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Section – Geohazards and Environment

Time-History Analysis of Collapse Impacts on Pipeline Buried in Different Depths

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Abstract: This research explores a numerical simulation analysis method for rock-collapse impacts on pipelines. Dynamic Time-History Analysis of the Transient Full-Newton's Method is conducted to gain the deformation, axial force, shear and moment of a 0.8 m diameter pipe under rock collapse when buried in six depths interval between 0.5 ~ 3 m. The results show a significant reduction in pipeline damages when the buried depth is 2.0 m, deeper than that, a gentle decrease appears in the response curves. This result indicates that in potential geological disaster areas, the buried depth of an oil / gas pipeline should be no less than 2.0 m. This research provides a practical guideline to pipeline construction in potential disaster areas.

Keywords: Dynamic Time-History Analysis, collapse, pipeline, buried depth, ANSYS

1 Introduction

Pipeline transport is one of the five major transportation modes alone with rail, road, water and air. Oil and gas pipelines, playing an important role in China's energy infrastructure. However, increasing geological disasters in China is heavily affecting the safety of pipelines, among which collapse is one of the most common yet hazardous influences. For instance, an investigation conducted along the LanCheng-ChongQing pipeline in 2006 showed more than 20 sites were prone to collapses. Especially the section in Kang county, Gansu Province, is in an intensive disaster risk area, affected by the Wenchuan earthquake occurred in 2008. For example, DuanYang dam in this area once collapsed in 2008 (Yu and Shang 2009) in a volume of 1,000 m^3, the diameter of the largest stone was up to 4 m. About 50 t stones have hit onto the pipe, caused a massive oil leak. Along the West-to-East gas pipeline, 23 collapse sites were detected till the end of 2008, mainly in Shanxi Province. Of these, soil slopes collapses are found in Yonghe county and Xi county, and rocks collapses are mostly in the eastern Linfen basin. Collapses in those areas typically result from when a slope becomes unstable, such as that near the Great Temple in Shandan county, where slops are featured with tension fissures rock mass, fragmented with sporadic caving, and debris falling here and there. This kind of conditions have great potential threats to the construction and operation safety of pipelines. Similar geological conditions are also found in the western section of the West-to-East gas pipeline in Henan province where the rock is in a loose gravel structure, which makes these areas particularly vulnerable. Our investigation has found that collapses mainly fell from high banks and/or high – steep soil slopes in gullies, such as that occurred in the three villages Zhaozhuang, Yuekou and Lizhuang (Zhang and Shao 2007).

The high potential of geological hazards along the West-to-East gas pipeline have drawn many researchers' attention. Disaster risks during the construction of West-to-East gas pipeline have been reviewed by Li et al (2004). The development and prevention of geological disasters in Gansu section of the pipeline were studied by Kang et al (2009). Wu (2012) proposed some geological disaster prevention and control methods in Henan province. Qu et al (2001) also conducted preliminary study of the gas pipeline project in Shanxi. Furthermore, the stress and deformation of buried pipelines under the impacts of rock-soil collapse were examined by Li et al (2010). Wu (2016) explored the influence and prevention of collapses along pipelines cross the Lancang river. Additionally, the impacts on gas pipelines buried in different depths were studied by Wang and Wang (2010). Xiong et al (2013) also conducted a safety evaluation of buried pipeline under the impacts of massive rockfalls.

The potential hazards of collapse to pipelines are mainly to cause pipeline overhead suspension, which may further lead to leakage or rupture. Once it happens, even a small leak could gradually build up an explosive concentration of gas. In addition to leading fire and explosion hazards, the long-term pollution impacts to surrounding environment could be significant. The impact of the rockfall on the pipeline should be determined by calculations. The buried depth of a pipeline determines its construction cost and the safety of pipeline operation. Dynamic analysis of oil and gas pipelines under the effects

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of collapse disasters has an important practical significance. Using time history analysis of Newton method with ANSYS (ANSYS Company, USA), this paper analyzes the effects of collapse geological hazards on pipelines in different buried depths.

2 Influence of Buried Depth on Pipeline under Dynamic Load

To explore the impacts of rockfall on oil and gas pipeline, transmission of dynamic elastic wave and the coupling of soil and pipeline are considered in the model.

