Jordan Journal of Civil Engineering, Volume **17**, No. **1**, **2023**
DOI: https://doi.org/10.14525/JJCE.v17i1.07

Numerical Investigation on Buried Pipelines Subjected to Permanent Ground Deformations Due to Shallow Slope Failures

Mohammed Bouatia [1)*], ***Rafik Demagh*** [1)] ***and Zohra Derriche*** [2)]

[1)] LGC-ROI, Laboratoire de Génie Civil-Risques et Ouvrages en Interaction, University of Mustafa Ben Boulaid-Batna 2, 0578 Batna, Algeria. * Corresponding Author: E-Mail: m.bouatia@univ-batna2.dz
[2)] LTPiTE, Laboratoire Travaux Publics, Ingénierie des Transports et Environnement,
Ecole Nationale Supérieure des Travaux Publics, 16051 Algiers, Algeria.

ABSTRACT

Permanent ground deformations (PGDs) induced by slope failures cause catastrophic damage to buried pipelines. This paper presents a 2D plane-strain numerical analysis of the behavior of a 800 mm water transport pipeline buried in the Aine-Tine slope (Mila, Algeria) subjected to shallow PGD, as it could be triggered by the recent earthquake of August 07th, 2020 (M= 4.9). The analysis is carried out through the application of an incremental displacement to simulate the soil-pipeline interaction while focusing on the effect of (1) the magnitude of the PGD and (2) the rigidity of the pipeline on the structural response of the pipeline. The elastic-perfectly Mohr-Coulomb model was used to simulate the soil behavior and the elastic model was used to simulate that of the steel pipe. Pipeline deformations (i.e., translation and ovalization) and radial internal forces' (i.e., axial forces F_A, shear forces F_S and bending moments M_B) results highlighted that shallow PGD can exert additional loads on pipelines that are proportional to the magnitude of the PGD. It has been found that the soil deformations as well as the internal forces induced on the pipeline ring are higher for rigid pipelines. Moreover, the results indicated that rigid pipelines are more effective than flexible ones as far as ovalization-serviceability limit state is concerned. In effect, for PGD magnitudes of 0.5, 1 and 2 m, the ovalization values of the flexible pipeline are, respectively, higher by 23%, 21% and 18% than those calculated for the rigid pipeline. Through a simplified linear numerical simulation such as that presented in this study, engineers and planners could be guided to foresee the possible causes of pipeline leaks and the mechanisms of ruptures that lead very often to severe disruption of pipelines' normal operation.

KEYWORDS: Soil-structure interaction, Slope failure, Permanent ground deformation, Pipelines, Radial internal forces, Ovalization.

INTRODUCTION

Pipelines are widely used to transport water over long distances, crossing a variety of geological and topographical conditions. Pipelines are usually buried at shallow depths within the ground to protect them from external loads induced by upward and downward movements of vehicle wheels, from soil expansion as well as from soil frost heaving. The behavior of a buried pipeline relies on the properties of the soil surrounding the pipe as well as on the physical properties of the pipe itself. Flexible pipelines are usually made of PVC and HDPE, whereas rigid pipelines are generally made of reinforced concrete.

Very often, pipelines have to be buried in sloping grounds. In such conditions, the safety of the pipelines depends strongly on the stability of these slopes which could fail under many factors (i.e., gravity loads, rainfall precipitation and earthquake movements). When this occurs, the slope failure may provoke soil movements that induce additional loads on the pipeline structure which may lead to the pipeline failure if the loads happen to reach the strength limit of the pipeline material. However, there are still other sources for pipeline damage that cannot be avoided and which may

---

Received on 4/6/2022.
Accepted for Publication on 28/8/2022.

equally lead to large and non-reversible PGDs. These sources are usually connected with natural hazards, such as fault movements, earthquake soil movements and unsaturated soil wetting and drying (Ariman & Muleski, 1981; Ng, 1994). It has been shown that lifeline pipeline failure may lead to catastrophic environmental and economic losses (Massanat, 2011).

Many researchers have worked on the issue of soil-pipeline interaction under various loading conditions (Rajani & Morgenstern, 1993; Li et al., 2013; Kaya et al., 2016; Randeniya et al., 2019; Polat et al., 2021). Using a graphical procedure, Palmer et al. (1999) developed a simple method to assess longitudinal compressive stresses acting on pipelines buried in an arbitrary slope profile. Vazouras et al. (2010) conducted rigorous three-dimensional numerical investigations on the mechanical response of buried pipelines subjected to PGDs caused by a strike-slip seismic fault. On the basis of the results that they found, they managed to suggest safe combinations of fault displacement and diameter-to-thickness parameter of two typical pipelines considering the developed strains on the pipeline structures for two different types of soil. Sarvanis & Karamanos (2017) developed a closed-form equation to analyze strains developed on pipelines subjected to PGDs.

Many experimental investigations were carried out to explore the interaction between slope failures and pipeline behavior. Zhang and Askarinejad (2019) performed small-scale centrifuge tests to assess the effect of slope failures induced by surcharge loading applied on the crest of a sandy slope on the external forces that act on pipes buried at various locations of the slope. The study proposed a method to predict the maximum external loadings exerted on the pipe whatever is the circular failure mechanism of the slope. In addition, it was highlighted that the location of the pipe within the sloped ground plays an important role in minimizing the effects of the induced movements. O'Rourke et al. (2008) conducted large-scale parametric investigations on the effect of rapid large deformations similar to sudden PGDs on pipelines buried within unsaturated compacted sands. Feng et al. (2015) studied the case of a large-scale landslide crossing a gas pipeline prototype. After a series of excavations, the induced lateral movements brought the pipeline towards the toe of the slope and it was found that the most affected locations on the pipeline body were both sides of the movable ground (i.e., landslide) limits and the central part of the landslide. Using a small-scale laboratory testing procedure, Al-Khazaali and Vanapalli (2020) defined a new experimental technique to study the axial behavior of buried pipelines in unsaturated sands subjected to longitudinal axial forces. The main conclusion that can be drawn from the previous discussion is that the literature is tremendously rich in terms of longitudinal pipeline investigations under different loading conditions, whereas studies on the transverse behavior of pipelines are very scarce.

