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INVESTIGATING THE EFFECT OF USING SOIL BENTONITE WALL ON DAMAGE MITIGATION OF STEEL BURIED PIPELINES SUBJECTED TO REVERSE FAULT RUPTURE

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Abstract. *As pipelines pass from large geographical regions, their passage through areas with active faults in seismic regions might be inevitable. On the other hand, map of active faults is faced with many uncertainties and it is not possible to estimate the precise place of fault, angle of fault and the fault line. Thus, as lifelines, pipelines are vulnerable to great dangers during an earthquake and resulting permanent ground deformations known as PGD. The previous earthquakes such as Chi-Chi (1999) and Wenchuan (2008) showed a wide ranges of damages caused to various structures subjected to reverse fault rupture. The aim of this study is to investigate the effect of using soft deformable wall (in order to diverting rupture path and absorbing the tectonic deformation) in the response of buried pipelines subjected to reverse fault rupture considering two cases: a) pipeline parallel to fault line b) pipeline perpendicular to fault line.*

In this method, a thick diaphragm-type soil bentonite wall (SBW) is used in the fault diversion path in order to absorb the fault movements. Three-dimensional finite element model including steel buried pipe in dense sand subjected to reverse fault rupture is considered. The results indicate that using soil bentonite wall can remarkably mitigate the damages caused to pipeline in parallel case. In perpendicular case, the location of damages on buried pipeline is confined in a small area around the SBW which is of great importance in quick discovery of pipeline's damaged section location in order to quick repair and return of pipeline to service.

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1 INTRODUCTION

In today societies, While the distribution of vital material is developed, pipelines are accounted as one of the most important and infra-structural facilities of every country. Water, gas, oil and other liquids are remarkably transferred into the long distances path through pipelines. Pipelines are installed in two forms of surface and buried which generally executed buried due to the immunity to environmental hazards. But as buried pipelines encompassed wide areas along its path, it fraught in various geotechnical dangers. One of the most important of these dangers is earthquake and its consequences. During the investigation carried out by O'Rourke and Liu, damages caused to pipelines mostly occurred by permanent ground deformation (PGD) resulted from earthquakes [1]. This matter is of a great importance regarding the fact that (PGD) happens in a short length of pipelines in comparison with transient ground deformation (inferred of earthquake waves) and shows the importance of pipeline behavior subjected to PGD. The PGD that caused by landslide, liquefaction or surface rupture can remarkably apply damages on buried pipelines.

The report of the damages caused to water and gas pipelines in the past earthquakes of Manjil (1990) [2], Northridge (1994) [3], Chi-Chi (1999) [4], Kokaeli (1999) [5] and Chili (2010) [6], are shown/showed the leakage and the stop of service of pipelines and in severe cases, explosion and fire of gas pipelines.

Fault rupture is one of the most common types of PGD and can occur in various types. Apparat from different types of fault rupture, Some of the important factors in the amount of damages applied to pipelines are: The ratio of buried depth to pipe dimeter (H/D), ratio of diameter to pipe thickness (D/t), soil types, fault angle (ψ figure 1) and pipe crossing angle with respect to fault line (β in figure 1).

The investigation carried out by Joshi et al on the effects of reverse fault rupture on buried pipelines showed that the capacity of buried pipeline to accommodate the reverse fault rupture could be increased if the pipe crossing angle with respect to fault line became near-parallel [7]. On the other hand, with current knowledge, it is not always possible to determine the precise place of fault and its path and therefore pipe crossing angle with respect to fault line (β). Moreover, even the passage of buried pipeline parallel to fault line (figure 1a) which was recommended by joshi et al [7], can cause severe damages to buried pipelines in some critical conditions.

In this research, by inspiring from researches of Fadaee et al [8], [9] with using a thick diaphragm-type soil bentonite wall (SBW) in a specific distance with buried pipelines which is parallel with fault line (figure 1a), SBW absorbs the deformation resulted from any possible reverse fault rupture and mitigates the damages caused to pipelines cross section (figure 2). More details about the performance of SBW in reverse fault rupture are shown in [8], [9].

In this paper, the effect of using SBW on buried pipelines crossing fault line in normal orientation (Figure 1b) in investigated.

