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Buckling behaviour analysis of a buried steel pipeline in rock stratum impacted by a rockfall

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ABSTRACT

Rockfall impacts have seriously threatened the operations of buried pipelines in geologically unstable regions. In this paper, the buckling behaviour of a buried pipeline impacted by a cube-shaped rockfall was simulated. Effects of the impact velocity, buried depth, impact position, rock height and base area on the stress and plastic strain of the buried pipeline were discussed. The buckling behaviour of a buried pipeline due to continuous impact was also studied. The results show that the cross-section of the buried pipeline evolves from an oval to a peach shape as the impact velocity increases. As the buried depth decreases, the length and depth of the impact dent, the high stress area and the plastic strain increase. However, they increase as the impact velocity, rock height and bottom area increase. The plastic strain distribution of the buried pipeline is more uneven for an eccentric impact. Buckling of the buried pipeline after the second impact is more serious than that after the first impact. After the second impact, the maximum plastic strain appears on both sides, not at the centre line of the impact dent.

1. Introduction

Energy demands have greatly increased, and recent estimates suggest that the world energy consumption will rise rapidly over the next 20 years. Long distance pipelines are the main method to transport oil and gas; inevitably, these pipelines traverse mountains, plateaus, hills and other complicated geological areas [1]. Rockfall impacts have seriously threatened the operations of buried pipelines in geologically unstable regions [2]. Rockfalls frequently collapse and fall in China's southwest, northwest and mountainous regions as well as the Three Gorges region. For example, the Zhong-Wu gas pipeline is an important part of China West–East Gas Engineering. According to incomplete statistics, there are 100 places with perilous rocks in the Zhangjigou-Shuanghe section, and the volume range is 10–3000 m^3. In 2005, a pipeline concrete cover plate was punctured by a 350 m^3 rockfall in Shunxi and a dent approximately 30 cm in diameter appeared in the pipeline [2]. A pipeline dent or rupture caused by a rockfall impact may lead to an accidental oil and gas leak. In recent years, the stress and strain of buried pipelines impacted by rockfalls have been studied. For example, Wang simulated the rockfall movement by a rock-fall software, and the impact load of the buried pipeline was evaluated using two methods [3]. Deng [4] and Xiong [5] simulated the dynamic response of a buried pipeline induced by a rock-fall impaction using finite element software. Li analysed the stress and strain of a buried pipeline due to an impact load [6]. However, these studies are mainly focused on the stress and strain of the buried pipeline when the impact load was very small, therefore, they did not consider the buckling behaviour. In this paper, the buckling behaviour of buried pipeline impacted by a cube-shaped rockfall was simulated in ABAQUS. Effects of the impact velocity, buried depth, impact position, rock height and base area on the deformation,

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von Mises stress and plastic strain of the buried pipeline were discussed. Buckling behaviour of the buried pipeline caused by continuous impacts also was studied.

2. Materials and methods

The problem of a rockfall impact on a buried pipeline has been studied using a 3D finite element model that considers geometrical and material nonlinearities. A general purpose advanced finite element programme, ABAQUS has been used. As shown in Fig. 1, four-node reduced integration shell elements are used for modelling the pipeline. Eight-node solid elements are employed for modelling the backfill soil, stratum and rockfall. Diameter of the pipeline is 813 mm, wall thickness of the pipeline is 8 mm, and side length of the rockfall is 1.4 m. To eliminate the edge effect, the size of the stratum is 10 m × 7.5 m × 15 m. The thickness of the backfill soil is 1 m.

A linear isotropic strain hardening model has been used in the plasticity model of the steel pipeline material. The related yield function is dependent on the equivalent pressure stress. This model has been combined with a von Mises yield surface criterion. Numerical results are obtained for the X65 steel pipeline. The yield stress is 448.5 MPa [7], the young's modulus of the steel is 206 GPa, Poisson's ratio is 0.3, and the density is 7800 kg/m^3. Mechanical behaviours of the stratum and rock material are represented by an elastic-perfectly plastic Mohr–Coulomb constitutive model [8]. The backfill soil's cohesion is 15 kPa, the friction angle is 15°, the elastic modulus is 20 MPa, the density is 1840 kg/m^3, and Poisson's ratio is 0.3. The rockfall and stratum are the same material, which is limestone with a cohesion of 6.72 MPa, friction angle of 42°, elastic modulus of 28.5 GPa, density of 2090 kg/m^3, and Poisson's ratio of 0.29 [9]. Dilation angle of the soil and rock is assumed to be zero for cases considered in this paper.

A contact algorithm with a friction coefficient equal to 0.5 is employed to simulate the interactions between the pipeline outer surface and the surrounding soil [10]. In the current study, a contact algorithm based on contact pairs is defined between the pipeline and backfill soil, and also between the backfill soil and rockfall. The outer surfaces of bodies that could potentially interact are identified before the analysis. The bottom surface of the stratum is fixed. Gravity loading is applied to the whole model first. The initial impact velocity is applied to the rockfall.

3. Simulation results for different impact velocities

When the impact velocity $v = 25$ m/s, an impact dent with a shape like a ship appears on the buried pipeline, and the dent depth change curve is shown in Fig. 2. The response of the buried pipeline to a rockfall impact is a dynamic process. The cross sectional shape of the impact location changes from circular to oval and finally becomes peach-shaped. At 0.64 s, the dent depth of the buried pipeline reaches the maximum value, and the velocity of the rockfall decreases to zero. Later, the dent depth decreases because of the recovery of the elastic deformation. However, the dent will not disappear, because the plastic strain formed during the impacting process.

Fig. 3 shows the velocity curves of points A and B (as shown in Fig. 1) when $v = 25$ m/s. The response velocities of these points in the same cross section differ from each other. The velocity fluctuation of point A is very serious, while the fluctuation of point B is very small. A velocity with a pulse wave is very harmful for the buried pipeline, because it can easily lead to localized buckling of the pipeline.

Fig. 4 shows the pipeline deformation in the XY and YZ planes for different impact velocities of a rockfall. When the impact velocity $v \leq 15$ m/s, the cross section of the buried pipeline is oval-shaped. As the impact velocity increases, a ship-shaped impact dent appears and the dent depth increases. Meanwhile, the length of the impact dent also increases as the impact velocity increases. Therefore, the buckling behaviour of a buried pipeline is more serious as the impact velocity of a rockfall increases. The oval cross section of buried pipeline is not conducive to pigging and reduces the ability to resist deformation. Buckling of a buried pipeline may lead to a rupture, which results in an oil or gas leak.

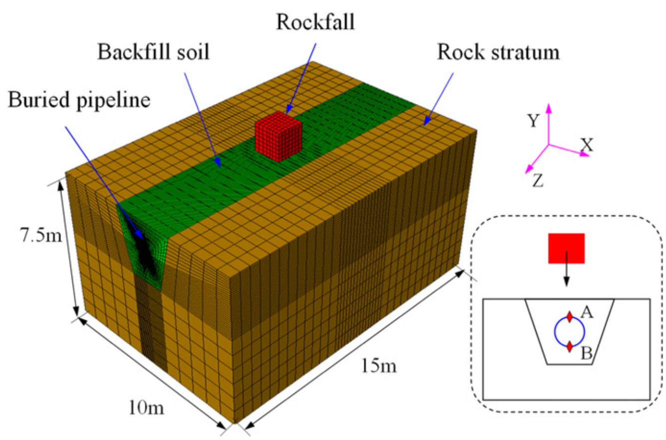

Fig. 1. Three-dimensional finite element model.