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Numerical simulation of strength failure of buried polyethylene pipe under foundation settlement

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ABSTRACT

Polyethylene (PE) pipes have a great ability to resist deformation, which is one of the important reasons that PE pipes are used more and more widely in urban gas transportation systems. In this paper, a numerical simulation was conducted in ABAQUS, for the most commonly used PE pipe of DN110-SDR11, under the action of foundation settlement. The situation that PE pipe is perpendicular to settlement section was considered. The variation of piping stress vs settlement displacement was analyzed, and influence of length of transition section on pipe yielding was discussed. It was found that the maximum Mises stress of PE pipe increases with the increment of settlement displacement, but the location is changing, and the dangerous section occurs at the junction of transition section and subsidence area or the junction of transition section and non-subsidence area. Pipe yielding was taken as the failure threshold, and the maximum settlement displacement under which PE pipe serves safely was analyzed. With increasing length of transition section, the settlement displacement for pipe yielding increases, that is PE pipe with longer length of transition section is safer than those with shorter one under the same settlement displacement.

1. Introduction

Buried polyethylene (PE) pipes are widely used in gas distribution in urban area, for its attractive properties such as high-chemical resistance against corrosive, flexibility, fatigue resistance and low cost, and furthermore, its great ability to resist deformation. The foundation settlement induced by the over-exploitation of urban groundwater, non-standard excavation of large buildings or other natural disasters such as continuous rainfall cause pipe deflection, leakage or even burst and so on, which will impair the safety of the local people's life and property [1]. This issue has attracted much growing research attention recently. For example, Chen et al. [2] carried out finite element analysis and experimental research on the flexible buried steel pipes in the case of uneven settlement of the building foundation. It was found that the maximum stress occurs at the intersection area of the ground and the buried pipes. Neupane et al. [3] modelled differential settlement by using beam element in ABAQUS, and the behaviour of the pipeline under differential settlement loads was investigated using three different material models. Erbay et al. [4] used a rigorous method utilizing nonlinear finite element in the seismic fragility evaluation

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Nomenclature

a	material constant derived from uniaxial tensile tests
b	material constant derived from uniaxial tensile tests
k	flow stress ratio
C	cohesion of soil (kPa)
E	deformation modulus of soil (kPa)
E_i	initial elastic modulus (MPa)
β	internal friction angle of Drucker–Prager model of soil (°)
ε	axial true strain
$\dot{\varepsilon}$	strain rate (s^{-1})
ε_p	plastic strain of soil
φ	internal friction angle of soil (°)
ρ	Density of soil (kg/m^3)
μ	Poisson's ratio
σ	axial true stress (MPa)
σ_1	the first principal stress (MPa)
σ_2	the second principal stress (MPa)
σ_3	the third principal stress (MPa)
σ_y	yield stress (MPa)
ψ	dilatancy angle of soil (°)

of the buried Auxiliary Cooling Water System (ACWS) intake pipeline when subjected to liquefaction-induced soil settlement. Shi et al. [5] systematically investigated the pipe responses to ground displacement induced by adjacent static pipe bursting using finite element method (FEM). The maximum pipe bending strain was directly estimated by a dimensionless plot of the relative pipe–soil stiffness vs the ratio of maximum pipe curvature to maximum ground curvature. For the failure of pipeline, Kunert et al. [6] developed a numerical model for integrity management of buried pipelines in unstable soils, and the stress state in the pipe due to soil movements could be reproduced, which was used to assist the Line Operators on the Integrity Management Policy. Majid et al. [7] conducted a failure analysis of natural gas pipes, the analysis methods including using NASTRAN to perform structural analysis and FLUENT for Computational Fluid Dynamics (CFD) analysis, and compared with the actual instance, these results were rational.

The great ability to resist deformation makes PE pipes use more and more widely, and even in the essential cooling water system of nuclear power plant in recent years. But for a specific type of PE pipe, it is crucial to understand the limit of deformation that pipes could possibly bear under different loading conditions. Therefore, based on the failure due to yielding, the situation that buried PE pipe of a specific type subjected to seismic landslide and surface load were comprehensively studied in our previous works [8–10] by FEM. To ensure the safety of buried PE pipes, and as a further supplementary on our works, the calculation and analysis of PE pipes' strength failure under foundation settlement are necessary. In this paper, the mechanical behaviour of PE pipe of DN110-SDR11 under foundation settlement was studied. The location of the dangerous section during the settlement process was determined, as well as the safe conditions for pipe serving and its influence factor.

2. Finite element model

2.1. Basic assumptions

- The pipeline in the finite element model only contains pipe itself, fittings and joints are not included.
- The pipe material PE and soil are isotropic material, PE is nonlinear viscoelastic, and the soil is considered as Drucker–Prager (D–P) model.
- The contact property between pipe and soil is finite sliding.
- Comparing with the diameter of pipe, the size of soil in the finite model is large enough to simulate infinite soil.

2.2. Material properties

2.2.1. PE

In this paper, the hyperbolic model proposed by Suleiman and Coree [11] is employed. This model uses semi-empirical equation for soil mechanics to represent the nonlinear viscoelastic behaviour of PE material. The strain rate effect is considered, through the uniaxial tensile test data at a special rate, parameters in the constitutive model can be obtained.

The hyperbolic constitutive model is expressed as [11]:

$$\sigma = \frac{\varepsilon}{a + b\varepsilon} \tag{1}$$