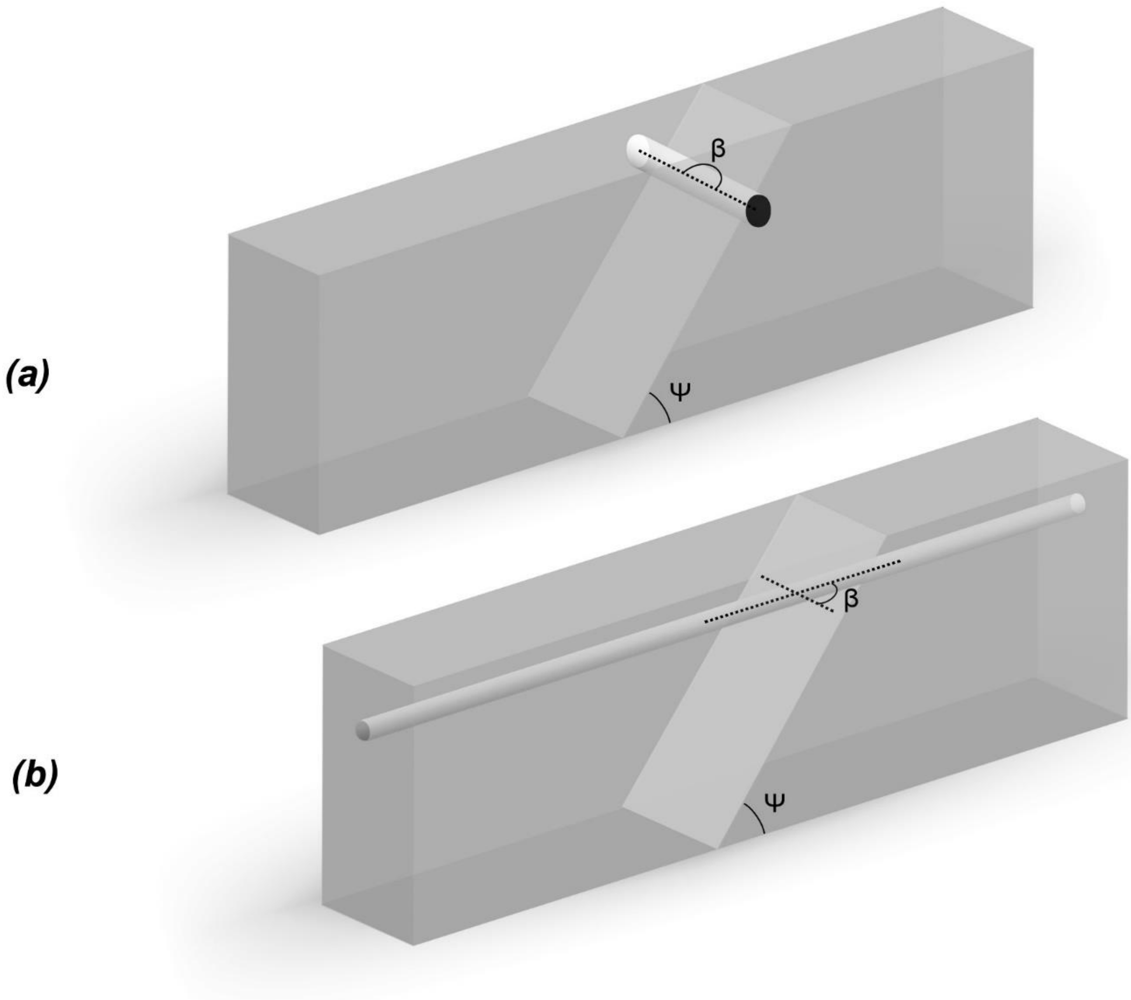


Figure 1. a schematic view of fault's angle (ψ) and pipeline crossing angle with fault line (β). a) Pipeline parallel to fault line (β =180). b) Pipeline perpendicular to pipeline ($\beta = 90$)

