wall thickness of the pipe is limited. In Canadian standard, for the case of crossing highway and street, $D/\tau < 150$ is required. For the case of railway, $D/\tau < 85$. D/τ is increased with the increase of D.

The yield stress of X80 pipeline is fully considered at the same time that the deformation is used as the criterion for determining the cross-section instability. Yield stress criterion is applied to check and supplement the criterion for determining cross-section instability of double-row large-diameter pipeline .

3 NUMERICAL SIMULATIO

3.1 Processing before numerical simulation and analysis

In the simulation, the X80 buried pipeline with 1219mm diameter is taken as the research object. The range of soil is 20×10×10 m3. The cube rockfall is used for simulation of ground load, and the volume is 1×1×1 m3.The Buried depth of the pipeline is 1cm. The overall structure model of rockfall soil pipeline based on BIM technology is as shown in Fig. 1.

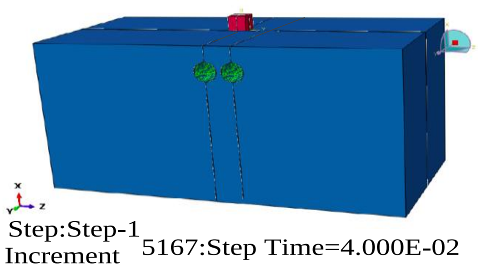

Fig.1.Structure model of rockfall soil pipeline based on BIM technology

In simulation, the DP model in ABAQUS software is used to describe the properties of soil material. X80 steel pipe is used as pipeline and the material model of Elastic-Plastic is used as a general elastoplastic material model. The elastic parameters of the pipeline are Young's modulus 206Gpa and Poisson's ratio 0.3. The plastic parameters of the pipeline are yield strength 480Mpa, tensile strength 600Mpa, and stretch ratio 0.2. The rigid body material model is selected for rockfall. The constraint of the rock density and the vertical displacement of rockfall is applied to the reference point of the rigid body

Dynamic-Explict display dynamic algorithm is selected as the analysis algorithm. The analysis step is set to 0.04s. The number of output steps is set to100. The overall stress-strain displacement of the output is controlled and the overall structure cloud chart of double-row large-diameter pipeline is showed.

Dynamic response of double-row large-diameter pipeline under rockfall impact load is researched, which should consider the contact between pipe and soil. Contact problem is actually a class of nonlinear problems under boundary condition. There are three main aspects of boundary conditions and constraints. (1) In order to prevent the vertical downward rigid displacement of the pipeline with the soil, the boundary of the soil bottom is set as a fixed boundary. (2) Considering the symmetry, the symmetric boundary conditions of the Y axis Z axis of the soil and pipe cross-section are set. (3) The translation of rockfall is in the constraint of along the direction of Y axis and Z axis and the rotation is along the three planes of XY, XZ, and YZ.

3.2 Processing after numerical simulation and analysis

(1) Analysis of impact load on cross section of double-row large-diameter pipeline

The velocity of rockfall is 20m/s and the buried depth is lm. The time history curve of the impact load at the top position of rockfall is shown in Fig. 2. The waveform of the impact load is a single pulse. The total action time is 20ms. The peak is reached near 9ms, followed by a peak state of about 3MS, and then the attenuation begins. The characteristics of impact load are as follows. (1) The action time is very short, usually at the ms level. (2) The load form is similar to the pulse wave, and instantaneously reaches the maximum.

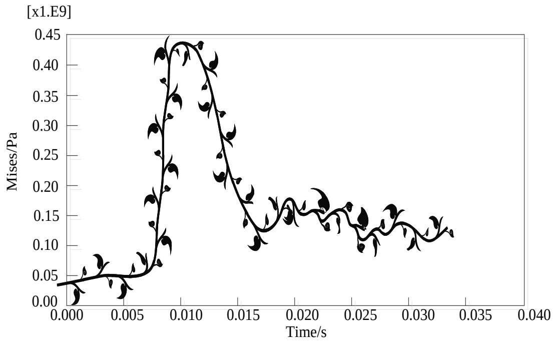

Fig.2.Time history curve of impact load

(2) Cross-section stress analysis of double-row large-diameter pipeline

(i) Integral stress analysis of cross-section of pipeline

From Fig. 2, it can be seen that, the influence of the impact load on the cross-section of double-row large-diameter pipeline is limited. The action range is to focus on the local area with the center of the position below the rockfall and both sides of the center along the axis. The maximum stress at the center of the cross-section appears near 13ms.