In the past years, the water pipeline network buried in the Mila basin (Mila, Algeria) suffered repetitive catastrophic damage as a result of PGDs induced by the slope failure. The majority of the recorded cases, as for the Ain-Tine slope case, are mainly related to shallow slope failures, where the slip planes pass through the body of the pipeline. The work presented in this paper is a part of an extensive research work that investigates the behavior of pipelines buried in sloping-soil areas. The paper presents a numerical investigation undertaken with the finite element SIGMA/W commercial software, to evaluate the transverse structural behavior of buried pipelines subjected to shallow PGDs. The study has been performed with the main objective to understand the effect of PGDs on the transverse soil-pipeline interaction expressed in terms of pipeline transverse deformations (movements and ovalization), induced radial internal efforts (i.e., axial forces F_A, shear forces F_S and bending moments M_B) that are developed on the pipeline ring. The study considered two pipeline rigidities (represented by Young’s moduli of 2GPa and 20GPa for flexible and rigid pipelines, respectively) and different magnitudes of the PGD ranging from 0 m to 2m. The pipeline used in the study is an 800 mm diameter water-supply pipe that comes from the Beni-Haroun Dam. It is assumed to be buried at 2-m depth in the landslide prone Aine-Tine slope (Mila, Algeria).

Permanent Ground Deformations (PGDs)

The seismic design of buried pipelines has a great importance in the field of lifeline structure engineering (IITK-GSDMA, 2007; ALA, 2005). Unfortunately, seismic design was not addressed for many cases of the pipeline networks in Algeria. PGD is defined as a non-reversible movement of the ground surface. Many PGDs that follow slope failures generate additional loadings on non-seismically designed buried structures (i.e., pipelines), which need to be evaluated. Figure 1 shows the idealized scheme of buried pipelines subjected to a transverse PGD exerted by a slope failure.

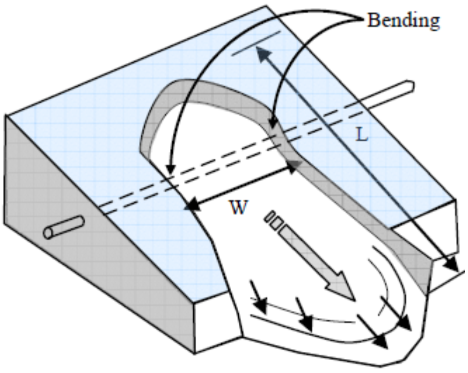

Figure (1): Situation of buried pipeline subjected to transverse PGD (IITK-GSDMA, 2007)

In the Mila basin, the PGDs induced by slope failures may have been triggered by two main factors, which are (1) earthquake movements and (2) rainfall precipitation events that reduce the shear strength of shallow-layer unsaturated clayey soils. On August 07th, 2020, two sequential earthquakes of magnitudes M= 4.5 and M= 4.9 stroke the Mila province at 2 and 3 kilometers, respectively, towards the south of the Hamala municipality which was classified as a devastated village due to the catastrophic economic losses that resulted (Figure 2). Following these earthquakes, many on-site interventions had to be carried out by the local authorities and professionals to investigate and repair the damaged pipelines. The resulting leaks and ruptures of pipelines affected the water supply of numerous municipalities, including Mila, in addition to the eastern provinces of the country (i.e., Batna, Constantine and Khenchela). The identified cases of damaged pipes had different diameters (i.e., 500 mm, 700 mm and 800 mm). As the pipeline buried in the Aine-Tine slope (D= 800 mm) suffered repetitive damages that hugely disrupted its normal operation, this paper presents a contribution to analyze the behavior of this lifeline structure under the effect of shallow PGDs.

Numerical Model

Geomtry

The structural behavior of Aine-Tine water pipeline under shallow sliding movements is studied numerically using the two-dimensional computational software SIGMA/W. For this purpose, the response of the cross-section of the pipeline is investigated to simulate the interaction between the steel pipe and the surrounding soil medium. Figure 3 shows the numerical model adopted in this study. A uniform soil profile is assumed to extend vertically down to a 4-m depth under the ground surface and to have an 8-m length horizontally. The burial depth of the pipe is assumed to be 2 m. Following many published investigations, the horizontal and vertical dimensions of the model are set as follows: Vertical= 5*D, Horizontal= 10*D, where D is the diameter of the pipe, in order to avoid the boundary condition effects (Vazouras et al., 2015; Bouatia et al., 2020).

Figure (2): The 7th August 2020 earthquake effects: Pipeline repair operation

For the soil mass, meshing is automatically generated where quadrilateral and triangular plane-strain elements are created, forming thereby a unified mesh size of 0.25 m. The pipe was modeled as a beam structural element, where the perimeter is divided into 24 equal segments. The total number of elements in the model is 1264. Simulation was conducted following two steps. The first step is the generation of the geostatic initial stresses of the model using the *in-situ* option and subsequently, in the second step, the PGD, due to an eventual slope-failure, is applied. On the basis of the results of the Aine-Tine slope-failure investigations which indicated a shallow slope-failure surface, the slip surface in the present analysis was assumed to be parallel to the ground surface and to pass through the center of the pipe. Consequently, the failure plane divides the soil mass into two equal blocks of 8 m by 2 m horizontal and vertical dimensions for each one

(Figure 3). The boundary conditions of the model are as follows: in the first step of the simulation (i.e., geostatic conditions), the left and right vertical boundaries are fixed only in the x-direction, whereas the bottom boundary is fixed in both x and y directions. In the second step, the vertical-boundary nodes of the bottom block remain fixed in the horizontal direction, whereas incremental uniform horizontal displacements are imposed on the nodes of the outer vertical edges of the top (moving) block in the horizontal direction to simulate the PGD. The PGD magnitude is gradually increased from 0 to 2m. A new analysis is carried out for every applied PGD value.