Stresses the pipeline received from dynamic loads can be described with elastic stress wave in the pipeline spreading to the viscoelastic half space body. The stress is calculated using the following equation (Wu et al 2003, Wang et al 2010):

$$\begin{vmatrix} \sigma_{yy} \\ \tau_{xy} \\ \tau_{zy} \end{vmatrix} = \begin{vmatrix} (2\mu+\lambda)m_1^2 - \lambda\left(k_x^2+k_z^2\right) & 2i\mu k_x m_2 & -2i\mu k_z m_2 \\ -2i\mu k_x m_1 & \mu\left(m_2^2+k_x^2\right) & -\mu k_x k_z \\ -2i\mu k_z m_2 & \mu k_x k_z & -\mu\left(m_2^2+k_z^2\right) \end{vmatrix} \bullet \begin{vmatrix} e^{-m_1 y} & 0 & 0 \\ 0 & e^{-m_2 y} & 0 \\ 0 & 0 & e^{-m_2 y} \end{vmatrix} \bullet \begin{vmatrix} A \\ B \\ C \end{vmatrix}$$

The stress of the pipeline is produced by soil vibration around the pipeline with dynamic load, as well as it is constrained on pipeline. Soil and pipeline is in a coupled vibration, i.e., the vibration of the pipeline is caused by the stress of soil spread, the vibration of the pipeline is also constrained by soil. The soil dynamic characteristic is premise of the stress analysis on coupled vibration of the pipe and the rockfall load vibration with the soil and pipe.

3 Model Calculation

3.1 Material model of soil

To calculate the deformation of under soil load, Drucker-Prager model was chosen because of its calculation stability, easy convergence and good precision. Drucker-Prager model uses the Von-Mises yield criterion (Xing et al 2009, Tang 2003). The shear stress is in a direct proportion relationship with normal stress of the same plane. An improved equation of the Von Mises yield criterion is:

$$f = \sqrt{J_2} + \alpha I_1 - k = 0 \qquad (1)$$

where, $J_2 = \frac{1}{2} s_{ij} s_{ij}$ (The second invariant deviatoric stress tensor); $I_1 = \frac{1}{3}\sigma_{kk}$ (The first invariant deviatoric stress tensor); s_{ij} is the deviatoric stress tensor; σ_{kk} is principal stress; α and k is material constant of D-P model, respectively. Their values are:

$$\alpha = \frac{2\sin\varphi}{\sqrt{3}(3-\sin\varphi)};$$

$$k = \frac{6c\cos\varphi}{\sqrt{3}(3-\sin\varphi)} \qquad (2)$$

where, c and φ is the cohesion and internal friction angle of the soil, respectively.

The parameters of soil dumping up around the pipeline used in this paper are: elastic modulus E = 15 MPa, internal friction angle φ = 31 °, cohesion c = 22 kPa, poisson's ratio μ = 0.32, and bulk density γ = 2000 kN/m^3.

3.2 Model of Collapse rockfalls

We assume that the rockfall deposit area is in a radius of 1.2 m, and its landing speed is 20 m/s, then the relevant mechanical parameters of rockfalls are: elastic modulus E = 52 GPa, density ρ = 2550 kg/m3, and poisson's ratio μ = 0.26.

3.3 Material model of pipeline

The pipelines we investigated is made of X70 steel, which is homogeneous elastic-plastic. Across all sections we have surveyed, pipelines did not show yield after hitting by rockfalls. This type of pipeline adopts the servo stiffness bilinear elastic-plastic model, and meets the Von-Mises yield criterion. Its mechanical parameters are as follows: elastic modulus E = 210 GPa, tangent modulus E_{tan} = 13.5 GPa, poisson's ratio μ = 0.3, yield stress σ_y = 540 MPa, and density ρ = 8,000 kg/m^3.

3.4 The finite element model

Buried pipeline can be taken as an extension stress system along the longitudinal direction. It is suitable to use the Plane Strain Model to simulate pipelines response to collapses. The surrounding rock and soil using plane42 unit element, using beam3 beam element for pipes. Soil material with D-P, considering large deformation, according to the Saint-Venant's Principle, the width of soil strips along both side of the pipe is 3 m; at the bottom, the soil strips at both sides are restrained. ANSYS/ls-dyna includes three methods for contact surface processing analysis, including the dynamic constraint method, the distribution parameter method, and the penalty function method. This research uses the penalty function method for its good stability and simple calculation. Time History Analysis takes transient analysis of the Newton's method, of which rockfall impact time is considered as 0.15 s in this research. The results of dynamic time history analysis can be calculated within this time. The ANSYS finite element model is set up as shown in Figures 1 & 2.

4 Dynamic Time History Analysis on Pipeline Elastic Plastic Deformation

Six buried depths, 0.5, 1, 1.5, 2, 2.5 and 3 m, are included in the calculations of *y* direction deformation, stress, deformation of the pipe, stress and the internal force and deformation of the pipe roof and side.

