Centrifuge Modeling of Buried Pipelines Response

Due to Normal Faulting

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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 normal 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.

1 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.

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. 2007). 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 pipe-
lines would be difficult, expensive and somehow im-
possible; So, centrifuge modeling would be the best
choice which can simulate effects of faulting close to
prototype conditions.

Fig. 2 An example of damaged pipeline due to faulting

2 CENTRIFUGE MODELING

2.1 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 cant-
lever beam and suspending basket.

Fig. 3 University of Tehran geotechnical centrifuge

This facility is consisted of parts such as a) suspend-
ing basket, b) centrifuge boom, c) adjustable coun-
terweight, 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>
<thead>
<tr>
<th>Property</th>
<th>Unit</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exerted acceleration</td>
<td>g</td>
<td>5 – 130</td>
</tr>
<tr>
<td>Acceleration accuracy</td>
<td>g</td>
<td>± 0.2</td>
</tr>
<tr>
<td>Rotational velocity range</td>
<td>rpm</td>
<td>38 – 208</td>
</tr>
<tr>
<td>Rotation radius</td>
<td>m</td>
<td>3</td>
</tr>
<tr>
<td>Maximum model weight (up to 100 g)</td>
<td>kg</td>
<td>1500</td>
</tr>
<tr>
<td>Maximum model weight (up to 150 g)</td>
<td>kg</td>
<td>500</td>
</tr>
<tr>
<td>Maximum model dimensions</td>
<td>m</td>
<td>1.0 × 0.8</td>
</tr>
<tr>
<td>(length×width×height)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2.2 Faulting Simulator Split Box

Experimental setup provision in order to use in cen-
trifuge instrument has its own limitations; for in-
stance, weight and dimensions of the box is thor-
oughly 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 direc-
tion. 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 be-
tween 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 direc-
tion 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 mov-
ing system has been chosen of hydraulic type to be
strong enough and less space occupying. The velo-
city and displacement control can be done by means
of electronic hydraulic valves with a satisfactory
level of accuracy and reliability. The hydraulic pres-
Soil 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.

2.3 Scaling Laws

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

Table 2. Scaling laws for centrifuge testing

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Model/Prototype</th>
<th>Dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>1/N</td>
<td>L</td>
</tr>
<tr>
<td>Strain</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Stress</td>
<td>1/N</td>
<td>ML-1T-2</td>
</tr>
<tr>
<td>Acceleration</td>
<td>N</td>
<td>LT-2</td>
</tr>
<tr>
<td>Axial Rigidity</td>
<td>1/N2</td>
<td>ML-2</td>
</tr>
<tr>
<td>Flexural Rigidity</td>
<td>1/N4</td>
<td>ML3T-2</td>
</tr>
</tbody>
</table>

2.4 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 compared with two other types of sand in below table (Table 3).

Table 3. Properties of Firoozkouh, Toyora and Sengen Yama Sand

<table>
<thead>
<tr>
<th>Sand type</th>
<th>$G_s$</th>
<th>$c_{max}$</th>
<th>$e_{min}$</th>
<th>D50 (mm)</th>
<th>FC</th>
<th>$C_u$</th>
<th>$C_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Firoozkouh 161</td>
<td>2.65</td>
<td>0.874</td>
<td>0.548</td>
<td>0.27</td>
<td>1%</td>
<td>2.58</td>
<td>0.88</td>
</tr>
<tr>
<td>Toyoura</td>
<td>2.65</td>
<td>0.977</td>
<td>0.597</td>
<td>0.17</td>
<td>0%</td>
<td>1.54</td>
<td>1.25</td>
</tr>
<tr>
<td>Sengenyama</td>
<td>2.72</td>
<td>0.911</td>
<td>0.55</td>
<td>0.27</td>
<td>2.3%</td>
<td>2.15</td>
<td>1.21</td>
</tr>
</tbody>
</table>

2.5 Instrumentation

Two types of instruments containing strain gauge and linear variable differential transformers (LVDTs) were installed in the model. 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 measured 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.

3 RESULTS

Two tests were conducted in this study. In the first one, a copper pipe with diameter of 22.18 mm and wall thickness of 1 mm was subjected to a 70 mm normal 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 normal faulting with 40g acceleration. The properties of model and prototype are indicated in Table 4.

Table 4. Properties of model/prototype for conducted tests

<table>
<thead>
<tr>
<th></th>
<th>1st Test</th>
<th>2nd Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pipeline Diameter</td>
<td>0.02218</td>
<td>0.877</td>
</tr>
<tr>
<td>Pipeline Wall Thickness</td>
<td>0.001</td>
<td>0.04</td>
</tr>
<tr>
<td>Faulting Magnitude</td>
<td>0.070</td>
<td>2.8</td>
</tr>
<tr>
<td>Pipe Material</td>
<td>Copper</td>
<td>Stainless Steel</td>
</tr>
<tr>
<td>Faulting Type</td>
<td>Normal (60%)</td>
<td>Normal (60%)</td>
</tr>
</tbody>
</table>

Following figures illustrate the deformations of pipeline and soil during the faulting process. In Figs. 9 and 10 bending and axial strains before pipe failure versus distance from the faulting in 2nd test are presented.
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 of steel pipe versus distance from the normal faulting before pipe failure for the first time in the literature. Pipe failure happened almost at 3 cm in model or 1.2 m in prototype offset.

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REFERENCES