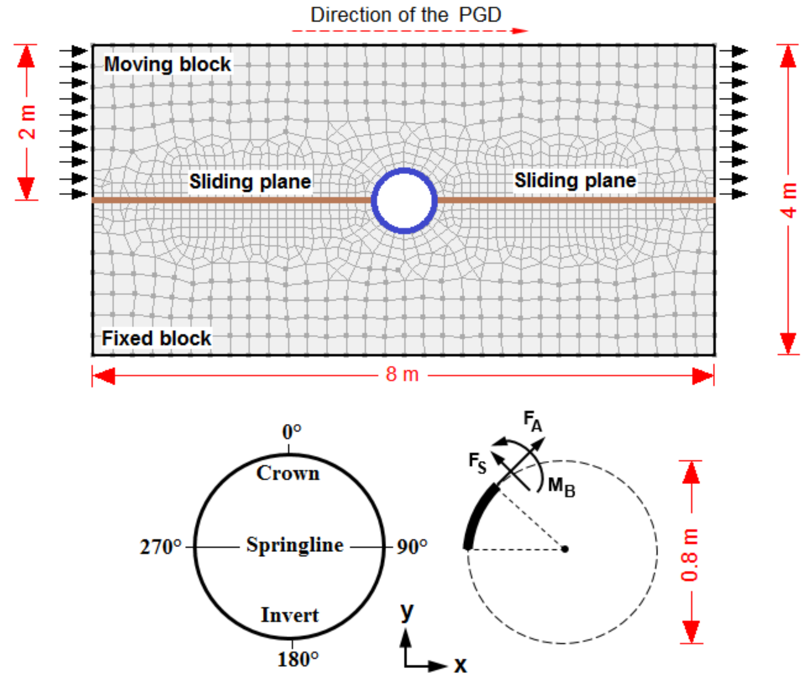

Figure (3): Finite element model and pipeline cross-section details

Material Characteristics

The site of the present study is located in the municipality of Aine-Tine (Mila, Algeria). The slope belongs to the Mila basin which is known to be facing many geotechnical problems, such as slope failures and soil shrink-swell movements due to the recent geological nature of the strata (Mio-Pliocene and Quaternary continental deposits) of its surficial-layer soil. The majority of the surface soils of this province are unsaturated alluviums and clays. The soils of the surface layer of Aine-Tine slope have a clay content of 52% and are classified as CH (inorganic clay of high plasticity) according to the USCS classification system. The geotechnical parameters of the soil of the studied case are summarized in Table 1.

The elastic-perfectly plastic Mohr-Coulomb (MC) constitutive model was used to simulate the clayey-soil behavior. This model was successfully used to analyze soil-pipeline interaction problems (Robert & Soga, 2013; Robert et al., 2016; Al-Khazaali & Vanapalli, 2019). The gravity is set to 9.81 $\mathrm{m/s^2}$. Rigidity is the parameter that controls the structural behavior of pipelines. Pipelines are classified by Moser and Folkman (2008) as flexible and rigid. The pipelines of the Aine-Tine area are made of steel and are buried at a 2-m depth. In the present study, the pipeline was modeled using beam element with the linear elastic model due to the high stiffness of steel material. The Young’s moduli E, used in this study, were as follows: 2 and 20 GPa to simulate flexible and rigid pipelines, respectively. The same values were adopted by Al-Khazaali et al. (2018) to consider the rigidity effect on the response of buried pipelines subjected to ground movements induced by unsupported excavations. The parameters used to perform the present analysis are summarized in Table 2.

Table 1. Aine-Tine clay geotechnical parameters

Material	Soil property	Value
Clay	Total unit weight γ_t [kN/m3]	20
	Elastic modulus E [MPa]	3.5
	Poisson's ratio μ	0.33
	Angle of internal friction φ [°]	15
	Cohesion c [kPa]	22
	USCS Classification	CH, Inorganic clay of high plasticity

Table 2. Aine-Tine pipeline parameters

Material	Pipe property	Value	
Aine-Tine Pipeline	External diameter Q_{ext} [mm]	800	
	Thickness t [mm]	20	
	D/t	40	
	Young's modulus E [GPa]	Flexible	2
		Rigid	20

Interface Modeling

In the present study, a linear analysis of the soil-pipeline interaction was performed. To simulate the weakness of the slip zone within the numerical model, interface elements were generated using the SIGMA/W software built-in option at the following locations:

- The external surface of the pipe;
- Between the moving and the fixed blocks of the numerical model.