1) The buried depth of 0.5 m

With a buried depth of 0.5 m (Figure 3), in the 15th step load of the modeling, the maximum deformation of the pipe achieved 25.9 mm. Bending moment shows an approximately symmetrical distribution, with the maximum bending moment up to 7,584 N.m occurs at the top of the pipe section. Shear is in a roughly antisymmetric distribution, the maximum shear force occurs at the top of the tube parts. Axial force is roughly into symmetrical distribution, the maximum axial force in a corner at the upper tube. The deformation time history curve shows that the top of the pipe damages occurred within 1.125 e^{-2} s, pipe deformation at the top is 25 mm. The pipe side deformation time history curve indicates that the soil lateral deformation at the top is 6.8 mm.

2) The buried depth of 3 m

The model result (Figure 4) shows that at the buried depth of 3 m, in the 26th step load, the pipe's maximum deformation is 5.4 mm. Bending moment is roughly into are symmetrical distribution, maximum bending moment occurs at the top of the pipe section, a maximum of 1,395 N.m. Shear is roughly into antisymmetric distribution, the maximum shear force occurs at the top of the tube parts. Axial force is roughly into symmetrical distribution, the maximum axial force is in a corner of the upper tube. According to the deformation time history curve, the top pipe damage occurred within 1.7 e-2s, pipe deformation is 25 mm at the top. Pipe side deformation time history curve shows that the soil lateral deformation at the top is 2.25 mm.

3) Pipe deformation and bending moment, shear force and axial force changing with the pipeline buried depth is shown in Figure 5.

