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Research article

Effect of Earthquake Waves on Buried Pipes in Infinite Soil Slope by Numerical Method

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English Extended Abstract

Summary

Past experiences of buried pipeline damage show that some of these significant damages that have caused various problems are caused by earthquake waves. Earthquake effects on buried pipes include transient deformation of the ground and permanent deformation of the ground with possible fractures, which are the result of displacements of active faults, landslides, and subsidence or lateral movements due to landslides (liquefaction). Most of the damages reported so far are due to permanent deformation, although authentic documents represent that wave propagation has contributed to a smaller percentage of pipe damage. With developing numerical methods and their accuracy in simulating the behavior of buried pipelines to deformations caused by earthquakes, in recent decades, the use of these methods has been used more by researchers. In this study, by using the finite difference numerical method and FLAC2D software, the investigation and analysis of buried steel pipelines in an infinite slope of the soil layer located on the bedrock and the effect of the landslide created in this soil layer caused by the earthquake load on the buried pipe is presented. Also, the sensitivity analysis of the behavior of the buried pipe under the dynamic load of the earthquake to the important and influential parameters in the resistance behavior of an infinite slope, including the slope angle, thickness, and underground water level, has been done. The results showed that with the increase of the underground water level and the infinite slope angle, the displacements of the soil layer and the buried pipe increase exponentially, and these displacements have caused elliptical deformations in the cross-section of the pipe. However, the effect of soil layer thickness on these deformations can be ignored.

Introduction

Buried pipelines are one of the most important and influential arteries in terms of the economic and social progress of developed and developing societies through the transmission of energy such as gas, oil, and water [1]. Seismic hazards that directly cause damage to pipelines include forces and deformations caused by ground movement and the effect of wave propagation. Past experiences show that buried pipelines are affected by earthquakes, which are divided into two main groups:

- Transient deformation of the ground due to seismic wave propagation
- Permanent deformation of the ground with possible fractures, which are the result of displacements of active faults, landslides, and subsidence or lateral movements due to landslides (liquefaction) [2].

Sakurai and Takanashi presented one of the first studies on dynamic stress analysis of buried pipelines by field tests during the Matsushiro earthquake. They observed that the axial deformations of the pipe when the earthquake intensity is low enough to cause landslides are consistent with the deformation values of the ground, and this is proved by the relationships used in the beam model based on the non-linear Winkler

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foundation [3].
Wang et al. considered a long pipeline buried in soil with homogeneous elastic behavior under surface and volume waves with an oblique incident angle in three-dimensional conditions. They obtained an analytical solution of the elasto-dynamic relations that describe the soil-pipe interaction motion by expanding the original wave potential function. In this method, the kinematic interaction and inertia of the soil-pipe contact surface and the scattering of waves by the free surface are included [4].
Nouri et al. studied the numerical simulation of transverse deformations of buried pipelines due to the instability of the ground slope and the effects of the geometrical parameters of the pipe and slope including the diameter and thickness of the pipe and the width of the slope respectively, and the resistance parameters of the soil including adhesion and friction angle on this deformation [5].
In this study, by using the finite difference numerical method and FLAC2D software, the investigation and analysis of buried steel pipelines in an infinite slope of the soil layer located on the bedrock and the effect of the landslide created in this soil layer caused by the earthquake load on the buried pipe is presented. Also, the sensitivity analysis of the behavior of the buried pipe under the dynamic load of the earthquake to the important and influential parameters in the resistance behavior of an infinite slope, including the slope angle, thickness, and underground water level, has been done.

Methodology and Approaches

The numerical analysis used in this study includes three steps:

1- Geostatic analysis to determine the initial stresses caused by gravity in the numerical model
2- Static analysis of removing soil elements from the buried pipe area and placing the pipe in a numerical model to determine the distribution of induced stresses in the environment around the pipe and the induced forces inside the pipe caused by removing soil elements and installing the pipe
3- Applying earthquake dynamic load to numerical model and dynamic analysis

Using the numerical sensitivity analysis of the effect of the boundaries on the response results of the infinite slope and the buried pipe under dynamic load, the lateral boundaries of the numerical model are at a distance of approximately 29 times the diameter of the pipe from the center of the pipe and the bottom boundary is between 28 and 39 times from the center of the pipe for different geometries, Was considered. As a result, the length of the numerical model is 70 meters in the direction of the x-axis and the maximum height of the numerical model is 50 meters. To simulate the behavior of non-sticky granular soil, multi-node two-dimensional grids were used with a fully plastic-linear elastic behavior model according to the Mohr-Coulomb criterion, which is the most common model used in geotechnical works [6]. Liner elements with linear elastic behavior have been used to simulate steel pipes, which are suitable for steel structures in numerical models and considered by most researchers. Also, the support conditions of the lateral boundaries in stages one and two of the analysis (geostatic and static) were considered rolling and the support conditions of the lower boundary were considered rigid in all stages of the analysis. In the dynamic analysis stage of the numerical model, free field boundaries were used in the lateral boundaries [6].
For dynamic loading, the mapping acceleration function of equation 1 has been used:

$$\ddot{u}(t) = \sqrt{\beta \cdot e^{-\alpha t} \cdot t^{\zeta}} \sin(2\pi f t) \qquad (1)$$