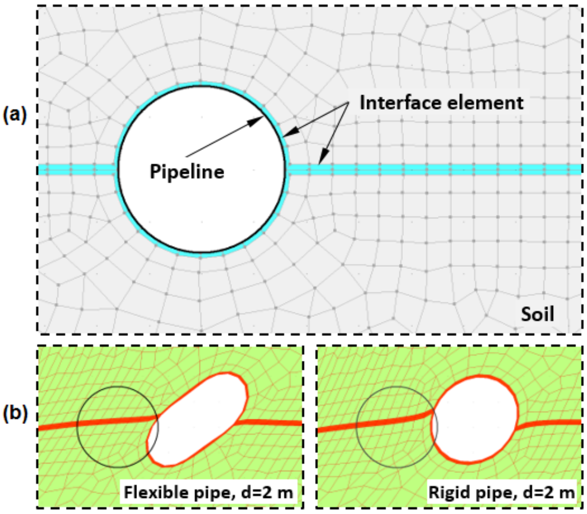

Figure (4): (a) Soil-pipeline interface element details and (b) Interface elements' deformation (PGD d= 2m)

The thickness of the interface elements was set to 0.05 m which is 1/5 smaller than the size of the soil elements because of the concentration of the expected stresses at these locations. Residual shear strength parameters (i.e., friction angle φ= 9° and cohesion c=8 kPa) were assigned to the interface elements to model their behavior considering a complete bond between the nodes of the soils and those of the pipe while applying the PGD incremental displacements. Figure 4 shows the interface locations and the deformation that occurred around the pipe after d=2 m of the PGD for both flexible and rigid pipes.

RESULTS AND DISCUSSION

The numerical simulation of this study presents a contribution aimed to the understanding of the effects of PGDs provoked by slope failures that recently occurred in the province of Mila on the pipelines buried in the clayey soil of the Mila basin. The results are presented into two parts (1) deformation and movement magnitudes of the soil and the pipeline cross-section and (2) the induced radial internal efforts that act on the perimeter of the pipeline with respect to the PGD magnitude. The effect of the PGDs on the pipeline is taken into account by applying incremental displacements of different magnitudes d= 0.1, 0.2, 0.3, 0.4, 0.5, 1 and 2 m.

Soil Deformations

The simulation of the PGD is carried out by applying incremental displacements acting in the x-direction on the outer vertical edges of the top block (moving block). The applied displacements resulted in strains and consequently changed the x and y stress components. Upward and downward vertical displacements at the top surface were induced (Figure 5). It can be noted that for the flexible pipeline, the upward displacements increase with the magnitude of the PGD, where the peak value (abscissa x=2 m) equals 7.45 cm under d=0.5 m and reached 37.5 cm for a magnitude d=2 m of PGD. The downward displacements (abscissa x=7 m) increased with the PGD magnitude d, where the peak values reached -12.1, -23.2 and -42.3 cm for d=0.5, 1 and 2 m, respectively. The same configuration of results was obtained for the case of rigid pipeline, but with different amplitudes of displacement. The peak upward components, which correspond to d=0.5, 1 and 2 m PGD magnitudes reached 8.9, 19.7 and 41.8 cm, respectively, while for the same PGD magnitudes, the obtained peak downward displacements reached -12.9, -24.3 and -43.1 cm, respectively. The results indicate that for the same embedding material and under the same PGD magnitudes, the induced soil deformations are higher for the rigid pipeline than those for the flexible one because of the high deformations that occur on the ring of the flexible pipeline.

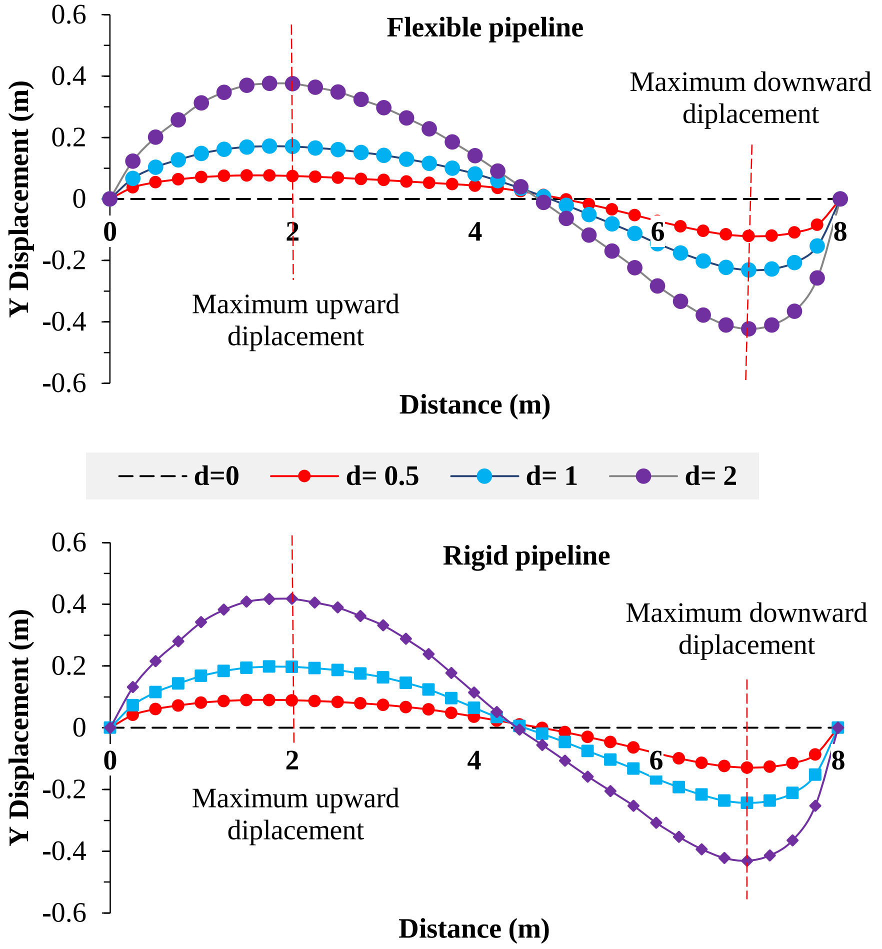

Figure (5): Vertical soil displacements at the ground surface for different PGD values

Pipeline Displacements and Ovalization

Figure 6 displays the results of the displacements and the deformation that occurred on the pipeline ring under different values of the PGD. Considering the displacement of the pipeline center, the pipeline has been moved by 18, 35 and 73 cm after PGD magnitudes of d= 0.5, 1 and 2 m, respectively. For the same magnitudes d, the rigid pipeline has been displaced by 17, 33 and 71 cm, respectively.