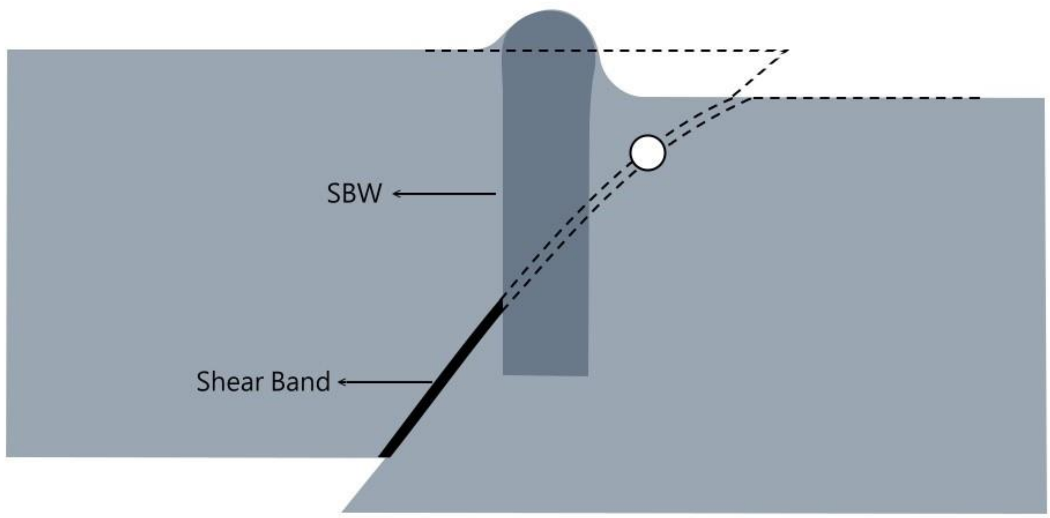


Figure 2. a schematic view of SBW performance in case of reverse fault rupture

2 NUMERICAL MODELING

A steel continuous buried pipeline was subjected to reverse fault rupture in two forms: a) Pipeline parallel to fault line (figure 3). b) pipeline perpendicular to fault line (figure 4). To do so, the finite element (FE) method was employed for numerical simulation of the problem. Apart from some limits in exact simulation of shear band formation, FE modeling has been shown to be able of competently reproducing fault rupture propagation in the free field [10], as well as under shallow and deep foundations [11], and pipelines. An essential prerequisite is the usage of a refined mesh and appropriate constitutive model for soil. Based on the findings of previous studies [10], an elastoplastic constitutive model with Mohr Coulomb failure criterion and isotropic strain softening are selected. the details of constitutive soil model are shown in [10].

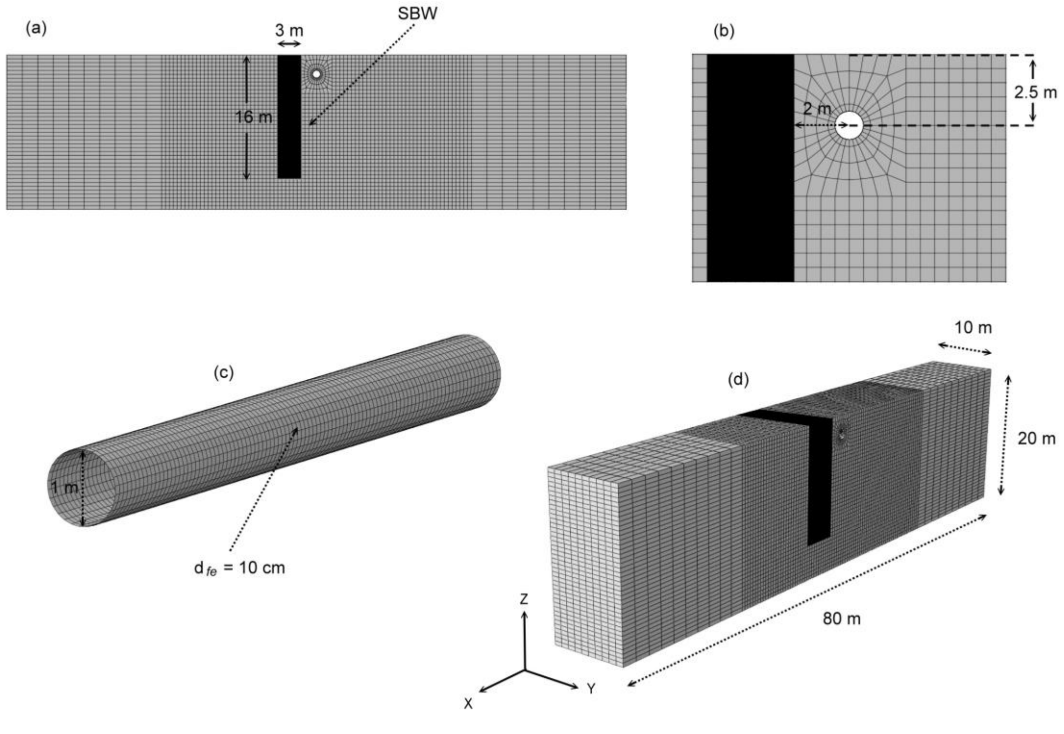


Figure 3. Details of FE model in parallel case a) The location of soil bentonite wall b) Pipe's burial depth and distance of SBW to pipe c) Details of pipe mesh d) Dimensions of soil blocks

