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CENTRIFUGE MODELING OF BURIED PIPELINES RESPONSE DUE TO REVERSE FAULTING

Mahdi Rojhani[1], Majid Moradi[2], Abbas Galandarzadeh[3], Shiro Takada[4]

ABSTRACT

Buried pipelines are commonly used to transport water, gas and oil. They are classified as lifelines as they carry materials essential to the support of human life. Due to the importance of lifelines survivability, it is of prime importance to study their threats to mitigate damages. Permanent ground deformation (PGD) such as fault crossing and lateral spreading are some of the most important threats for pipelines. Especially, localized PGD or faulting is a severe hazard for them. Many analytical, numerical and statistical researches have been done since almost four decade ago, but their results must be evaluated and verified by records of field case histories. As well-documented field case histories are quite limited, physical modeling can be used for verification. Physical modeling includes 1g modeling (full-scale or near full-scale) and centrifuge modeling. Centrifuge modeling is somehow preferred to 1g modeling for its accuracy, validity and expense point of view, especially for pipeline modeling with very long effective unanchored length.

This study focuses on behavior and response of buried continuous pipelines subjected to reverse faulting using centrifuge modeling technique. In this technical paper laboratory equipments, modeling setup and procedure and split-box container are demonstrated. Especially, physical characteristics of the university of Tehran centrifuge are described. Finally the recorded strains induced in model pipelines are presented.

Keywords: Centrifuge Modeling, Faulting, Lifelines, Pipeline, Earthquake

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[1] Ph.D Candidate, Dept. of Soil Mechanics and Foundation Engineering of School of Civil Engineering, Univ. of Tehran, E-mail addresses: mrojhani@ut.ac.ir.

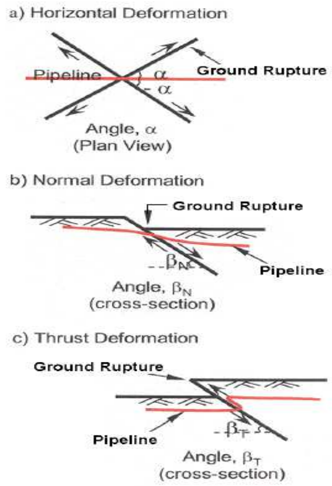
[2] Assistant Professor, Dept. of Soil Mechanics and Foundation Engineering of School of Civil Engineering, Univ. of Tehran, E-mail addresses: mmoradi@ut.ac.ir

[3] Assistant Professor, Dept. of Soil Mechanics and Foundation Engineering of School of Civil Engineering, Univ. of Tehran, E-mail addresses: aghaland@ut.ac.ir

[4] Adjunct Professor, Dept. of Soil Mechanics and Foundation Engineering of School of Civil Engineering, Univ. of Tehran, E-mail addresses: takada@lifeline-eng.com

INTRODUCTION

Buried pipelines often serve as lifelines in that they may carry resources that are essential to the support of human life and this is the reason to retain them in serviceable condition in every situation. Among various kinds of natural hazards, earthquakes happen to be the most serious threats for lifelines serviceability. They can damage lifelines through faulting, permanent ground deformation (PGD) and deformations due to seismic wave's propagation. Faulting can affect pipelines in various ways (Fig.1) and cause severe damages (Fig.2) depending on faulting movement direction.



a) Horizontal Faulting

b) Normal Faulting

c) Reverse Faulting

Figure 1. Differect ground rupture patterns and pipelines' response

Figure 2. An example of damaged pipeline due to faulting

Considering mentioned hazards, lots of statistical, analytical and numerical studies have been conducted since 1970s in order to predict pipelines response and vulnerability level and also to investigate methods of damage mitigation; but it has been a difficult and somehow impossible way to evaluate theoretical and analytical research results due to loss of accurate and efficient records about pipelines response to faulting in actual case histories of earthquakes [Choo et al.]. In order to compensate such a gap, studies turned towards applying experimental and physical modeling of this phenomenon. Since 2003, significant researches have been started in U.S.A. and Japan with support of companies and institutes such as Tokyo Gas Company, US lifelines Agency, National Science Foundation in U.S.A, Earthquake Engineering Research Center and etc. Most of mentioned conducted studies have been focused on strike-slip faulting.