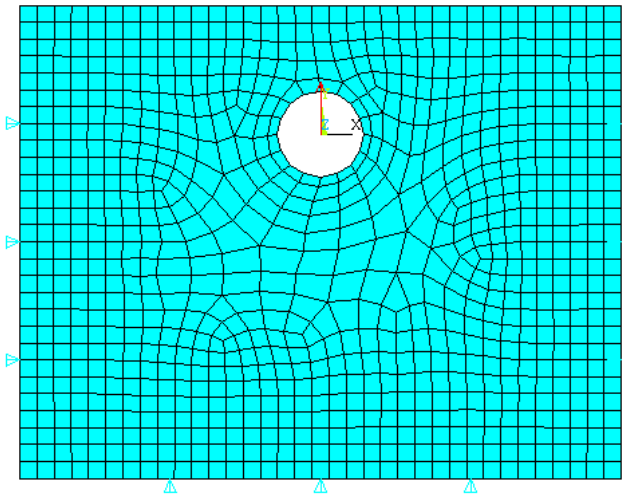


Figure 1 The finite element model

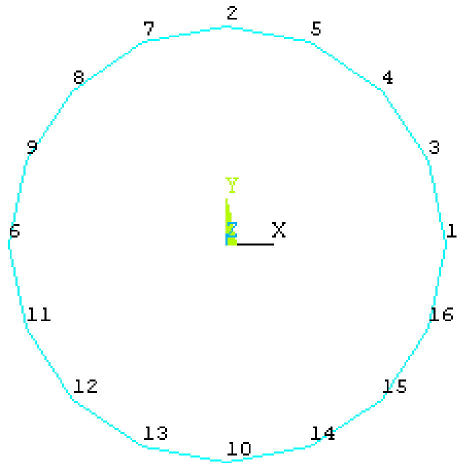
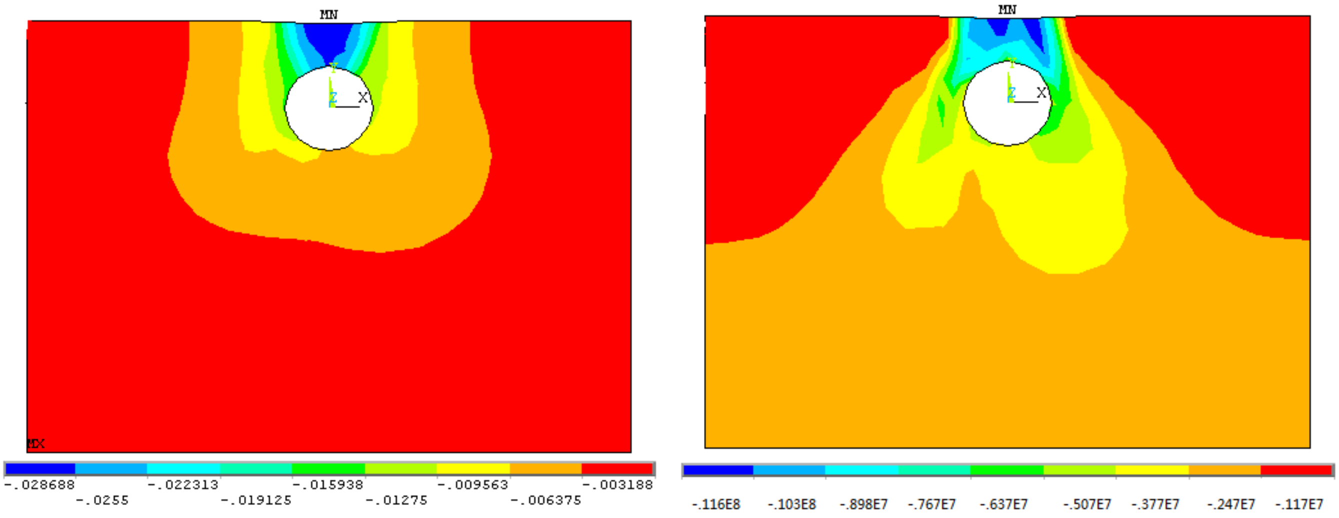
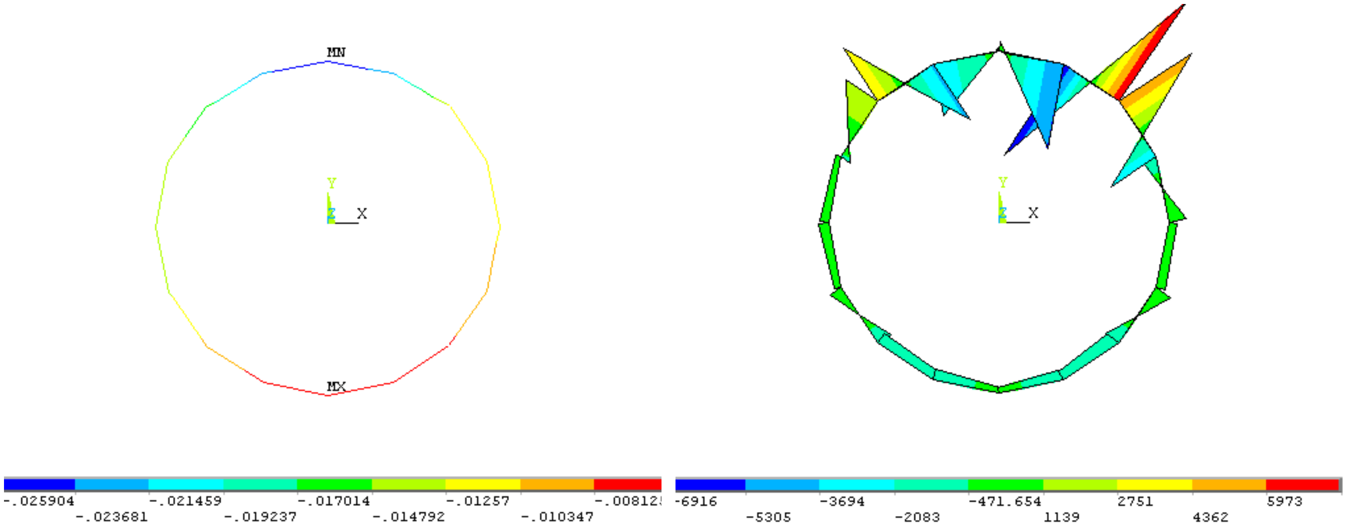


