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Experimental and finite element study of the reverse faulting effects on buried continuous steel gas pipelines

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ABSTRACT

Permanent ground displacement (PGD) caused by surface faulting is considered as one of the most significant hazards affecting buried pipelines. Pipelines crossing reverse-slip faults are subjected to compressive actions (stresses and strains) which can result in buckling of the pipe. In current work, the results obtained from the full-scale laboratory testing and finite element analyses of 4″ (114.3 mm) and 6″ (168.3 mm) steel gas pipes (without internal pressure) buried inside a split box and subjected to a reverse faulting of 0.6 m (pure dip-slip) are presented. These pipes are commonly used in gas distribution lines and networks. The experimental setup, procedure and instrumentation as well as the finite element (FE) modeling of the problem are described in detail. It is observed that the soil failure in the moving part of the split-box occurs along vertical surfaces extending from the sides of the pipe to the ground surface. The experimental results indicate that both pipes exhibit an S-shape deformation with two local buckling sections where the excessive yielding and plastic deformations of the pipes could lead to rupture failure. Both pipes exhibited “diamond-shape” buckled sections. The buckled sections of the pipes in the fixed and moving parts of the split box were unsymmetrical with respect to the fault plane. Using the factor of ovality to measure the pipe cross-section distortion, it is found that the cross-section distortion is more severe for the buckled section of the pipe in the moving part of the split box in comparison to its fixed part. Also, the distance between the buckled sections increases by increasing the pipe diameter, while the distortion of the pipe cross-section increases by increasing the pipe diameter over thickness ratio. Using the FE models that were validated utilizing the experimental results, the maximum equivalent soil–pipe interaction forces and their distribution along the pipes were determined and the results were compared with that of American Lifeline Alliance Guidelines for the Design of Buried Steel Pipe (ALA, 2005) [33]. The obtained maximum bearing force is less than the suggested values by ALA, while the maximum uplift force slightly exceeds those of ALA. The results indicate that for the considered cases, the uplift force is sensitive to the pipe diameter and its relative stiffness, while the ALA (2005, [33]) suggests a constant force for the burial depths considered in this study.

1. Introduction

Buried pipelines are the most reliable and economical way of transportation of different materials such as water, gas, or other petrochemical products, etc., in and out of urban areas, and are vital for maintaining the comfort of their residents. Not surprisingly they have become an integral part of modern cities' infrastructure. Therefore, maintaining their performance under different natural hazards, including earthquake events is of great importance. Since buried pipelines usually traverse large geographical distances; they could experience a variety of failures due to permanent ground displacement (PGD) and/or wave propagation during an earthquake episode. Permanent ground displacements, caused by surface faulting, landslides, seismic settlement and lateral spreading due to soil liquefaction, can result in considerable damages to buried pipelines. Many reports are available with regard to the inflicted damages to gas and water supply pipelines caused by different earthquakes such as 1906 San Francisco [1,2], 1972 Managua [3], 1978 Miyagiken-Oki [4], 1983 Nihonkai-chubu [5], 1985 Michoacan [6], 1989 Loma Prieta [7], 1990 Manjil [7], 1994 Northridge [8], 1995 Hyogoken-nanbu [9], 1999 Chi-Chi [10], Kocaeli [11] and 2010 Chile [12]. The reported damages to the pipelines often included leakage

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and stoppage of their serviceability and in severe cases resulted in fire hazard for gas pipelines.

Faulting is a common type of permanent ground displacement that could happen in different forms. For pipelines crossing reverse faults, a combination of axial compression and bending could be expected. These deformations can result in local buckling of the pipe, thus leading to the distortion of the pipe cross-section and restricting the flow of its content. In case of severe buckling, it may lead to loss of content and fire hazard due to rupture failure. Thus, it is essential to study the effect of reverse faulting on buried steel gas pipelines to identify the potential hazards.

Due to importance of the pipelines to remain operational after an earthquake and the complicated behavior of soil–pipe interaction of the pipelines crossing an active fault, comprehensive analytical, numerical and experimental researches have been conducted during the last few decades. Analytical studies on pipelines crossing strike-slip and normal faults have been carried out by many researchers [13–18]. Ariman and Lee [19] evaluated axial and bending strains in buried steel pipelines using the finite element method. O'Rourke and Liu [20] reviewed the behavior of continuous and segmented buried pipelines subjected to PGD and wave propagation hazards, and considered the existing numerical and analytical methods to quantify their behavior. Takada et al. [21] performed a parametric study on shell-mode response of buried pipelines to large fault movements to investigate the effect of local buckling in the analyses. Vazouras et al. [22] performed a three dimensional finite element study on buried steel pipelines subjected to strike-slip faulting of right angle and considered various parameters such as diameter-to-thickness ratios, cohesive and non-cohesive soils and different steel materials. More recently Vazouras et al. [23] extended their work to account for different fault angles and evaluated the critical fault offset based on different performance criteria.