Where f and t are the loading frequency and time respectively and β, α and ζ are the loading parameters which are chosen as 55, 5.5, and 12 respectively [7].
In this study, the input wave is applied to the numerical model with a maximum acceleration of 0.2 g and a frequency of 3 Hz and using equation 1 in the internal nodes at the level of one meter above the lower boundary. Wave propagation inside the numerical model, a type of hysteresis constant damping, which is introduced in the software as local damping, was used, and the damping value of 8% was chosen for the frequency of 3 Hz [7]. To validate the numerical model, the safety factor calculated for the non-sticky soil layer with an infinite slope in dry conditions was used from equation 2, considering that the friction angle of the soil layer (φ) is equal to 35 degrees and the slope is infinite (β)) is 25 degrees, the value of the safety factor was calculated as 1.5. The value of the safety factor calculated by the numerical method is equal to 1.46 [8]:

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$$FS = \frac{\tan\varphi}{\tan\beta} = \frac{\tan(35)}{\tan(25)} = 1.5 \qquad (2)$$

The calculation of the safety factor for the situation where the underground water level is 2 meters below the ground surface was calculated as 1.29 and 1.24, respectively, from analytical and numerical methods. The results showed that there is a good agreement between the analytical and numerical results. The geometric characteristics, behavioral model, and mechanical characteristics of the numerical model used to analyze the effect of the underground water level are similar to the geometry described in the verification mode with the soil layer at a slope of 25 degrees and a height of 3 meters. The underground water level for the time when its depth is 2.5, 2, and 1.5 meters from the ground surface was investigated to present this effect. Although numerical modeling was done for a lower depth (1 meter) the results showed that for depths equal to or less than one meter of groundwater level, the slope is geostatically unstable and it is not possible to analyze it dynamically. After validating the desired numerical model for simulating the behavior of the soil layer with infinite slope, numerical simulation was done for the values of underground water level (dw) equal to 2.5, 2, and 1.5 meters and dynamic earthquake loading was done. To analyze the effect of the infinite slope angle on the behavior of the infinite slope and the buried pipe based on the earthquake load, four values of 15, 20, 25, and 30 degrees of the infinite slope angle were selected, numerical modeling was performed and the behavior of the infinite slope and the buried pipe was analyzed under seismic loading. To analyze the behavior of the pipe buried in the soil layer with different thicknesses under the earthquake load, values of 2, 3, 4, and 5 meters were chosen for the thickness of the soil layer. The infinite slope angle of the soil layer is 25 degrees, the depth of the buried pipe is 1.5 meters, and the geometrical, mechanical, and hydraulic characteristics and parameters of the numerical model were considered as in the previous section.

Results and Conclusions

- The displacements of the soil layer with an infinite slope under the dynamic loading of the earthquake are very dependent on the depth of the underground water level, and the number of displacements increases with the increase of the underground water level, and the higher the underground water level, the displacements increase with a higher slope compared to the increase of the underground water level.
- Displacements in the soil layer with an infinite slope placed on the bedrock from the bottom of the layer to the ground surface gradually increase with the passage of dynamic time, and plastic strains and permanent displacement occur in the soil layer. The difference in displacement values at the bottom and top of the pipe indicates elliptical deformations in the cross-section of the pipe and the need to check the allowable strains for these types of deformations.
- Elliptical deformations of the pipe cross-section induce forces and moments into the pipe wall. The maximum moment and axial force are induced in the wall of the pipe at an angle of approximately -45 and +45 degrees from the vertical line passing through the center of the pipe. As the underground water level increases, the value of the axial force increases, but the moment value for the time when the underground water level is the maximum for the sections that are placed at an angle of 45 degrees is the maximum, and when the underground water level is the minimum for the sections that are at the angle of -45 are placed at the maximum.
- The displacements in the soil layer for all the slope angle states considered in the numerical modeling increase with time until it reaches a constant value and the displacements decrease with the increase in the depth of the soil layer. Also, the maximum displacement in the soil layer is more than the value of the displacement after the end of the earthquake loading for the slope angles of 15 and 20 degrees.
- The thickness of the infinite slope layer does not affect the amount of displacements

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