Figure 2 Pipe model

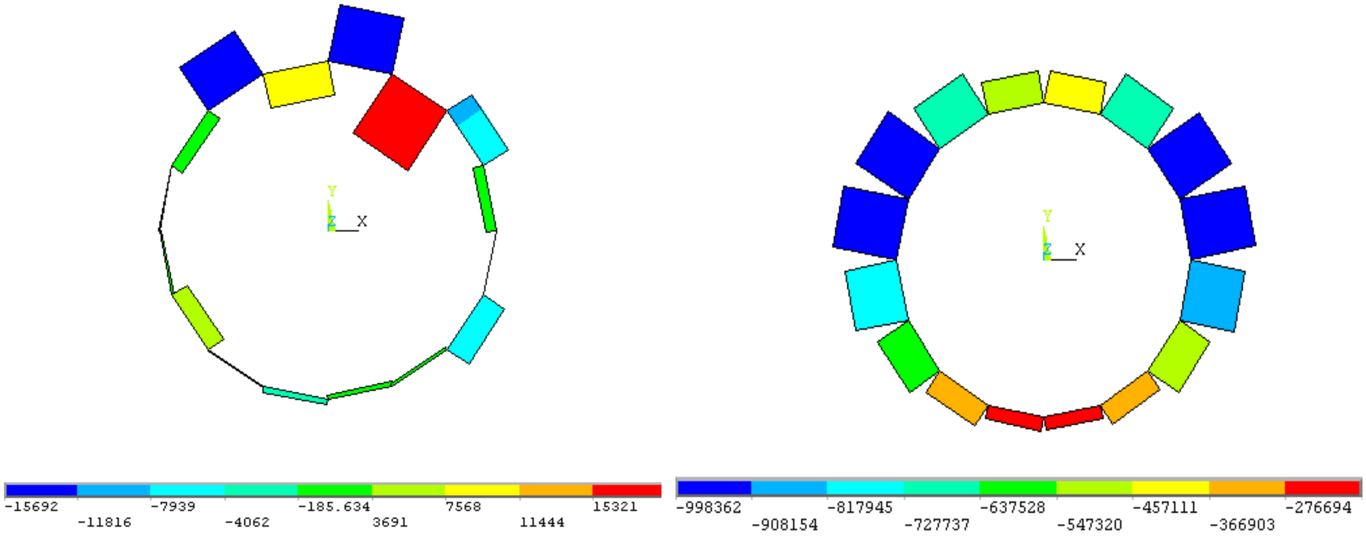


(a) *Y* direction deformation

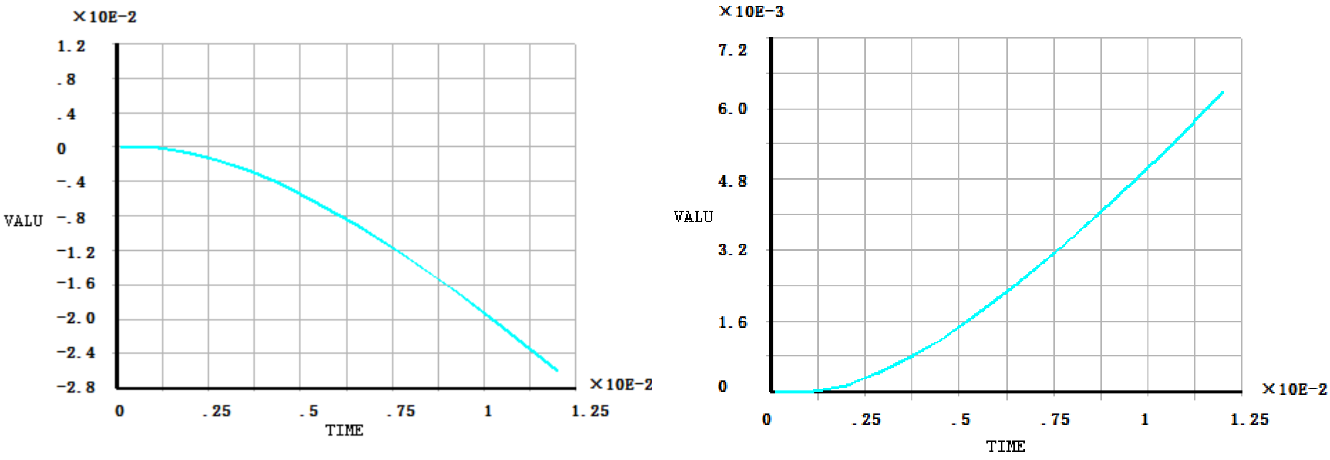
(b) *Y* direction stress



(c) Pipe deformation (d) Pipe bending moment