So, still there is lack of studies on normal and reverse faultings' effects and this puts them in prime importance of research priority.
As a very long unanchored length of pipeline is affected due to faulting, 1g physical modeling of pipelines would be difficult, expensive and somehow impossible; So, centrifuge modeling would be the best choice which can simulate effects of faulting close to prototype conditions.

CENTRIFUGE MODELING

Geotechnical Centrifuge of University of Tehran

Geotechnical centrifuge of engineering faculty of university of Tehran is the first active geotechnical centrifuge set-up in Iran. This facility, manufactured by the French company of ACTIDYN SYSTEMS, firstly established and used in the current research. The instrument is of C67-2 model (Fig.3) with cantilever beam and suspending basket.

Figure 3. University of Tehran geotechnical centrifuge

This facility is consisted of parts such as a) suspending basket, b) centrifuge boom, c) adjustable counterweight, d) fluids rotary joint and electrical slip ring, e) driver system, f) aerodynamic covering, g) automatic balancing system and some minor parts which are indicated in table 1.

Table 1. Centrifuge Facility Properties

Property	Unit	Quantity
Exerted acceleration	g	5 – 130
Acceleration accuracy	g	± 0.2
Rotational velocity range	rpm	38 – 208
Rotation radius	m	3
Maximum model weight (up to 100 g)	kg	1500
Maximum model weight (up to 150 g)	kg	500
Maximum model dimensions (length×width×height)	m	1.0 × 0.8 × 0.8

Faulting Simulator Split Box

Experimental setup provision in order to use in centrifuge instrument has its own limitations; for instance, weight and dimensions of the box is thoroughly tied to the used centrifuge facility properties and it is of prime importance for the box to have the minimum weight and dimensions possible together with having enough strength for high magnitude forces caused due to high exerted accelerations. Regarding these limitations, the group-7000 aluminum alloy which has low density and high strength is used to build up the faulting simulator split box in this study. Outer dimensions of the box are 102×76×68 ^{cm} (l×w×h) and the inner dimensions are 96×70×23 ^{cm}. The split line of the box which is the faulting line itself, makes the angle of 30° from the vertical direction. The box setup is assembled and fixed on a 4 ^{cm} thick aluminum block of 15 ^{cm} width that can bear the hydraulic jack caused 5 ^{ton} horizontal force and high magnitude vertical force which is exerted due to high accelerations. Holes have been cut in the two ending walls of the box as the backrests for studied structures such as pipelines. Regarding lack of space in the centrifuge basket, the motivating system and the other constituents of the simulator must occupy the minimum space possible.

Moving mechanism has been designed to be enough stable during the faulting movement and also can bear the high magnitude unbalanced forces derived from soil-structure friction.

A wedge-sliding mechanism has been applied for the box movement to direct the faulting through the 30° specified direction and prevent form any strike between fixed and moving parts of the split box. The wedge-sliding mechanism is consisted of two rails installed with the angle of 30° from the vertical direction and high level force tolerating ball bearings to guide the movement as desired. Sliding the wedge forward and backward, the moving part of the box would have an upward-downward movement (Fig. 4). Considering the high magnitude forces and weight increase in high order accelerations, the moving system has been chosen of hydraulic type to be strong enough and less space occupying. The velocity and displacement control can be done by means of electronic hydraulic valves with a satisfactory level of accuracy and reliability. The hydraulic pressure generator is installed out of the centrifuge basket to save a significant amount of space and is connected to the inside basket moving system by means of hydraulic pipe and rotary joints.

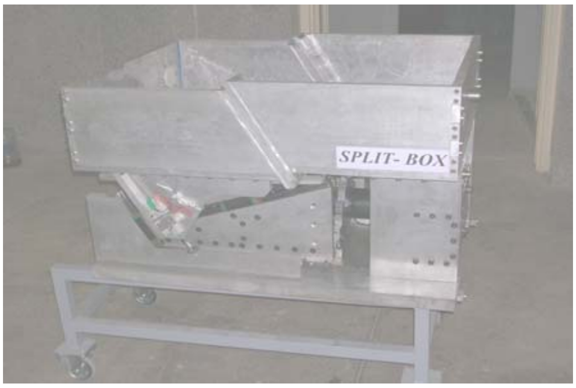


Figure 4. General view of Split-Box

Scaling Laws

The scaling laws used for this modeling are indicated as below (Table 2).

