Analysis of dynamic response of underground pipelines to earthquake waves based on FLAC3D

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Abstract. As one of the five major transportation industries, pipeline transportation is an essential energy-transportation tool. China is in an earthquake-prone area. Earthquake is a vital factor for pipeline damage. For this reason, FLAC3D numerical simulation is used to study the dynamic response of pipelines under earthquake wave loads. The dynamic response can be mastered by analyzing the changes in acceleration, velocity, and displacement. The research results show that the destruction of the underground pipeline is mainly due to the earthquake wave effect and the displacement of the surrounding rock of the pipeline. The pipeline has the effects of increasing the earthquake wave acceleration and amplifying the earthquake stress, and it also causes the loosening of the surrounding rock of the pipeline. The pipeline after the earthquake is challenging to repair quickly, and it causes more secondary earthquake disasters. The research results are of great significance for reducing the damage caused by earthquakes to pipeline transportation projects and guiding the earthquake design of underground pipelines.

1. Introduction

The pipeline is a vital means of energy transportation. China is located in an earthquake-prone area. The frequent earthquake activity in recent years has damaged the city’s buried pipeline system. The pipeline is buried in the soil layer and surrounding rock, and the stress is more complicated. When the earthquake occurs, it causes the fault to move and the impact of the earthquake wave. In addition to affecting the normal operation of the pipeline system, it will also bring about other serious secondary disasters, such as fire, explosion, flood, etc. [1].

Many scholars have studied the dynamic response of pipelines under earthquakes, such as the Newmark [2]. as early as the late 1960s, earthquake research was conducted on underground pipelines. The effect of inertial forces was ignored in the analysis, and the pipelines were assumed to move with soil. At present, the relevant regulations of many countries including the United States and China are based on this assumption. In 1975, Japanese scholars [3] proposed a pipe-soil interaction model, which simplified the pipeline as an elastic foundation beam, the soil as a uniformly distributed linear elastic yellow, and the earthquake wave as a simple harmonic, which is called the reaction displacement method. In 1979, Hindy and Novak [4] used effective methods to systematically study the effects of factors such as burial depth, pipe diameter, shear wave velocity, and pipe joints on pipe displacement. Through his experiments in 1982, Ye Yaoxian [5] et al. found the stress decreased in the axial direction of the pipe buried in the soft soil layer. There will be relative displacement between the pipe and soil. In 2004, based on the response of buried pipelines under the action of earthquake waves, Huang Qiangbing [6] et al. used the quasi-static method to analyze various parameters of pipe-soil and the earthquake pressure on buried pipelines. During the 60 years, those researches have played a positive
guiding role in the earthquake-based pipeline research. However, the use of FLAC3D numerical software to carry out pipeline earthquake dynamic response system research is still rare. Therefore, based on the FLAC3D numerical platform, this paper establishes a dynamic analysis numerical model of the pipeline, analyzes its dynamic response from the change system of parameters such as acceleration, velocity, displacement, and provides some theoretical guidance for its earthquake design.

2. Establishment of numerical model for dynamic analysis

2.1. FLAC3D dynamic analysis principle
The dynamic analysis of underground pipelines aims to analyze the damage process, damage mechanism, and stability conditions of underground pipelines under the action of earthquake waves. The dynamic response specifically includes the response of the velocity, acceleration, displacement, and deformation of the corresponding point of the underground pipeline during the earthquake. In dynamic calculations, the equation of motion can be solved by the mass of the concentrated nodes obtained from the surrounding actual grid density. This equation can be coupled with structural elements to analyze the effect of earthquake ground motion on the structure [7].

2.2. Numerical simulation of underground pipelines

2.2.1. Constitutive model and parameters
The constitutive model is used to describe the relationship between stress, stress rate, strain, and strain rate. It can be divided into elasticity, plasticity, viscosity, and any combination of them, and can subdivide more models, such as linear elasticity and hyperelasticity. A certain constitutive model determines the size and shape of the stress-strain curve of the material. For example, the curve can be divided into several stages and several key turning points. Macroscopically speaking, it is the relationship between the force and deformation of the object [8]. In this numerical model, the Mohr-Coulomb model is commonly used as the constitutive model, and Mohr-Coulomb yield criterion with tensile failure is used to judge the failure of the rock mass, and it is assumed that the compressive stress is negative and the tensile stress is positive. The discriminant expression of Mohr-Coulomb yield criterion with tensile failure is shown in formula (1):

\[
\begin{align*}
 f^s &= \sigma_1 - \sigma_3 N_\phi + 2C(N_\phi)^{1/2} \\
 f^t &= \sigma_3 - \sigma_1
\end{align*}
\]

In the formula, \( \sigma_1, \sigma_3 \) are the maximum and minimum principal stress respectively; \( C, \phi \) are the adhesive force and internal friction angle, \( \sigma^t \) is the tensile strength; \( N_\phi = \frac{1 + \sin \phi}{1 - \sin \phi} \) when \( f^s = 0 \), the material will undergo shear failure; When \( f^t = 0 \), the material produces tensile failure.