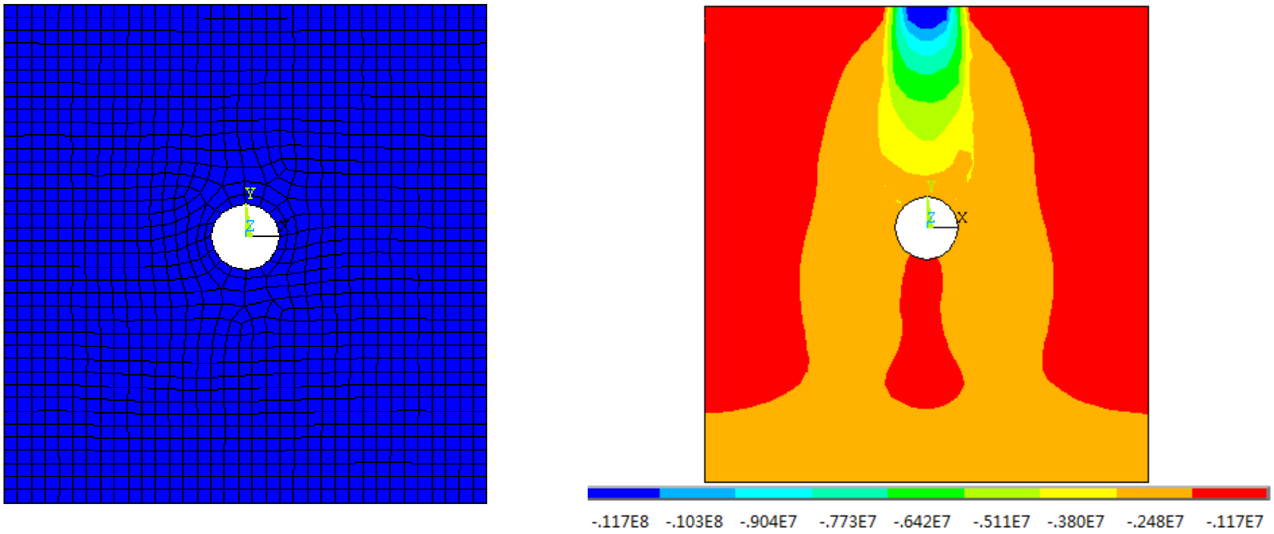


(e) Pipe shear (f) Pipe axial force

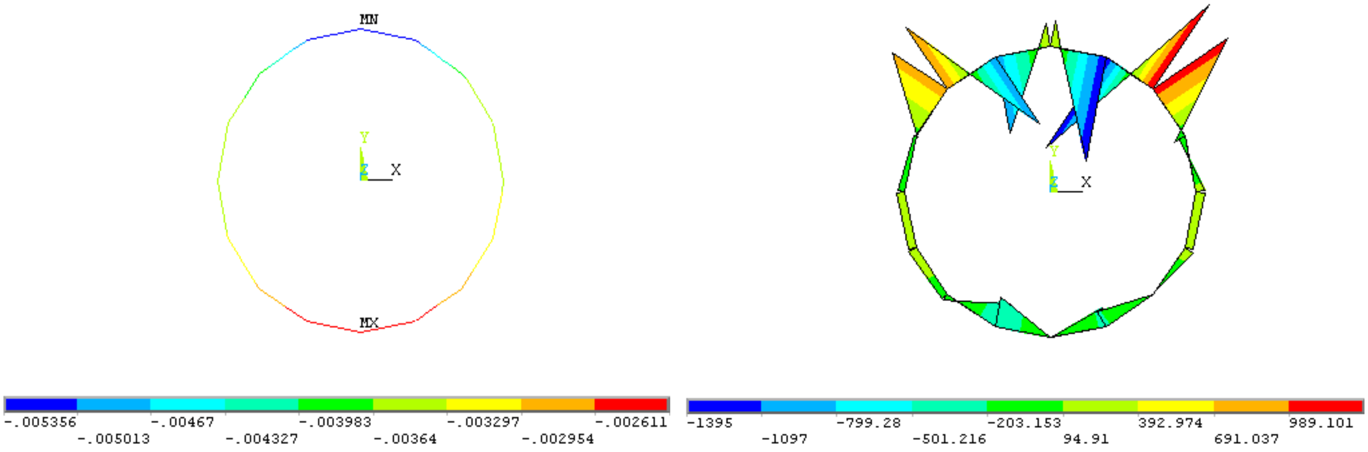


(g) Pipe roof deformation time history curve (h) Pipe side deformation time history curve