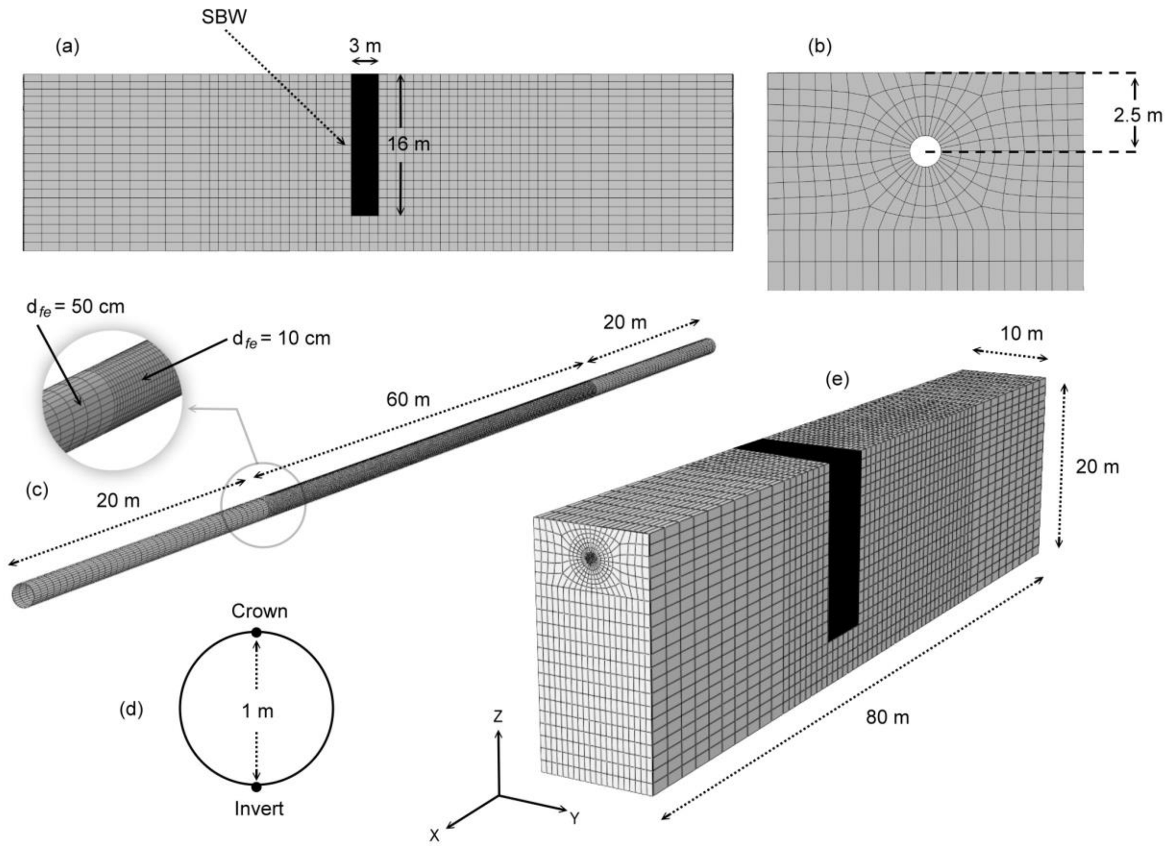


Figure 4. Details of FE model in perpendicular mode a) The location of soil bentonite wall b) Pipe's burial depth and distance of SBW to pipe c) Details of pipe mesh d) Dimensions of soil blocks

Dense sand was used in this research which was calibrated and verified in previous research [9]. Table 1 shows the soil property.

E (first layer, kPa)	12000
E (last layer, kPa)	50000
$\emptyset_p$	42
$\emptyset_{res}$	32
ψ_p	12
ψ_{res}	1
γ_f	0.165
ρ (t/m^3)	1.8

Table 1- summary of soil property

Elastoplastic behavior for pipe was considered too. The pipe which used was constructed from API/5L X65 which is commonly used in oil and gas industries. A large-strain J_2 flow (von Mises) plasticity model with isotropic hardening is employed for describing the mechanical behavior of the steel pipe material.