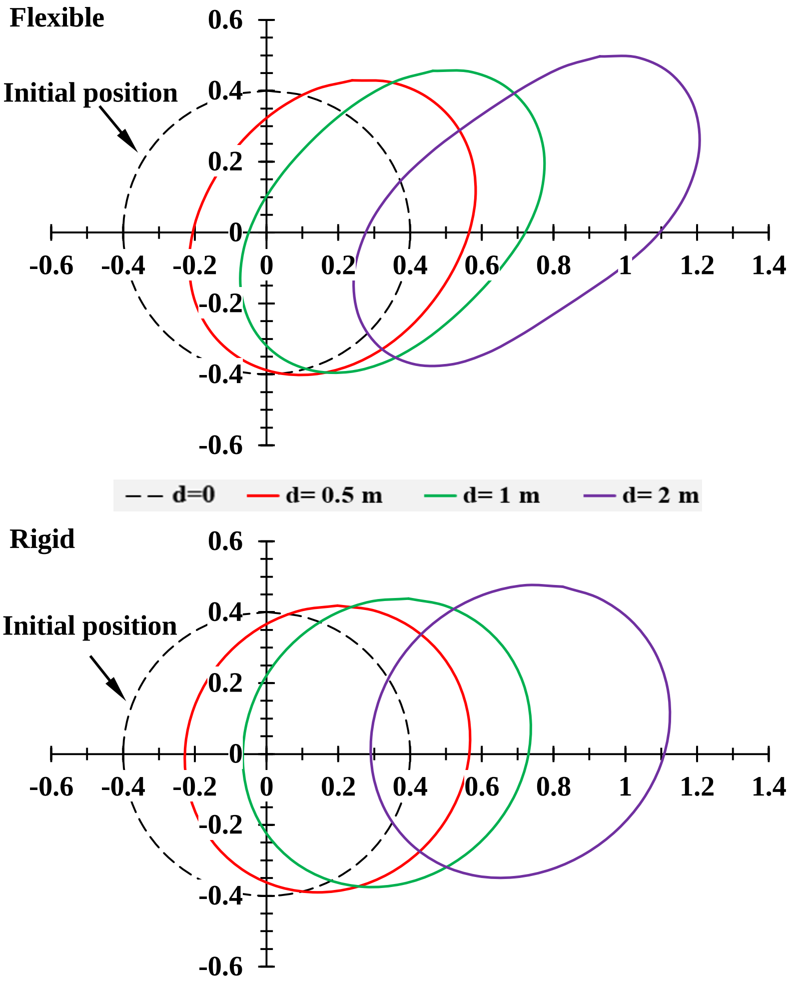

Figure (6): Displacement and deformation of pipeline cross-section under different PGD values for flexible pipes and rigid pipes

As a serviceability limit, the ovalization of the pipe cross-section is one of the relevant conditions that are taken into consideration when designing buried pipelines to maintain their normal operation. This condition can be expressed through the so-called flattering parameter f which is written as follows $f = \Delta D/D$, where ΔD is the maximum variation of the pipeline diameter and D is the pipeline diameter. The ovalization values calculated in the present study increase with the magnitude of the lateral displacement d. The ovalization of the flexible pipeline reached 13%, 24% and 39% for PGD magnitudes of d= 0.5, 1 and 2 m, respectively and they are higher by 23%, 21% and 18% than those calculated in the case of the rigid pipeline for the same magnitudes of the PGD. For this reason, it can be concluded that flexible pipelines are very sensitive to shallow-slope failures in terms of ovalization serviceability limit compared to rigid pipelines. According to Gresnigt (1986), who proposed 15% as a serviceability limit for the flattering parameter, it can be observed in Figure 7 that the rigid pipe is safe with regard to ovalization whatever the PGD magnitude applied. On the other hand, the flexible pipe is however safe only for the low PGD magnitude d= 0.5m. The finite element deformations of the pipe and soil that correspond to magnitudes of PGD of 0.5, 1 and 2m for both rigid and flexible pipeline are presented in Figure 8.

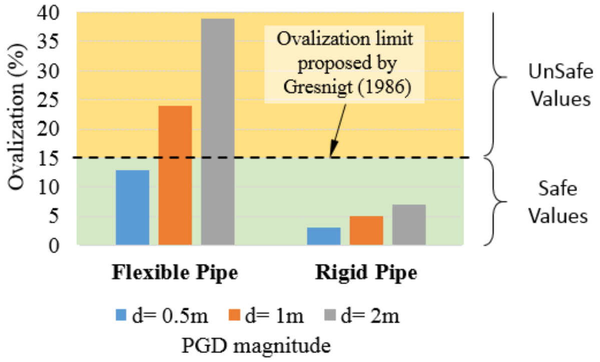

Figure (7): Results of the flattering parameters for flexible and rigid pipes

Radial Internal Forces

The PGDs induced by slope failures triggered by natural hazards will produce stresses and strains on buried pipeline structures and subsequently lead to the generation of additional internal forces that can damage these structures.

The induced radial-axial forces F_A that occur along the pipeline perimeter for the two different Young's moduli (2 and 20 GPa) pipes and assumed to be subjected to different magnitudes of shallow PGD ranging from 0.1 to 2 m are presented in Figure 9. It is clear that, for both flexible and rigid pipeline conditions, the pipeline ring is suffering compressive and tensile forces, where the maximum compression forces are shown as two positive peak values that are calculated at the angles of 45° and 210°, while the maximum tensile forces are calculated at the angles of 135° and 300° and represented by negative peak values.