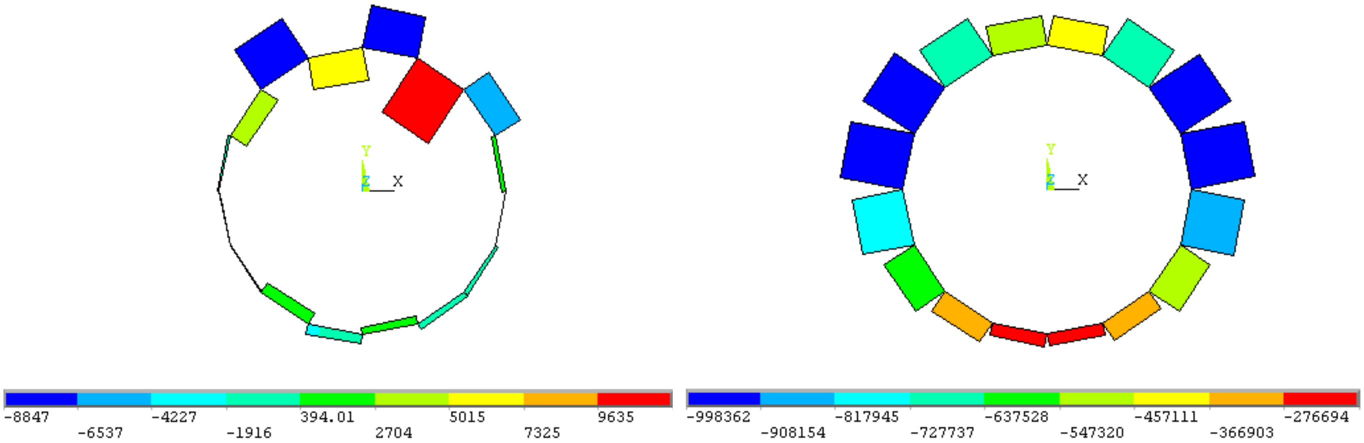
Figure 3 The results of the buried depth of 0.5 m



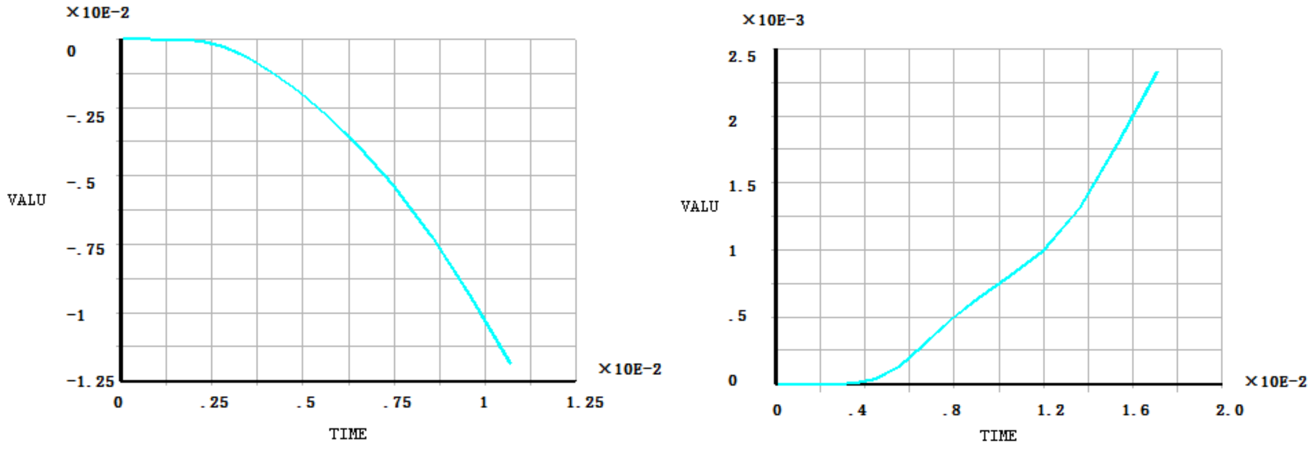
(a) The overall deformation (b) *Y* direction deformation