Figure 4 shows the stress-strain curve obtained from uniaxial tensile test done by Vazouras et al [13].

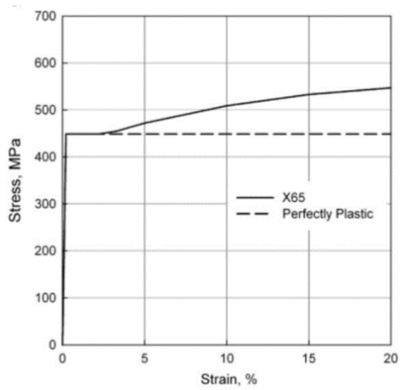


Figure 4. Uniaxial nominal stress-engineering strain curve, APL-5L-X65 [13]

Soil block dimension as shown in figure 3&4 was chosen as below:
depth of 20 meters, length of 80 meters and the width of the model, based on the sensitive analysis was considered as 10 meters.

A burial depth of 2.5 meters was chosen for steel pipe. For modeling of pipeline, four–node reduced-integration shell elements (type S4R) was used in order to observe the wrinkle, local buckling and ovalization of pipe's cross-section, whereas eight-node reduced-integration "brick" elements (C3D8R) was used for simulation of surrounding soil.

The dimension of soil mesh was also considered equal to d_{FE}=1 based on the recommendations of Anastasopoulos in the rupture area [10]. The dimensions of SBW and its distance from pipe (for parallel mode) was chosen equal to 3, 16 and 2 meters for width, depth and distance from pipe, respectively based on sensitive analysis.

A contact algorithm was considered to simulate the interface between the outer surface of the steel pipe and the surrounding soil. To this end, interface friction was taken into account for the algorithm, using a coulomb friction criterion and also allows for the separation of the soil medium and pipe surface. According to Yimsiri et al [14], The friction coefficient, μ ,was computed based on the reduced interface friction angle between the soil and the pipe equal to 2/3$\emptyset$, which $\emptyset$ is soil internal friction. So based on given soil property is table 1, for the selected soil, μ, was set to 0.52.

The analysis was conducted in two consecutive steps:

a) Application of gravity loading to simulate the initial stress state in the soil
b) Application of reverse faulting motion

The bottom boundary of the model represents the interface between the soil and the underlying bedrock. Therefore, it was divided in two parts, one on the right representing the footwall which remains motionless, and the other on the left been subjected to the tectonic movement of the hanging wall.

3 MODELLING RESULTS

3.1 Pipeline parallel to fault line

In this section, by using expressed numerical modeling, at first, the effects of reverse fault rupture in the angles of $\psi = 30^\circ$ and $\psi = 45^\circ$ on buried pipelines in parallel case without using SBW is investigated. Then, the effects of using SBW in reducing damages caused to pipeline is examined. For this purpose, several analysis with different fault line distance from pipeline in both angles of $\psi = 30^\circ$ and $\psi = 45^\circ$ performed and the most critical ones selected. These sensitive analyses showed that the most critical situation happens when the shear band formed in soil due to fault movement, is passed from pipe cross section. In fact, pipe section is placed between footwall and hanging wall. Figure 5 shows a schematic view of critical situation.

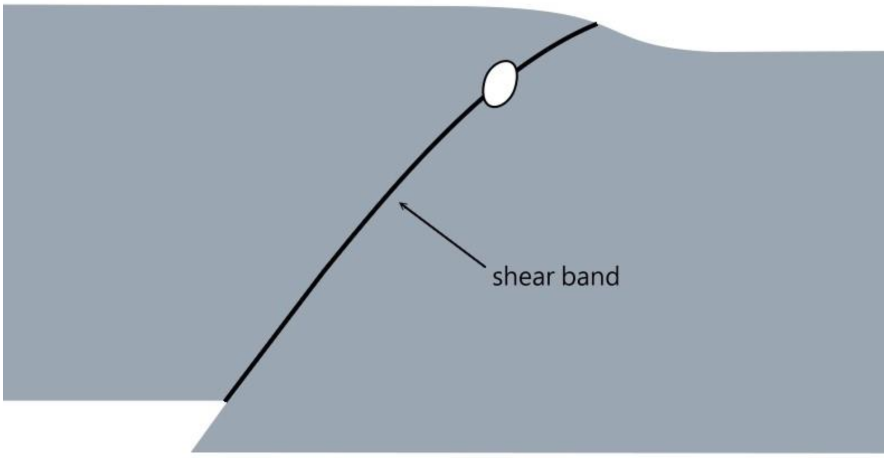


Figure 5. schematic view of critical condition of pipeline parallel to reverse fault rupture.