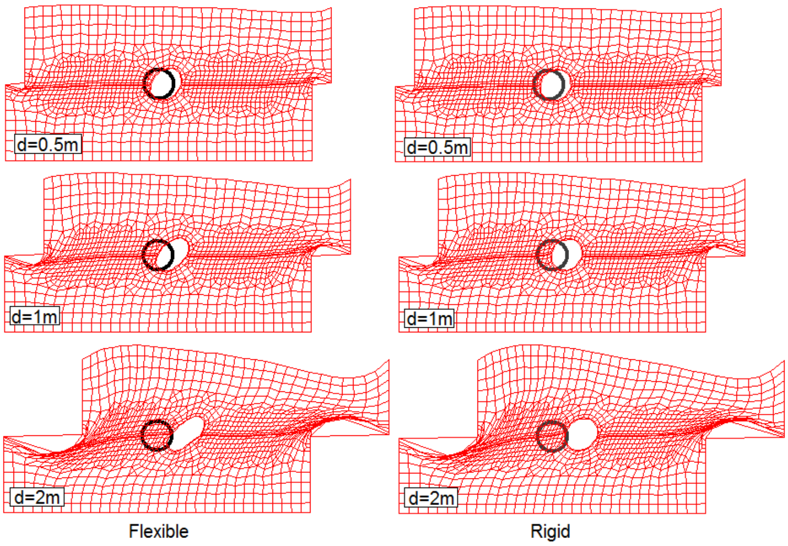

Figure (8): The deformed model mesh of the pipe and soil for different PGD values for flexible and rigid pipes

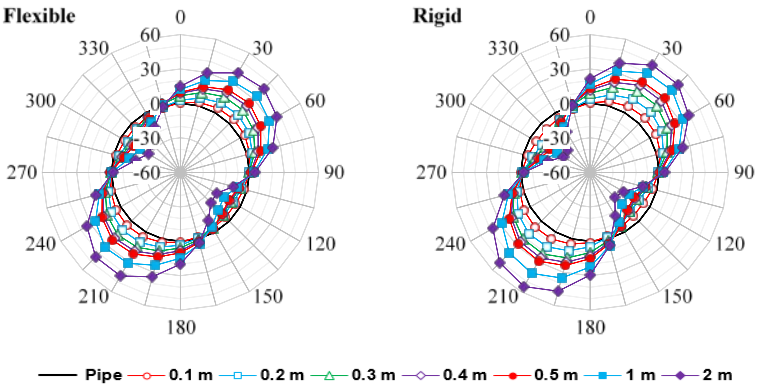

Figure (9): Axial force [kN] distribution for flexible and rigid pipelines

The developed axial forces increase proportionally to the PGD magnitude; nevertheless, they are higher in the case of rigid pipeline than for the flexible pipeline because of the high rigidity of the rigid pipeline (10 times higher). If one examines the flexible pipeline, the applied PGD on the top block increases the maximum tension forces at the angle of 45° from 5.31 to 42.69 kN, which corresponds to an increase of the PGD from 0.1 to 2 m. Simultaneously, these forces increase from 4.97 to 44.06 kN for those calculated at the angular location of 210°. In the case of the rigid pipeline, these values increase from 7.19 to 47.96 kN and from 6.92 to 54.82 kN, respectively at the same angular positions. For magnitudes of PGD (0.1 and 2 m), the compressive axial components that are developed with the flexible pipeline increase from 4.64 to 23.47 kN and from 4.29 to 27.9 kN at the locations of 135° and 300°, respectively, while those of the rigid pipeline ranged from 6.82 to 29.6 kN and from 6.19 to 33.34 kN at the same angular locations. To sum up, the results indicate that rigid pipelines should withstand higher induced internal forces than flexible pipelines.

The second component of the internal forces is the shear forces F_S. As can be seen in Figure 10, shear forces are symmetrically distributed along the cross-section of the pipeline, where the peak values correspond to null values of the axial forces. As for the axial forces, the shear forces have four peak values located at 0°, 90°, 180° and 255°. The maximum values, which correspond to 0.5, 1 and 2 m of PGD magnitude, are equal to 7.69, 13.51 and 21.04 for the flexible pipeline, whereas for the case of the rigid pipeline, they are equal to 17.85, 25.5 and 33.9 kN, respectively. These values were obtained at the angular location of 255° for both pipeline rigidities. Based on the results displayed by the plotted curves, one can conclude that the induced shear forces are higher for rigid pipelines.