The geomechanical parameters used in this dynamic analysis are shown in table 1.

| Rock layer | Possion ratio | Elastic module (Gpa) | Cohesion (Mpa) | Internal friction angle(°) | Tensile strength (Mpa) | Density (kg/m³) |
|------------|---------------|----------------------|---------------|---------------------------|----------------------|----------------|
| Soil       | 0.34          | 0.07                 | 0.1           | 25                        | 0.05                 | 1920           |
| Pipeline   | 0.23          | 9                    | 2.8           | 45                        | 3.5                  | 2720           |

2.2.2. Numerical grid and monitoring point layout
In this model, a six-sided block grid is used, which is simulated by plane strain. The size of the model is 8m(x) * 8m (z), the pipe diameter is 1.4m, the buried depth is 3.3m, and the pipe wall thickness is
To analyze the specific dynamic value of the underground pipeline, the experiment set 12 observation points on the simulated underground pipeline (Figure 1). The dynamic analysis of displacement, velocity, stress, and acceleration is carried out on these twelve points.

In dynamic analysis, earthquake waves will reflect on fixed boundaries, which will affect the accuracy of numerical analysis results. Therefore, the boundary condition of dynamic analysis is set as: the left and right sides of the model are set as viscous boundaries in the \( x \)-direction. The bottom of the model is set as viscous boundaries in both \( x \) and \( z \) directions, and the top surface of the model is a free boundary, that is, no boundary conditions of any form are imposed. The earthquake wave is input from the bottom of the model in the form of acceleration time history. To analyze the dynamic value of the underground pipeline, the experiment set 12 observation points on the simulated underground pipeline. The displacement, velocity, stress, and acceleration of these twelve points are analyzed respectively.

2.3. Earthquake wave
This time the pipeline dynamic calculation uses EL wave. This earthquake wave is the first earthquake wave in the world to successfully record the whole process data, and it is the first time that a strong earthquake with a maximum acceleration exceeding 0.3g has been captured by humans. The earthquake acceleration includes numerical waveforms in NS, EW, and numerical directions. In this simulation, the earthquake waveform in the EW direction is used (Figure 2). The EL wave was originally recorded as 54s, and the time acceleration in the EW direction reached a peak value of 0.2142g at 11.46s. It can be seen from figure 2 that the acceleration after the 30s is close to 0, so we can intercept the data of 0 ~ 30s for dynamic analysis in order to save power calculation time.

3. Dynamic analysis of underground pipelines

3.1. Velocity analysis of monitoring points
Under the action of the earthquake load, the velocity of vibration will affect the stability of the surrounding rock of the pipeline. Velocity monitoring analysis was performed on a total of 12 monitoring points in the 30-second earthquake period, which is above, below, and the right of the pipeline, as shown in figure 3. If the horizontal velocity is positively aligned with the \( x \)-axis, it is marked as a positive value, otherwise, it is a negative value (Figure 3).

It can be seen from figure 3 that under the action of earthquake load, the horizontal time-velocity curve of each monitoring point in different directions of the pipeline is consistent, and the value is not much different, so the time-history curve of each monitoring point overlaps. The difference in the values of monitoring points 1-4 is very small. For example, the velocity of point 1 reaches a peak of

![Figure 1. Model meshing and monitoring point layout.](image1)

![Figure 2. EL earthquake wave acceleration time history curve.](image2)

![Figure 3. Velocity analysis of monitoring points.](image3)
-6.23 m/s at 2.5s, and the velocity reaches a positive peak at 26.35s, which is 5.21 m/s. The values of monitoring points 5-8 are not much different. For example, when the velocity of point 5 reaches 2.3.24 m/s at 2.3s, the velocity reaches a positive peak at 26.15s, which is 5.22 m/s. The monitoring points at No. 9-12 have a small difference in value. For example, the velocity at point 9 reaches a peak of -6.25 m/s at 2.1s, and the velocity reaches a positive peak at 26.15s, which is 5.24 m/s. After the end of the earthquake wave, the vibration effect will not completely disappear, there is still a certain velocity, the velocity above the pipeline is 0.05 m/s, the velocity below the pipeline is 0.048 m/s, and the velocity on the right side of the pipeline is 0.04 m/s.

![Horizontal velocity diagram of different monitoring points of pipeline.](image)

From the line chart of velocity in figure 3 we can see that change of horizontal direction velocity at each monitoring point. The velocity of the monitoring point at the wall of the pipeline is higher than that of other parts. Because the density of pipeline material is greater than that of surrounding rock, there is a sudden change in the speed of this monitoring point. In the surrounding rock of the pipeline, the surrounding rock is loosened due to excavation disturbance, which reduces the horizontal velocity and gradually increases toward the deeper of the surrounding rock. The resulting plastic damage zone will reduce the velocity propagation, and reduce the velocity, reduce the stability of the surrounding rock of the pipeline, and then damage the pipeline.

3.2 Displacement analysis of monitoring points
Under the action of the earthquake load, the pipeline will affect the displacement of the earthquake wave. Velocity monitoring analysis was performed on a total of 12 monitoring points in the 30-second earthquake period, which is above, below, and the right of the pipeline, as shown in figure 4. The meaning of displacement positive and negative in figure 4 is that if the horizontal displacement is positively aligned with the x-axis, it is marked as a positive value, otherwise, it is a negative value.