Yoshizaki et al. [24] carried out an experimental investigation on the effects of PGD caused by pure strike-slip fault offset on buried steel gas distribution pipelines with elbows during earthquakes, using large split-box at Cornell University, and calibrated the FE models for further studies. A number of researches [25–30] have focused on centrifuge testing as well as finite element techniques to study the effect of various parameters on the behavior of buried High Density Polyethylene (HDPE) pipelines subjected to strike-slip faulting. These centrifuge tests were performed at Rensselaer Polytechnic Institute (RPI) and were accompanied by several large-scale experiments at NEES facility at Cornell University on buried HDPE pipes subjected to strike-slip faulting with different diameters, with/without internal pressure. Details of the experiments can be found in the NEESR-SG final report [31]. In the case of HDPE pipes subjected to strike-slip faulting that leads to axial compression and bending, severe pipe cross-section distortion associated with high compressive strains were monitored at locations of local buckling, which were found to be symmetrical with respect to the fault plane. Rofooei et al. [32] performed a full-scale experiment on a 4″ (114.3 mm) steel pipe under reverse faulting of 0.6 m with a dip angle of 61° and developed a three dimensional FE model that was validated using the experimental results.

Clearly, more research is needed to investigate the behavior of buried pipelines subjected to reverse faulting and their complex soil–pipe interaction caused by a combination of compressive and bending deformation of the pipeline. Lack of experimental data on the behavior of buried pipelines under reverse faulting is another major shortcoming since no real data is available for validation of the FE models that are usually prepared for parametric studies and predicting the pipeline performance under seismically-induced PGD.

In this paper the results of two full-scale tests on 4″ (114.3 mm) and 6″ (168.3 mm) steel gas pipelines subjected to reverse faulting (pure dip-slip) of 0.60 m are presented to study the effect of different parameters such as the size of the fault offset, the ratio of the burial depth to the pipe diameter as well as the ratio of the pipe diameter to wall thickness on the pipe behavior. The pipes are commonly used in distribution lines and networks. It should be noted that the degree of importance is higher for transmission lines compared to distribution lines subjected to reverse faulting; yet, due to experimental limitations, it was not possible to perform the tests using pipes operating in transmission lines. Also, distribution lines are more vulnerable to lower magnitudes of PGD as compared to transmission lines. Two FE models are prepared and verified using the experimental results. Also the soil–pipe interaction forces along the pipelines are determined and compared to the criteria suggested by American Lifeline Alliance Guidelines [33], and the American Society of Civil Engineers [34]. Furthermore, both finite element and experimental results are used to compute the deformation of the pipe cross-section, and the results are compared.

2. Experimental program

2.1. Experimental setup

The full-scale laboratory testing of the pipeline under reverse faulting should allow for field conditions to be closely accounted for. However, it should be noted that simplifying some of the field conditions for laboratory testing is inevitable. The ground deformation caused by reverse faulting is very complicated and spatially distributed deformation is expected for ground deformation [35]. However, by concentrating the deformation along the planes of the soil failure, it is possible to set an upper bound on their effects on pipelines [36,37].

A large split-box test basin was built for studying the behavior of buried gas distribution pipelines subjected to reverse faulting (Fig. 1). The split-box was designed to test a number of 9 m-long steel pipes with end reaction force being around 785 kN. The approximate dimensions of the split-box are $8.5 \times 1.7 \times 2$ m (length × width × height) with a fault-dip angle equal to 61° with respect to the horizontal plane. The fault plane is close to the center of the box, dividing the box into fixed and moving parts. In each test, the moving part was displaced around 60 cm along the fault plane (Fig. 1(c)). The floor of the test basin is bolted to 8 laterally restrained columns, each 1 m high, which are attached to the laboratory strong-floor. The configuration of the test basin can be reasonably modified in order to meet alternative test configurations.

The truss-like configuration of the box and the floor framing is composed of W-shape steel sections with 18 mm oriented strand board (OSB) panels as sheathing and steel plate as decking. C-shape steel sections were considered for the bracing of the basin as well as supporting the OSB panels. Each part of the split-box when filled with sand will have a weight of approximately 250 kN. Four rails, two at the fault-interface and two on the external frames were used to guide the moving part of the split box, as it is shown in Fig. 1. The three 490 kN hydraulic jacks used in the tests were synchronized to have the same vertical displacement. High performance, force tolerating ball bearings was used inside the rails to ease the slippage of the moving part under applied loading. The external frames were considered to improve the stability of the moving part. Three hydraulic jacks were placed under the test basin and were configured as apices of a triangle, aligned with the fault line.