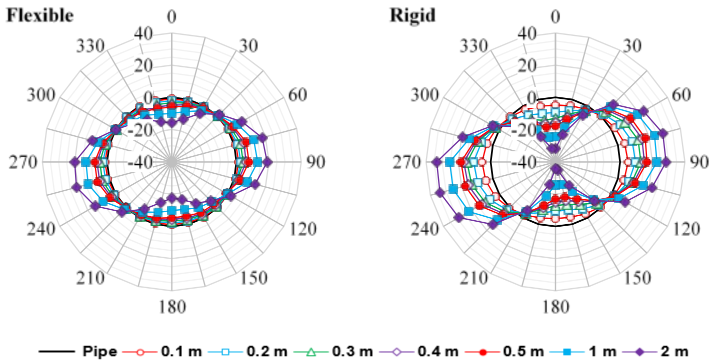

Figure (10): Shear force [kN] distribution for flexible and rigid pipelines

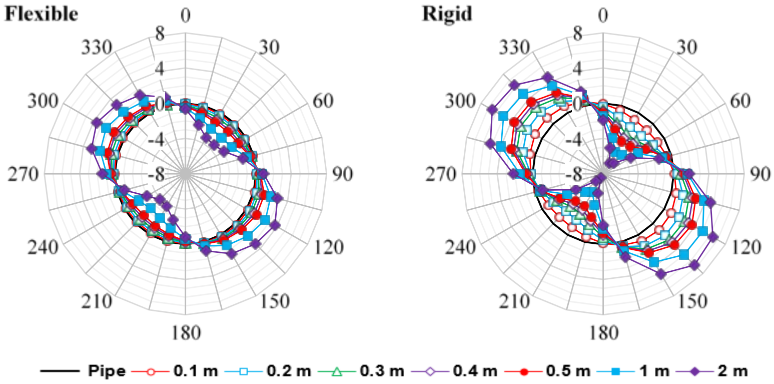

Figure (11): Bending moment [kN.m] distribution for flexible and rigid pipelines

The bending moment is the third component of the structural response of the pipeline to the induced PGD. The results of circumferential bending moment M_B calculated along the pipeline perimeter are illustrated in

Figure 11. Bending moments have the same evolution with the previous results of internal forces (F_A and F_S) when considering their increasing proportionally with respect to both (1) the PGD magnitude and (2) the rigidity of the pipeline. The maximum values are obtained at the same angular locations of the axial forces, but with opposite signs. The maximum bending moment M_B calculated, in the case of the rigid pipeline, for d= 0.5, 1 and 2 m of PGD is 3.43, 4.98 and 6.66 kN.m, respectively (at 135°). These values are higher by 156%, 102% and 80% than those calculated in the case of the flexible pipeline for the same PGD magnitudes (at 120°).

Magnitudes of the internal forces calculated on the ring of the pipeline are higher in the case of the rigid pipeline than those calculated in the case of the flexible pipeline. This can be explained by the fact that the flexible pipeline is able to dissipate stresses and strains by deforming much more than the rigid pipelines can do (Figures 4, 6 and 8).

CONCLUSIONS

This study presented a numerical analysis to investigate the transverse structural behavior of a buried pipeline subjected to PGDs, focusing on the effect of the pipeline rigidity and PGD magnitude on the additional loads that are induced by slope failures triggered by the earthquake that happened in Mila basin (Algeria) on August 07th, 2020. The water-supply steel pipeline that brings water from Beni-Haroun dam, which was buried in the Aine-Tine slope, was considered to study the performance of such buried structures. The results obtained allow for the following conclusions to be drawn:

- Flexible pipes, such as PVC and HDPE pipes, are defined by their ability to yield under loading without fracturing. Rigid pipes, such as concrete, clay and ductile iron pipes, are limited in their ability to yield under load without sustaining damage.
- The deformation and ovalization of the buried pipeline subjected to shallow-slope failures are proportional to the magnitude of the applied PGD. Such deformations can be the main cause of the leakages recorded on the site of Aine-Tine slope pipeline.
- Considering the ovalization serviceability limit, rigid pipelines are more effective than flexible pipelines to ensure safe functioning of water-supply pipes in unstable areas.
- The radial internal forces as well as the shear forces and the bending moments increase proportionally with the magnitude of the PGD applied. They are higher in rigid pipes than in flexible pipes. Rigid pipelines should withstand higher induced loads than flexible ones.

The present work serves as an interesting tool for engineers and planners to understand the behavior of pipelines buried in sloping areas which are subjected to shallow-slope failures that can be induced by sudden natural hazards, such as earthquakes or intense rainfall precipitations. As the Mila basin area is classified as a semi-arid region, future investigations need to address the soil characteristics' changes that can occur within the pipeline-surrounding soil as a result of soil wetting or drying to achieve more realistic results. As the nature of the soil-pipeline interface is dominant in such investigations, future studies should consider it more judicious to use, instead of an interface integrated in the material, another type of interface composed of nonlinear springs connecting the nodes in the soil elements to their corresponding nodes in the pipeline elements. The authors believe that using such interface type, would give results that are somewhat more close to reality.

Acknowledgements

The first author gratefully expresses his appreciation to the Algerian Ministry of Higher Education and Scientific Research, which funded this research. Thanks are extended to Pr. Aminaton Marto (Universiti Teknologi Malaysia) and Pr. Azman Kassim (Universiti Teknologi Malaysia) for their support and recommendations.

Funding

This research was funded by the Algerian Ministry of Higher Education and Scientific Research; Grant ID: PNE628-20192020.

List of Symbols

PGD: Permanent Ground Deformation
d: Magnitude of the PGD
ΔD: The maximum variation of the pipeline diameter

D: The pipeline diameter
MC: Mohr-Coulomb model
M: Magnitude of earthquake
$\mathbf{F_A}$: Axial forces developed on the pipeline ring
$\mathbf{F_S}$: Shear forces developed on the pipeline ring
$\mathbf{M_B}$: Bending moments developed on the pipeline ring
IITK-GSDMA: Indian Institute of Technology Kanpur - Gujarat State Disaster Management Authority
ALA: American Lifelines Alliance
USCS: Unified Soil Classification System
CH: Inorganic clay of high plasticity
f: Flattering parameter ($f=\Delta D/D$)
E: Young's modulus
$\boldsymbol{\mu}$: Poisson's ratio
$\boldsymbol{\gamma_t}$: Total unit weight
c: Cohesion
$\boldsymbol{\varphi}$: Angle of internal friction
$\mathbf{Q_{ext}}$: External diameter of the pipe
t: Thickness of the pipe
PVC: Poly-vinyl-chloride
HDPE: High-density poly-ethylene.

REFERENCES

ALA. (2005). "Seismic guidelines for water pipelines". American Lifelines Alliance.