(c) Pipe deformation (d) Pipe bending moment

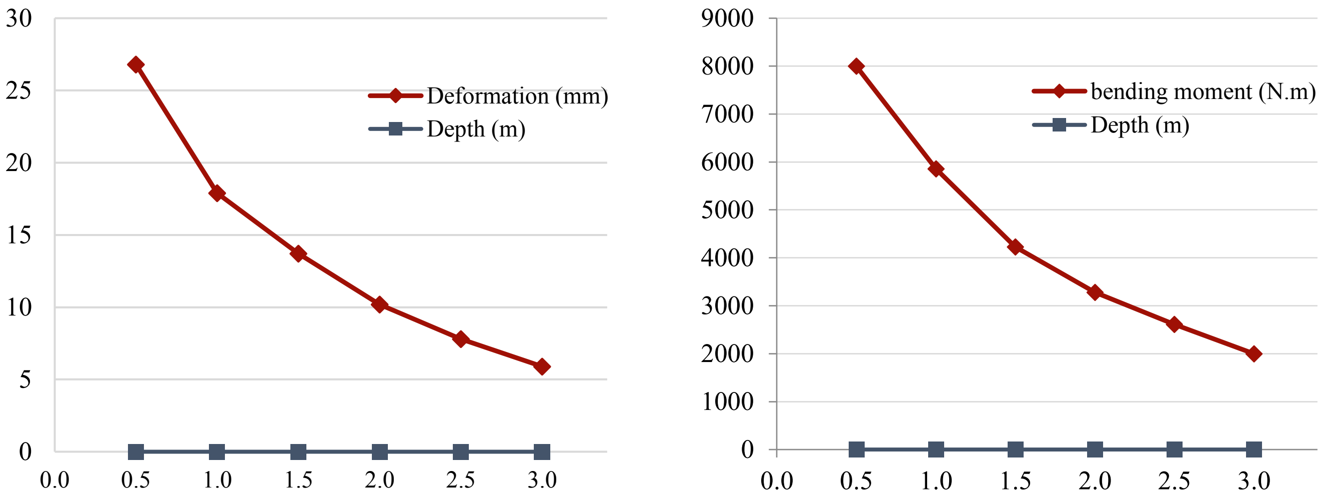


(e) Pipe shear force (f) Pipe axial force

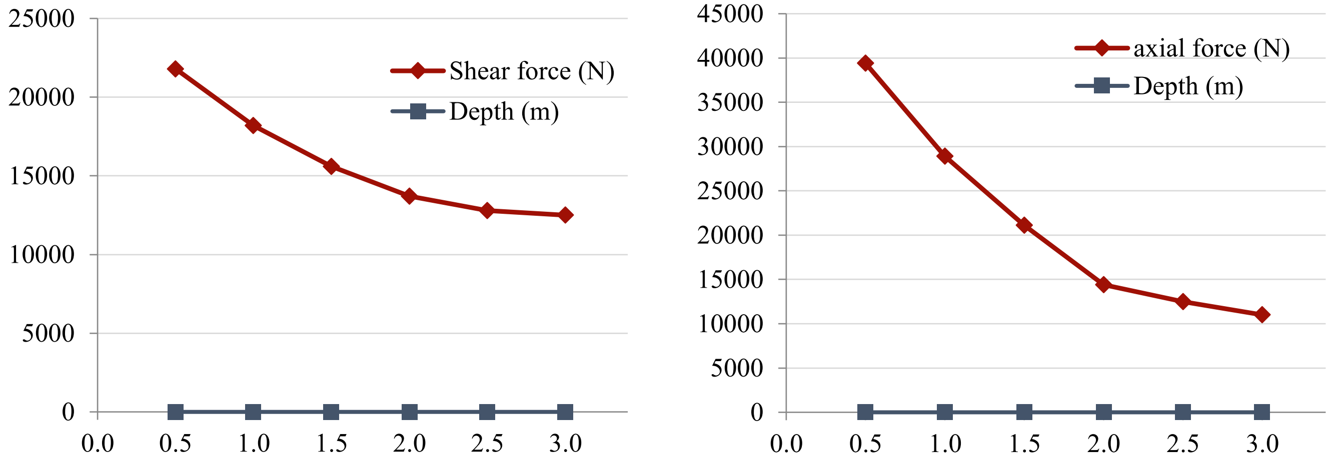


(g) Pipe roof deformation time history curve (h) Pipe side deformation time history curve

Figure 4 The results of the buried depth of 3 m



(a) Pipe deformation (b) The maximum bending moment on pipe top



(c) Pipe maximum shear (d) Axial force of pipe roof

Figure 5 Pipe deformation and internal force curves along with the change of buried depth

5 Conclusions

1) The embedment depth of a pipeline determines construction cost and operation safety of the pipeline, therefore it is practically important to study the influence of embedment depth on the dynamic response of a pipeline to collapses with different embedment depths.

2) The large-scale finite element program ANSYS provides a great tool to conduct the dynamic time history analysis of transient Newton method, Drucker-Prager model, which provides accurate simulation of the impacts of falling rocks on pipelines.

3) According to the numerical simulation, pipe bending moments are in a symmetrical distribution. The maximum bending moment occurs at the top of the pipe; Shear into antisymmetric distribution, the maximum shear force occurs at the top of the pipe; Axial force distribution is symmetrical, and maximum axial force in the upper pipe, under the effect of collapse.

4) The responses of pipeline deformation and internal force indicate that the dynamic effects of pipe, measured with various parameters, are decreasing with increased pipe buried depth. The response curves show a rapid decrease before the buried depth reaches 2 m, and then the decrease trend slows down. Therefore, in order to ensure the operation safety of pipelines, we recommend that a pipeline's burial depth should be no less than 2 meters in an area with potential rockfall hazards.

5) This study provides an sample methodology to analyze the collapse impacts on pipelines in different diameters and different heights of rockfalls, as well as the influence of falling points of rocks on the pipeline.

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