The factor of ovalization and pipe movement is also investigated. The ovalization of pipe section is of great importance from the standpoint of performance reduction. Moreover, in gas pipeline which is undergone inside pressure, this ovilization can lead to severe dangers. Finally, the influence of SBW in fault rupture deviation and its effects on pipeline movements is examined.

3.1.1 Pipe strains

The figure 6 and 7 compares the maximum compressive and tensile strains in pipe cross section under the fault angles of 30° & 45° in two modes of with SBW and without SBW. It can be clearly seen that with using SBW, pipe's strains are remarkably decreased. A closer look at these two figures shows that using SBW can reduce tensile and compressive strains up to 90%.

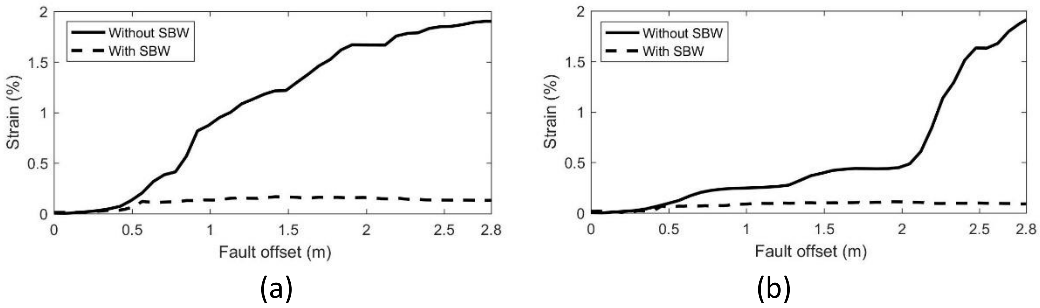
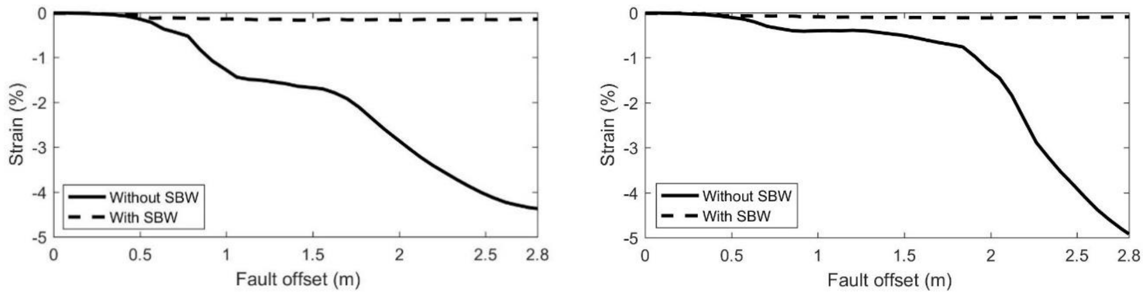


Figure 6. comparison of maximum compressive strains. A) $\psi = 45°$ B) $\psi = 30°$



(a) (b)

Figure 7. comparison of maximum tensile strains. A) $\psi = 45°$ B) $\psi = 30°$

3.1.2 Pipe's cross-Section deformations

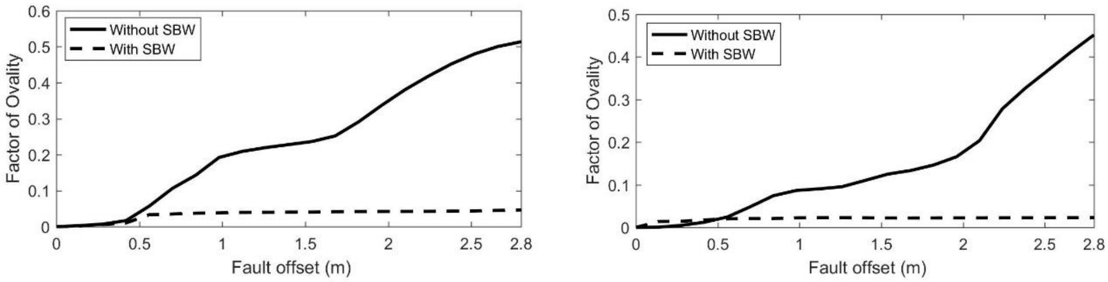
As pipes are modeled by using shell elements of S4R, the pipe's cross-section deformations can be seen. Also, factor of ovality which is defined in Eq. (1), [15] as a representation of the degree of distortion of pipe's cross-section can be monitored. f_o, D_{max}, D_{min} are factor of ovality, maximum diameter and minimum diameter of pipe cross section, respectively.

$$f_o = \frac{D_{max}-D_{min}}{D_{max}+D_{min}} \quad (1)$$

Figure 8 shows the changes of f_o by increasing fault offset for the fault angles of 30° and 45°, respectively in two modes of with and without SBW.