Al-Khazaali, M., and Vanapalli, S.K. (2019). "Axial force–displacement behaviour of a buried pipeline in saturated and unsaturated sand". Géotechnique, 1-18. https://doi.org/10.1680/jgeot.17.P.116

Al-Khazaali, M., and Vanapalli, S.K. (2020). "A novel experimental technique to investigate soil–pipeline interaction under axial loading in saturated and unsaturated sands". Geotechnical Testing Journal, 43 (1), 70-93. https://doi.org/10.1520/GTJ20180059

Al-Khazaali, M., Vanapalli, S.K., and Oh, W.T. (2018). "Numerical investigation of soil–pipeline system behavior nearby unsupported excavations in saturated and unsaturated glacial till." Canadian Geotechnical Journal, 56 (1), 69-88. https://doi.org/10.1139/cgj-2017-0411

Ariman, T., and Muleski, G.E. (1981). "A review of the response of buried pipelines under seismic excitations". Earthquake Engineering & Structural Dynamics, 9 (2), 133-152. https://doi.org/10.1002/eqe.4290090204

Bouatia, M., Demagh, R., and Derriche, Z. (2020). "Structural behavior of pipelines buried in expansive soils under rainfall infiltration (Part I: Transverse behavior)". Civil Engineering Journal, 6 (9), 1822-1838. https://doi.org/10.28991/cej-2020-03091585

Feng, W., Huang, R., Liu, J., Xu, X., and Luo, M. (2015). "Large-scale field trial to explore landslide and pipeline interaction". Soils and Foundations, 55 (6), 1466-1473. https://doi.org/10.1016/j.sandf.2015.10.011

IITK-GSDMA. (2007). "Guidelines for seismic design of buried pipelines". Indian Institute of Technology Kanpur-Gujarat State Disaster Management Authority.

Kaya, E.S., Uckan, E., Cakir, F., and Akbas, B. (2016). "A 3D nonlinear numerical analysis of buried steel pipes at strike-slip fault crossings". Građevinar, 68 (10.), 815-823.

Li, C., Wang, L., Jing, H., and Liu, Q. (2013). "Protection control scheme and evaluation of effects on pipeline crossing beneath landslide area." Journal of Pipeline Systems Engineering and Practice, 4 (1), 41-48. https://doi.org/10.1061/(ASCE)PS.1949-1204.0000130

Massanat, Y.M. (2011). "Parametric evaluation of the stability of natural slopes". Jordan Journal of Civil Engineering, 5 (3), 401-411.

Moser, A.P., and Folkman, S. (2008). "Buried-pipe design". Third Edition, McGraw-Hill Education/ content/book/9780071476898

Ng, P.C.F. (1994). "Behaviour of buried pipelines subjected to external loading". PhD Thesis, University of Sheffield. http://etheses.whiterose.ac.uk/1823/

O'Rourke, T.D., Jezerski, J.M., Olson, N.A., Bonneau, A.L., Palmer, M.C., Stewart, H.E., O'Rourke, M.J., and Abdoun, T. (2008). "Geotechnics of pipeline-system response to earthquakes". Geotechnical Earthquake Engineering and Soil Dynamics, IV, 1-38. https://doi.org/10.1061/40975(318)193

Palmer, A.C., Tebboth, L., Miles, D., and Calladine, C.R. (1999). "Instability of pipelines on slopes." Journal of Applied Mechanics, 66 (3), 794-799. https://doi.org/ 10.1115/1.2791757

Polat, N., Erenson, C., and Uğur Terzi, N. (2021). “The deformation characteristics of buried HDPE transfer lines in trenches under the effect of temperature”. Revista de la Construcción, 20 (3), 452-462. https://doi.org/10.7764/RDLC.20.3.452

Rajani, B., and Morgenstern, N. (1993). “Pipelines and laterally loaded piles in elastoplastic medium”. Journal of Geotechnical Engineering, 119 (9), 1431-1448. https://doi.org/10.1061/(ASCE)0733-9410(1993)119:9(1431)

Randeniya, C., Robert, D.J., Li, C.-Q., and Kodikara, J. (2019). “Large-scale experimental evaluation of soil-saturation effect on behaviour of buried pipes under operational loads.” Canadian Geotechnical Journal, 57 (2), 205-220. https://doi.org/10.1139/cgj-2018-0544

Robert, D.J., Soga, K., O’Rourke, T.D., and Sakanoue, T. (2016). “Lateral load-displacement behavior of pipelines in unsaturated sands”. Journal of Geotechnical and Geoenvironmental Engineering, 142 (11), 04016060. https://doi.org/10.1061/(ASCE)GT.1943-5606.0001504

Robert, D., and Soga, K. (2013). Soil-pipeline interaction in unsaturated soils”. In: L. Laloui, Mechanics of Unsaturated Geomaterials (303-325). John Wiley & Sons, Inc. https://doi.org/10.1002/9781118616871.ch13

Sarvanis, G.C., and Karamanos, S.A. (2017). “Analytical model for the strain analysis of continuous buried pipelines in geohazard areas.” Engineering Structures, 152, 57-69. https://doi.org/10.1016/j.engstruct.2017.08.060

Vazouras, P., Dakoulas, P., and Karamanos, S.A. (2015). “Pipe–soil interaction and pipeline performance under strike-slip fault movements”. Soil Dynamics and Earthquake Engineering, 72, 48-65. https://doi.org/10.1016/j.soildyn.2015.01.014

Vazouras, P., Karamanos, S.A., and Dakoulas, P. (2010). “Finite element analysis of buried steel pipelines under strike-slip fault displacements”. Soil Dynamics and Earthquake Engineering, 30 (11), 1361-1376. https://doi.org/10.1016/j.soildyn.2010.06.011

Zhang, W., and Askarinejad, A. (2019). “Behaviour of buried pipes in unstable sandy slopes”. Landslides, 16 (2), 283-293. https://doi.org/10.1007/s10346-018-1066-1.