



Mechanical behaviour analysis of a buried steel pipeline under ground overload

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ABSTRACT

Ground overload is one of the most important factors that threaten the safe operations of oil and gas pipelines. The mechanical behaviour of a buried pipeline under ground overload was investigated using the finite element method in this paper. The effects of the overload parameters, pipeline parameters and surrounding soil parameters on the stress–strain response of the buried pipeline were discussed. The results show that the maximum von Mises stress appears on the top of the buried pipeline under the loading area when the ground load is small, and the stress distribution is oval. As the ground load increases, the maximum stress increases, and the high stress area extends. The von Mises stress, plastic strain, plastic area size, settlement and ovality of the buried pipeline increase as the ground load and loading area increase. The buckling phenomenon of the no-pressure buried pipeline is more serious than the pressure pipeline. As the internal pressure increases, the high stress area and the maximum plastic strain of the buried pipeline first decrease and then increase, the settlement of the buried pipeline increases, and the ovality decreases. The von Mises stress, maximum plastic strain, settlement and ovality of the buried pipeline decrease with increasing buried depth, the surrounding soil's elasticity modulus, Poisson's ratio and cohesion. The maximum von Mises stress, high stress area, the maximum plastic strain, plastic area and ovality increase as the diameter–thickness ratio increases. The critical diameter–thickness ratio is 60, and the settlement of the buried pipeline first increases and then decreases as the diameter–thickness ratio increases. Finally, a protective device of the buried pipeline is designed for preventing ground overload. It can be repaired in a timely manner without stopping the transmission of oil and gas and widely used in different locations because of its simple structure and convenient installation.

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1. Introduction

As the main method to transport oil and gas, long distance buried pipelines traverse mountains, rivers, marshes, plateau, city, permafrost and so on [1]. Buried pipelines not only bear the gravity of backfill soil and the internal pressure but also inevitably support ground loads such as roads, constructions, depositions, mechanical equipment and other loads [2]. According to the investigation of 22 areas of China National Petroleum Corporation (CNPC), there are 23,045 illegal buildings above the buried oil and gas pipelines from April 2004, there are more than 11,000 illegal buildings within 5 m on the two sides of the buried pipeline [3] and there are more than 440 illegal overloads in the gas production plant of the Zhongyuan oil field. The length of the Shen-mao long distance gas pipeline is 115 km, and pipeline deformations appear on many sections under the vehicle loads [3]. Therefore, ground loads have affected the safe operations of oil and gas pipelines. Generally, ground loads cause the following hazards.

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Inspection and maintenance of the buried pipelines are not done under the loading areas. Pigging equipment is not passed into the pipelines for deformation, which may lead to a pipeline block. The local settlement of the buried pipeline appears under the ground load, which may result in a pipeline rupture or the leakage of oil and gas. Therefore, mechanical behaviour analysis of the buried pipeline under ground load is very important for its safety evaluation.

The Boussinesq method can be used to solve the stress and displacement of any point under a ground concentrated load. The stress and displacement of the foundation can be gained through an integral solution. Then, the vertical and horizontal forces of the buried pipeline can be studied using the elastic foundation beam method [4]. Li [5] studied the effect of adjacent construction on the deformation, shear and bending moment of a buried drainage pipeline by elastic foundation beam theory. Gong and Sun [6] investigated the mechanical characteristics of the buried pipeline under adjacent surcharge but did not consider the plastic strain. Noor [7] investigated the finite element model of a buried pipeline under vertical load and showed that the soil–pipeline interaction should be considered for shallow buried pipeline. Trickey [8] studied the effects of cyclic ground loads on the buried pipeline by finite element method. Shuai [2] researched the stress and elastic deformation of a buried pipeline under a ground load. However, there are few studies on the plastic deformation of a buried pipeline under a local ground overload.

In addition, Liu [9] and Zheng [10] studied the failure mechanisms of a buried pipeline due to the deflection of a landslide process. Zhang [11] and Vazouras [12] researched the buckling behaviour of a buried pipeline crossing a strike-slip fault and a reverse fault. Liu [13] and Zhang [14] investigated the stress and strain of a buried pipeline under the impact of rockfalls and falling objects. However, they did not pay attention to the effect of ground overload on buried pipelines. In this paper, the mechanical behaviour of a buried steel pipeline under ground overload was investigated by numerical simulation. The effects of the overload parameters, pipeline parameters and surrounding soil parameters on the stress–strain response of the buried pipeline were discussed. These results can provide a theoretical basis and reference for the safety evaluation, repair and maintenance of buried pipelines.

2. Deformation of the buried pipeline

The soil pressure of a buried pipeline under ground loads can be divided into two parts. One is the soil pressure caused by the weight of the overlying soil, and it increases as the buried depth increases. The other is the additional force caused by ground loads, and it decreases as the buried depth increases [2]. For a ditch buried pipeline, it is assumed that the vertical pressure distribution of the backfill soil is even at any depth, and the pipeline roof bears all the soil pressure. The vertical soil pressure at the top of the pipeline is:

$$W_e = K_g \rho_s g D H \quad (1)$$

$$K_g = D[1 - \exp(-2KHf/D)]/(2HKf) \quad (2)$$

where W_e is the soil pressure per unit length, K_g is the concentration factor of the vertical soil pressure, K is the concentration factor of the lateral soil pressure, f is the friction coefficient between the pipeline surface and the soil, ρ_s is the soil density, D is the diameter of the buried pipeline, and H is the thickness of the backfill soil.

The additional force caused by ground loads can be calculated by the diffusion angle method and elastic mechanics. The diffusion angle method is more suitable for a shallow stratum [15].

The additional force under a strip load is:

$$F = \frac{Qb}{b + 2H \tan \varepsilon} \quad (3)$$

where Q is the ground load, b is the length of the loading area, H is the depth of the calculation plane, and ε is the diffusion angle.

The cross-section of the buried pipeline becomes an oval shape under the joint action of the soil pressure, the additional force caused by the ground load and the reaction force of the support foundation. As shown in Fig. 1, the maximum horizontal radial deformation, Δ , of the non-pressure buried pipeline is [15]

$$\Delta = \frac{JKq_v R^3}{EI + 0.61E'R^3} \quad (4)$$

where J is the hysteresis coefficient of the pipeline deformation, 1.5; K is the pipeline base coefficient; q_v is the vertical load per unit length above the pipeline; R is the radius of the pipeline; E is the elasticity modulus of the pipeline; I is the inertia moment of the pipeline section, $I = t^3/12$; t is the wall thickness of the pipeline; and E' is the base coefficient.

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