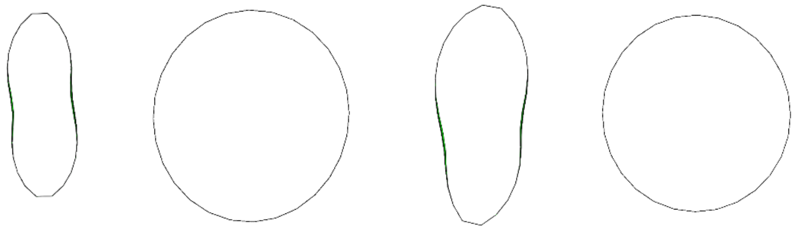
As it is expected, using SBW has remarkable effects on the reduce of pipe's cross-section ovalization. The precise investigation shows that using SBW can lead to reduction of up to 90% in factor of ovality.

Figure 9 shows deformed shape of pipe cross-section for two modes of with and without SBW after 2.8m fault offset for fault angles of 45° & 30°. The results indicate that using SBW is hugely effective in preventing pipe cross-section deforming.



(a) (b)

Figure 8. changes of f_o A) $\psi = 45°$ B) $\psi = 30°$



(a) (b) (c) (d

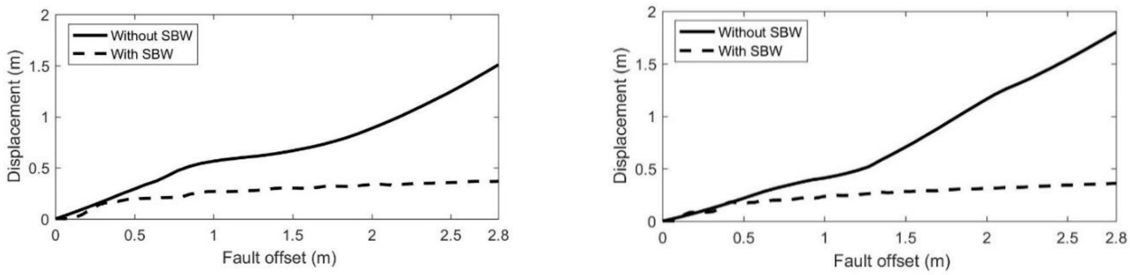
Figure 9. pipe cross-section deformation at 2.8 m fault offset. a) Without SBW, $\psi = 45°$ b) With SBW, $\psi = 45°$ c) Without SBW, $\psi = 30°$ d) With SBW, $\psi = 30°$

3.1.3 Pipe movements

As discussed earlier, in parallel form, critical situation happens when the pipeline placed between hanging wall and footwall (figure 5). So the pipeline movement in the direction of soil movement is inevitable. These movements can lead to some issues in pipe joints and welds as a result of fault offsets.

Figure 10 shows the pipe movements for different fault offsets for two fault angles of 30° and 45°. In ψ =30°, until the fault offset of 0.5m, the movement of pipeline with and without SBW is approximately equal, but after 0.5m fault offset, pipe movements increases with an almost constant trend without using SBW and in the fault offset of 2.8m, pipe moves 1.8 m. While by using SBW, the pipe almost remains stable. For comparison, at 2.8 m fault offset, pipe movement reaches 0.4m which is less than 25% of pipe movement without using SBW.

The trend is almost the same For ψ =45°.



(a) (b)

Figure 10. Pipeline movement: A) $\psi = 45°$ B) $\psi = 30°$

3.2 Pipeline perpendicular to fault line

In this section, another case is investigated where the pipe crosses fault line perpendicularly (figure 4). In this case the fault angle is considered to be 45°. SBW with the same dimensions is used. In order to investigate the effect of SBW, like previous case, at first, a model without SBW is subjected to reverse fault rupture and then, the response of pipeline with SBW wall which is placed in fault dispersion path (X=37 to X=40) compares to each other.

