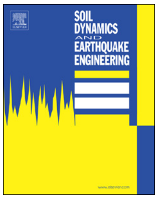
Soil Dynamics and Earthquake Engineering 114 (2018) 281–297

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

journal homepage: www.elsevier.com/locate/soildyn



Experimental study of burial depth effect on embedded pipe deformations in sandy slopes under dynamic landsliding

Hadi Farahi Jahromi[a], Fardin Jafarzadeh[a,*], Masood Samadian Zakaria[b]

[a] Department of Civil Engineering, Sharif University of Technology, P.O. Box 11365-11155, Tehran, Iran
[b] Tehran Gas Company, No 701, Vali Asr St., Tehran, Iran

ARTICLE INFO

Keywords:
Earthquake
Landslide
Shaking table tests
Embedded pipe
Burial depth
Slope response

ABSTRACT

This paper studies the influence of burial depth on slope response and pipe performance under earthquake induced landslide. Three physical models are constructed and tested using 1 g shaking table device. The slope is divided into four sections as toe, lower and upper sections of the slope face and crest. The pips which perpendicularly cross the slope are embedded at these positions in three burial depths to demonstrate burial depth effect in each section.

According to the experiments, dynamic slope response which moderately develops at deeper depths at toe and lower section, displays a clear downtrend at upper section and crest. Also, the pipe response depends on pipe route and slope displacement pattern. The pipe deformations have positive correlation with depth at upper section and crest, but show opposite behavior at toe and lower section. Moreover, the horizontal strains impact on total strains in buried pipes reduces at greater depths.

1. Introduction

Pipelines, as an important type of lifelines, are certainly vulnerable to Permanent Ground Deformations, PGDs. Numerous case histories have been reported in different countries in which pipelines have been adversely affected [1–8]. Thus, much research has recently been carried out to investigate the mechanisms of the seismic-induced damages to buried pipelines.

In general, pipeline damages are classified into two categories, namely "total damages" and "local instability". The first type of damage, includes failures caused by perpendicular bending [9], compressional buckling [10] or tension applied to a large length of a pipe [11]. Total damaging is studied immensely using beam element theory [12]. Local instability, however, occurs when the pipe is subjected to massive axial compression, but total buckling does not take place due to overburden pressure. The limit state for local instability occurrence is defined when a pipe is exposed to the maximum allowable bending moment and deforms 1% of a relative curvature of its axis [13]. As a consequence of the local instability, the circular cross section of the pipe deforms into a non-circular geometry [14]. In this paper, total pipe damage in pure bending mode of deformations is studied in detail.

A wide range of experimentation including full scale testing, laboratory physical modeling, numerical modeling and analytical formulations have been developed to investigate the interaction between the buried pipelines and PGDs. Due to limitations in applying similitude parameters and difficulties in performing linear structure modeling, analytical approaches have been frequently used as a basis for past studies [15–20]. However, apart from the analytical solutions, the necessity for decreasing buried pipe deformations, have driven many scientists to propose damage mitigation techniques. For example, pipe rerouting, drainage and retaining wall construction as a treatment technique against landslides are suggested [21]. Directional drilling is also recommended as suitable solution to lower pipe deformations [22]. This technique allows the pipeline to traverse the landslide under predicted slope failure line. Towhata et al. [23] measured the variation of drag forces required to laterally pull an embedded pipe by using shaking table tests. It is concluded that the drag force during strong shaking has been dramatically smaller than after shaking, in both dry and liquefied sands.

In the investigations of Challamel and Buhan [24] the effects of

---

Abbreviations: λ, Geometrical Scaling factor; $\lambda\rho$, Density Scaling factor; $\lambda\varepsilon$, Soil strain Scaling factor; λ_f, Loading frequency Scaling factor; λ_u, Soil displacement Scaling factor; λ_{acc}, Loading acceleration Scaling factor; λ_{EI}, Structural stiffness Scaling factor; A, a geometrical parameter; D, Slope length; d, Pipe outer diameter; N_{eq}, Equivalent number of cycles; E, Pipe elastic modulus; EI, Pipe bending stiffness; F, Loading frequency; h, Burial depth; I, pipe inertial moment; I_c, Characteristic Intensity; L_r, Length ratio; M, Moment magnitude; V_{sp}, Prototype shear wave velocity; V_{sm}, Model shear wave velocity

[*] Corresponding author.