Soil Properties

Soil material used in present study is chosen to be the granular soil of standard Firoozkouh 161 sand. Physical and mechanical properties of this soil are represented in table 3.

Table 2. Scaling laws for centrifuge testing

Parameter	Model\ Prototype	Dimensions
Length	1/N	L
Strain	1	1
Stress	1	$ML^{-1}T^{-2}$
Acceleration	N	LT^{-2}
Axial Rigidity	$1/N^2$	MLT^{-2}
Flexural Rigidity	$1/N^4$	ML^3T^{-2}

Table 3. Properties of Firoozkouh 161 Sand

Sand type	G_s	e_{max}	e_{min}	D_{50} (mm)	FC	C_u	C_c
Firoozkouh 161	2.65	0.874	0.548	0.27	1 %	2.58	0.88

Instrumentation

Two types of instruments containing strain gauge and linear variable differential transformers (LVDTs) were installed in the model for 2nd test. The strain gauges are installed in axial and circumferential directions on the pipelines with the number of 26 in 7 stations. Strain gauges are placed in a way that axial and bending strains could be measures separately. Strain gauges are of the high strain type and are connected in the quarter bridge form.

Three LVDTs of the whole 5 ones are installed on the surface of the pipeline to record the deformation profile and the 2 other ones measure the axial displacement of the two endings of the pipeline. Apart from above, colorful grids were being used on the surface and between the soil layers.

RESULTS

Two tests were conducted in this study. In the first one, a copper pipe with diameter of 12.8 ^{mm} and wall thickness of 0.8 ^{mm} was subjected to a 70 ^{mm} reverse faulting with the acceleration of 40g. In the second experiment, the stainless steel pipe with 8.0 ^{mm} diameter and 0.4 ^{mm} wall thickness was subjected to the reverse faulting with 40g acceleration. The properties of model and prototype are indicated in table 4.

Table 4. Properties of model/prototype for conducted tests

	1st Test		2nd Test	
	Model	Prototype	Model	Prototype
Pipeline Diameter (m)	0.0128	0.512	0.008	0.32
Pipeleine Wall Thickness (m)	0.0008	0.032	0.0004	0.016
Faulting Magnitude (m)	0.070	2.8	0.070	2.8
Pipe Material	Copper		Stainless Steel	
Faulting Type	Reverse		Reverse	
Instrumentation	-		Strain gauge & LVDT	

Following figures illustrate the deformations of pipeline and soil during the faulting process. In figures (8) & (9) bending and axial strains versus distance from the faulting in 2nd test are presented.

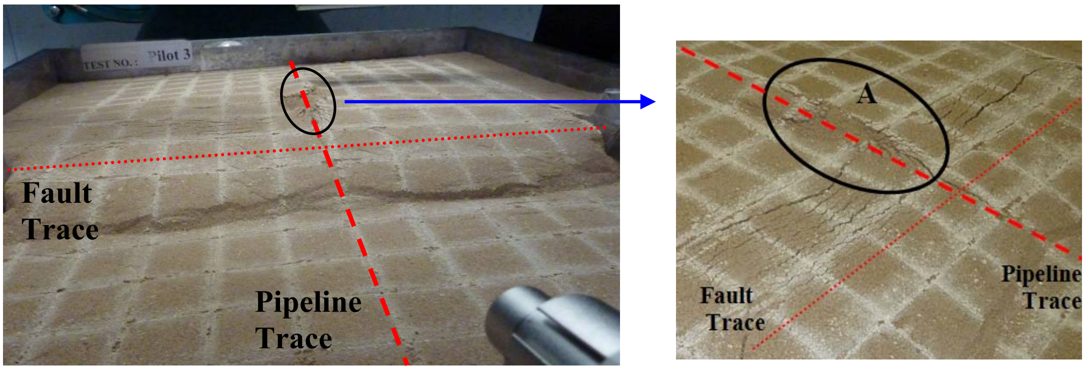


Figure 5. Surface Observation of 1st test (A: Location of maximum bending strain of pipe)