(ii) Axial stress analysis at the center of tip pipeline

The time history curve of the axial stress of the cross-section of the pipeline is shown in Fig. 3. From comparison between Fig. 2 and Fig. 3, the impact load from the soil surface to tip pipeline requires about 5ms when the buried depth is 1m. The axial stress at the center of tip pipeline and the impact load on the whole pipe reaches the maximum at about 9ms. The axial stress at the center of tip pipeline is pressure stress before 13ms and then becomes tensile stress.

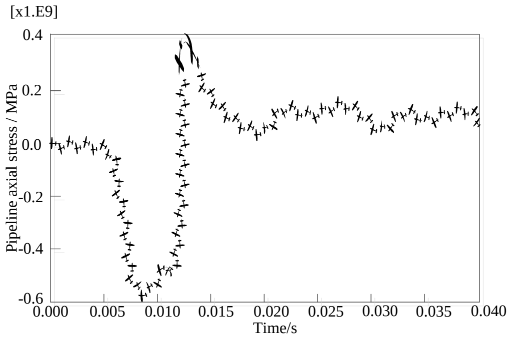

Fig.3.Time history curve of the axial stress of the cross-section of the pipeline

From Fig. 3, it can be known that, the axial stress at the center of tip pipeline at 9ms is pressure stress and the maximum 543.3MPa is reached. The theoretical value is 563.5MPa. The simulation results agree with the theoretical results.

(3) Analysis of vertical displacement of cross-section of tip pipeline at different axial position

The deformation area of the pipeline affected by the impact load is in the range with the origin of the center of the pipeline and axial radius 0.5m.

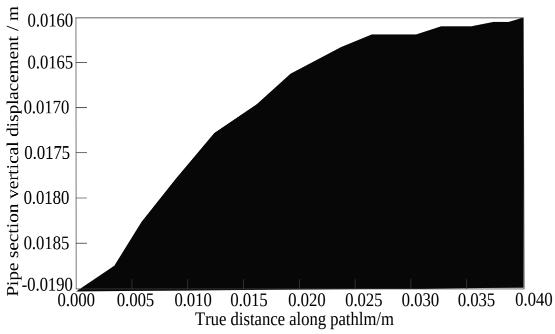

Fig.4.Vertical displacement curve of cross-section of tip pipeline at different axial position

From Fig. 4, at the end of the impact load, the center of pipeline will eventually protrude up to 19.08mm, close to the theoretical value 22.6mm. In the range with the origin of the center of the pipeline and axial radius 1m, the slope of the vertical displacement curve is larger. The inward uplift of the pipeline is obvious.

4 CONCLUSIONS

At present, the problem of the stability of the pipeline has become more and more important. For buried pipeline, besides the upper overburden pressure, it will also be influenced by external loads such as static load and impact load, which will cause instability of cross-section of pipeline. Therefore, it is of practical significance to research the stability of the cross-section of large-diameter buried pipeline.

Conclusions of this paper are as follows.

(1) The nonlinear problem of material and boundary conditions should be considered by the analysis of the deformation mechanism of the cross-section of double-row large-diameter pipeline under impact load of rockfall based on BIM technology.

(2) The axial dynamic response of pipeline is more complex under the impact load of rockfall impact load. The main pipe center is mainly with the axial compression stress response. The maximum value of compressive stress reaches 543.3Mpa, which is the main cause of the inward protruding deformation of the pipeline and the instability of the pipeline cross-section. The axial stress is dominated by tensile stress from 2m until the end of the pipeline. But the tensile stress is not affected by the yield limit of the pipeline, and does not affect the stability of the pipeline cross-section.

In this paper, the X80 buried pipeline with 1219mm diameter is taken as the research object, only the influence of external load on the stability of cross-section of double-row large-diameter pipeline is simply analyzed. The next step is to analyze the stability of X90, XI00 and other double-row large-diameter pipeline under the conditions of different diameter to thickness ratio and buried depth. In addition, the stability of the cross-section considering the influence of the initial defect conditions of the pipeline will be researched.

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