E-mail addresses: hadi.farahi@student.sharif.edu (H.F. Jahromi), fardin@sharif.edu (F. Jafarzadeh), m_samadian@nigc-tpgc.ir (M.S. Zakaria).

https://doi.org/10.1016/j.soildyn.2018.06.038
Received 9 June 2017; Received in revised form 29 June 2018; Accepted 30 June 2018
0267-7261/

various parameters (including slope width, slope angle, burial depth, pipe-soil strength ratio and pipe geometry) on pipe deformations in static landslide motion are investigated. It is found out that the pipe geometry is a key factor in pipe deformation response. O'Rourke et al. [25] experimentally investigated pipeline responses under large PGD's. In this research, several comprehensive large scale strike-slip fault models and centrifuge tests in both dry and partially saturated sand are carried out. It is demonstrated that High-Density Poly-Ethylene, HDPE pipes and larger h/d values (burial depth to pipe diameter ratio) can lead to smaller deformations. The application of deeper burial depths is also recommended as it decreases pipe deformations.

Li et al. [26] combined the idea of inclined shaft and horizontal tunnels to study the stability problems of gas pipelines passing through Loess slopes. Using numerical analysis, it is suggested that burial depth change and rerouting the pipe outside of failure line can result in smaller pipe deformations.

Cocchetti et al. [27,28] investigated Soil-Pipeline interaction analytically and numerically along unstable slopes movement. Slope deformation algorithm, slope width, pipe-slope intersection angle and pipe placement geometry are taken into account as significant factors affecting pipe deformations. Similarly, a steel pipe buried in dense and loose sand and soft clay is analytically modeled by Lee [29]. As a result, burial depth increase is considered a suitable approach in pipe strain reduction in level ground condition. Furthermore, the positive correlation of uplift resistance of pipelines with burial depth have been demonstrated by several researchers [30–32]. Faizi et al. [32] have also verified that the uplift resistance is more dependent on burial depth than the pipe diameter.

Jafarzadeh et al. [33,34] experimentally examined effective parameters on Soil-Pipeline interaction through eight shaking table tests. They used a 2D laminar shear box, sand as the ground material type and PVC pipes as the fluid transferring line. It is inferred that the buckling and bending failure modes have been dominant in non-uniform and uniform bases respectively. Moreover, the effect of soil density on pipe deformation has been more pronounced in loose to medium sands than dense sands.

Jafarzadeh et al. [35] numerically modeled buried pipelines placed in cemented slopes subjected to dynamic loading. In this research, a finite element model is developed in ABAQUS and the boundary conditions and model dimensions are calibrated using a non-linear constitutive model. The results indicate that the slope toe is the safest route for pipe placement.

Wang et al. [36] numerically analyzed the effect of Slope-Pipeline intersection angle on buried pipe strains. It is proved that as the intersection angle decreases, bending mode will turn gradually into buckling mode and the pipe deformations will consequently decrease. It is also recommended to use different material types for the pipe, increase the wall thickness and use flexible joints as alternative solutions to achieve lower stresses in pipes.

The combined effect of dynamic loading and shear deformation of confining soil on buried pipelines is experimentally examined by Sim et al. [37]. A 20 mm diameter acrylic pipes have been buried in two backfill material types including dry Toyoura sand and Tire-Derived Aggregate (TDA) surrounded by Toyoura sand. This study indicates that the magnitude of bending moment is directly affected by the magnitude of fault displacement irrespective of other factors. Moreover, TDA backfilled pipe is found to be capable of reducing the bending moments. If the pipe axis is perpendicular to the direction of the fault, the induced earth pressure on the pipe will be increased significantly.