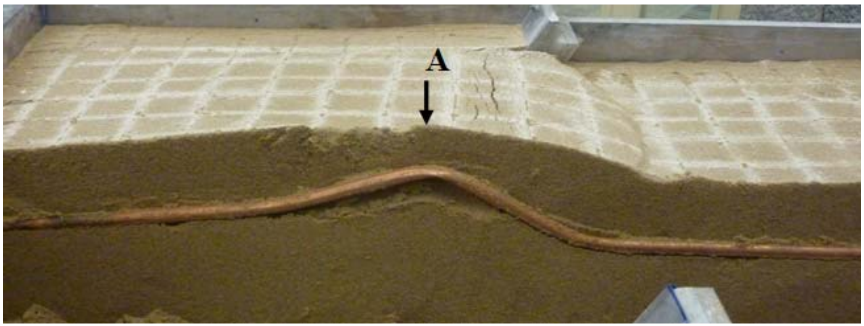


Figure 6. Section Observation of 1st test (A: Local buckling due to reverse faulting)

Figure 7. Surface Observation of 2nd test (Beam buckling of pipe due to reverse faulting)

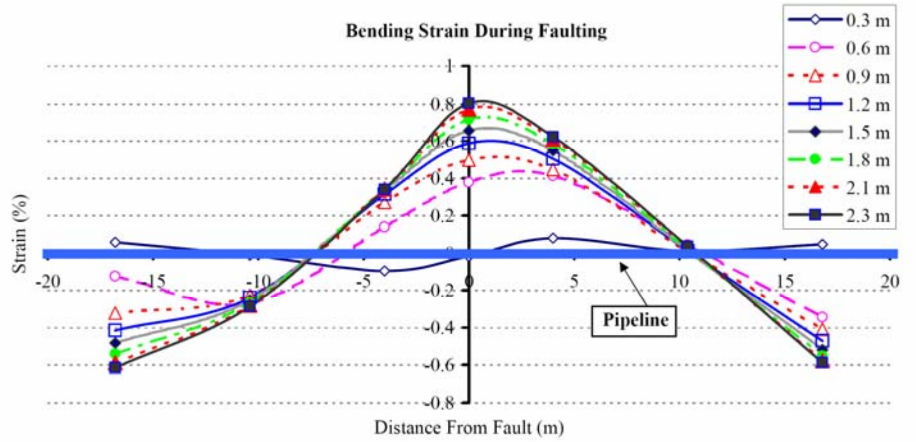


Figure 8. Bending strain during faulting-2nd test

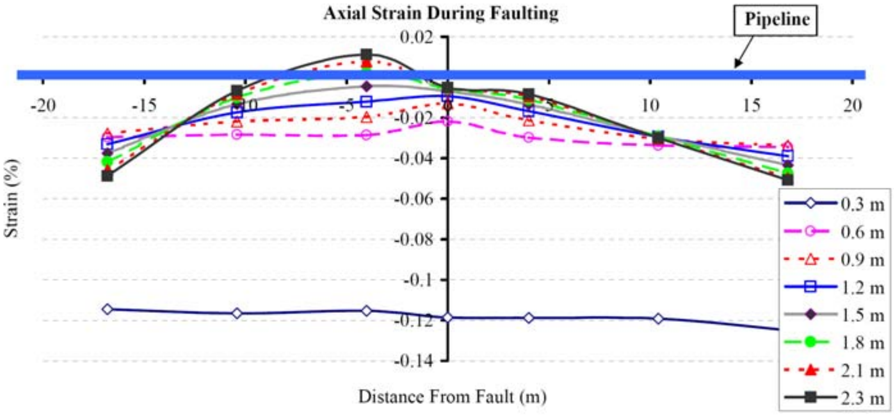


Figure 9. Axial strain during faulting-2nd test

CONCLUSION

In this article the report of establishment of the first geotechnical centrifuge in Iran and its initial application in buried pipelines modeling subjected to faulting are presented. Also, a brief summary of the modeling details, related scaling laws and used facilities and instruments are described. Reported in this experimental study are the axial and bending strains diagrams versus distance from the reverse faulting for the first time in the literature. According to figures (8) & (9), buckling of pipe started between 0.3 to 0.6 m offset. For the faulting offset less than 0.6 m, the axial strain is important. After buckling of the pipe, the axial strain reduced and became negligible. The axial and bending strain at the ends of pipe were not zero, because the end pipe supports aren’t free.

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