As shown in figure 4, it can be known from the analysis of the horizontal displacement fluctuation curves of the monitoring points in all directions of the pipeline, vertical monitoring points 1-8 eventually stabilized at a displacement of about 0.4mm, and the displacement on the right side of the roadway also tends to 0.4mm, through the analysis of the maximum horizontal displacement of the monitoring point, the closer the monitoring point is to the pipeline, the greater the disturbance response to the earthquake wave. After the earthquake wave ends, the impact of earthquake waves will cause permanent displacement of the surrounding rock of the pipeline, final displacement is 0.4mm.
Figure 4. Horizontal displacement map of different monitoring points of pipeline.

Analysis from the line chart of figure 4 we can see that the horizontal displacement of the monitoring point above the pipeline is collectively vaster than the displacement of the monitoring point below the pipeline. The horizontal displacement in all directions is the largest at the wall of the pipeline. In the process of dynamic monitoring, the monitoring point farther away from the pipeline, the smaller the horizontal displacement of surrounding rock, it shows that the pipeline can increase the effect of earthquake waves on the maximum horizontal displacement of rock and soil.

3.3. Acceleration analysis of monitoring points

In the dynamic response analysis, acceleration is also an essential factor. Velocity monitoring analysis was performed on a total of 12 monitoring points in the 30-second earthquake period, which is above, below, and the right of the pipeline, as shown in figure 5. The meaning of the positive and negative accelerations in figure 5 is that if the horizontal acceleration coincides with the positive direction of the x-axis, it is marked as a positive value, otherwise, it is a negative value.

Figure 5. Acceleration diagram of different monitoring points of pipeline.

It can be seen from figure 5 that after the earthquake wave ends, there is a lag in the response of the pipeline and surrounding soil to the earthquake wave, and the acceleration will not disappear immediately. The acceleration above the pipeline is -0.9m/s², the acceleration below the pipeline is -0.7m/s², and the acceleration on the right side of the pipeline is -0.95m/s².

As can be seen from the line chart in figure 5, the acceleration response under the pipe is the weakest. The acceleration dynamic response of the pipeline wall is greater than that of the surrounding rock, and the farther the distance is, the weaker the acceleration response is. By consulting data analysis, rock mass has an amplification effect on acceleration, so the earthquake waves are amplified through the pipeline, and the acceleration response above is greater than that below the pipe. To sum up, the pipeline has the effect of increasing the maximum acceleration of earthquake waves, and this effect becomes weaker with distance.

3.4. Stress analysis at monitoring points

Under the action of the earthquake load, it has a great test on the strength of the pipeline. Velocity monitoring analysis was performed on a total of 12 monitoring points in the 30-second earthquake period, which is above, below, and the right of the pipeline, as shown in figure 6. The meaning of the
positive and negative stresses in figure 6 is that when the pipeline is under tension, it is marked as a positive value, and when it is under pressure, it is marked as a negative value.

![Figure 6. Vertical stress fluctuation diagram of different monitoring points of pipeline.](image)

As shown in figure 6, the analysis shows that the monitoring points with the highest stress fluctuation in the vertical direction of earthquake waves are monitoring No. 1, 5, and 9 at the pipeline wall. After the earthquake wave ends, the vertical stress of the pipeline will not disappear immediately, and the residual stress will still act on the pipeline. The stress value above the pipeline is -3Mpa, below the pipeline is -0.7Mpa, and on the right side of the pipeline is 0.1Mpa.

As can be seen from the line chart in figure 6, the vertical stress at the pipe wall is maximum, in the law of vertical stress, the stress should be increased in the vertical direction and distributed in the horizontal direction, however, because the monitoring points No. 1 above and No. 5 below the pipeline are affected by the seismic wave amplification effect of the pipeline, leading to a sharp increase in stress, if the pipe strength is not enough, it will cause damage.

4. Conclusion

(1) The velocity of the monitoring point at the pipe wall is more significant than other parts. There will be a sudden change in velocity, in the surrounding rock of the pipeline, excavation disturbance will cause loosening of surrounding rock, resulting in reduced horizontal velocity, and gradually increase towards the deeper surrounding rock. It can be seen that the plastic damage zone caused by the excavation pipe disturbance will reduce the velocity. Due to the higher material density, the pipeline has the effect of increasing the earthquake wave disturbance, leading to a decrease in the stability of the surrounding rock of the pipeline, and destroy the pipeline.

(2) The horizontal displacement of the surrounding rock at the pipe wall is maximum. The further the monitoring point is from the pipeline, the smaller the horizontal displacement of the surrounding rock is. The effect of this increase becomes weaker from the pipe to the surroundings, it shows that the pipeline can amplify the earthquake wave displacement.

(3) The pipeline has the effect of increasing the maximum acceleration of earthquake waves, and this effect decreases as the distance from the pipeline to the surrounding rock become larger. The increased acceleration leads to a sharp increase in the vertical stress at the pipe wall, this adversely affects the stability of the pipeline.

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