Many vertical pull-out tests, lateral sliding tests, axial pull-out tests and uplift tests are performed on steel pipes by Liu et al. [38]. The pipes are buried in soft clay soil with different depth-to-diameter, h/d, ratios between 1 and 9. It is shown that the h/d = 5 can be taken as the limit to divide the soil failure mode into shallow and deep failures. The normalized soil resistance is also affected by the covered depth.

Burial depth influence on induced forces and pipe design methods in a gas transmission line in China has been analytically studied by Li et al. [39]. In contrast to Lee's [29] studies, Li et al. [39] find out that deeper burial depths will not necessarily lead to lower pipe deformations in slopes; since it causes undesirable increased deformations, shear forces and moments.

Pipelines responses, buried in five different routes of a cemented slope, have been numerically investigated by Jafarzadeh et al. [40]. The results illustrate that increasing pipe thickness is an effective retrofitting method which improve the performance of the pipe undergoing dynamic loading. It is also inferred that the midsection of the slope imposes the highest stresses on the pipe and thus should be circumvented in pipeline route selection. In order to calibrate the numerical models with observed slope displacements, Jafarzadeh et al. [41] suggest slope layering with respective elastic modulus and damping ratio functions. It is proposed that number of soil layers should be selected based on slope displacement pattern and soil characteristics determined from shear strain observations during testing.

Choo et al. [42] have performed centrifuge tests which show the applicability of the EPS Geofoam (Expanded Poly-Styrene Geofoam) in trenches to decrease the pipe deformations exposed to PGD's. Lingwall and Bartlett [43] and Lingwall [44] investigate the influence of EPS as steel pipe flexible covers against ground vertical movement. Bartlett et al. [45] performed several full scale site modeling, large and small scale laboratory testing and numerical analysis to show the impact of EPS on the pipe strains during large PGDs. The use of flexible high damping capacity material as a pipe covering in trenches is suggested in order to decrease the loads and pipe deformations.

A pressurized gas distribution pipes subject to oblique-reverse faulting has been studied by Rofooei et al. [46]. In the study, it is suggested that the pipes which are planned to be buried in the vicinity of fault zone should be placed at a shallow depth to minimize the compressive strains. In addition, the results of several full-scale laboratory tests of steel gas pipes undergoing a reverse faulting [47] show that decreasing the burial depth will increase the distance between the pipe buckled sections and reduce the failure intensity. The contribution of bending in the pipe response shows negative correlation with the burial depth, but the peak compressive strains have opposite behavior.

Wenkai et al. [48] performed large scale tests to examine pipe response during a static landslide. In their physical modeling, a steel pipe perpendicularly crosses the slope which consists of the semi-hard clay with cobbles. Sliding is triggered with controlled excavations. The results prove symmetrical deformation and saddle-shaped stress distribution in the pipeline. During the induced landslide, part of the confining soil under the body of the pipe is displaced and thus the midsection of the pipe will be partially suspended. In this section, vertical strains are larger than horizontal strains and eventually both ends of the pipe experience low stresses.

Various pipe burial depths in mid-section of a cemented soil slope has been numerically analyzed by Jafarzadeh et al. [49]. It is shown that an increase in the burial depth can cause reduction of strains on the pipe. Also the dependency of a pipe vertical strains on the soil vertical displacement is investigated. Unlike at shallow burial depths, where the maximum pipe strains occur at the mid-section, at deep burial depths, the maximum pipe strains take place at the first one-fifth of the pipe length from the supports. It is also shown that there is a threshold burial depth of 3 m over which increasing the burial depth has little influence on the pipe strains.

The previous studies show the effective parameters on pipeline deformations. Such parameters include ground conditions (PGD type), Soil-Pipe interaction properties, slope material type, pipe installation route, the relative intersection angle of the ground movement and pipe axis, pipe material type, size and wall thickness and its burial depth.

The literature reviews demonstrate that the majority of the scientific research addressing the burial depth effect in slopes are undertaken by numerical modeling [24,26,35,39,40,49]. Furthermore, the available experimental studies mostly investigate burial depth effect in PGD types