3.2.1 Localizing pipe damages

Figure 11 shows the location of pipe strains along the pipe length for different fault movements away from the wall. As can be seen, the location of pipe damages is localized in

2m from left side of the SBW to 3m from right side of the SBW for various fault lines away from the SBW.

So considering existing uncertainties in the exact determination of fault line location and Regarding the fact that the SBW absorbs deformations of reverse fault rupture, with using SBW, the location of damages subjected to pipeline can be localized in a small area around the SBW. So that in case of reverse fault rupture on buried pipelines and subsequent damages (like pipe rupture and leakage which is inevitable in large fault offsets), the process of repair and return of pipeline to service can be done more rapidly. It should be noted that in case of not using SBW, the location of pipe damages is not clear and it may cause delays in repairing the pipeline.

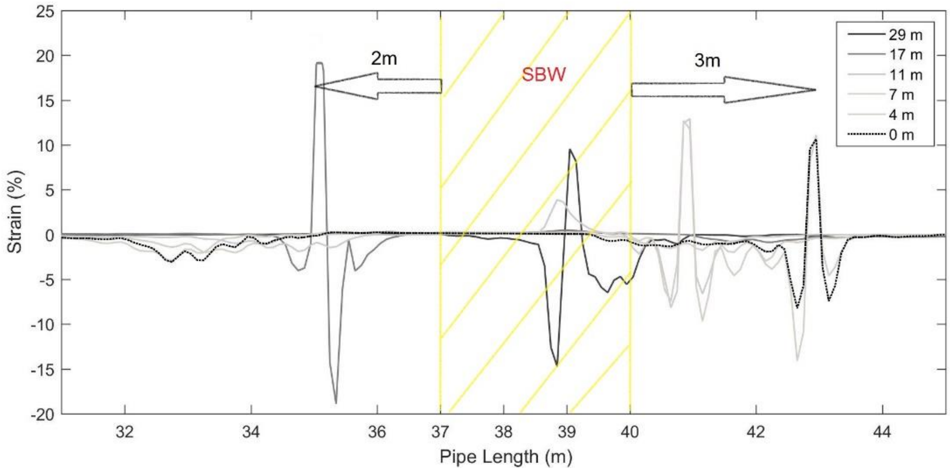


Figure 11. Location of crown strains for different fault lines away from SBW

4 CONCLUSION

In this research, the effect of using soil bentonite wall (SBW) on damage mitigation caused to pipeline subjected to reverse fault rupture in two cases of pipeline parallel to fault line and pipeline perpendicular to fault line by using 3D FE method is investigated. The analyses are carried out on dense sand and steel pipeline. The results are as follows:

1- In parallel case, using SBW with the dimensions of 3*16m distanced 2m away from pipe center, can remarkably reduce damages when subjected to reverse fault rupture. The results of investigation show that using SBW with mentioned dimension, after low fault offset (0.5m) with fault angles 30° and 45°, the pipe cross-section strains, factor of ovality and pipe movements remains minor and constant throw different fault offsets. The comparison of pipeline responses with and without using SBW indicates the reduction of up to 90% in pipe strains and factor of ovality and up to 70% reduction in pipe movements with/ using SBW.

2- Comparison of pipe responses with two fault angles of 30° and 45° shows with using of SBW, the effect of fault angle eliminates and the pipe responses remains the same.

3- For perpendicular case, with a matter of fact that SBW absorbs the deformation of reverse fault rupture and inevitable severe pipe damages subjected to large reverse fault offsets, using SBW can confine the area of damages subjected to pipeline in a small zone around the SBW. So in case of earthquake and subsequent reverse fault rupture, the location of pipe which needs to be repaired is obvious. This is of great importance in terms of quick repair and service of pipeline as lifelines.

REFERENCES

[1] O'Rourke, M.J., and Liu, X. (2012). "Seismic Design of Buried and Offshore Pipelines," Monograph MCEER12-MN04, Buffalo, N.Y., USA.

[2] Towhata I. Geotechnical earthquake engineering. Springer series in geomechanics and geoengineering. 2010. p. 684.

[3] O'Rourke TD, Palmer MC. Earthquake performance of gas transmission pipelines. Earthq Spectra 1996;12(3):493–527.

[4] Earthquake Engineering Research Institute. The Chi Chi, Taiwan earthquake of September 21, 1999. EERI special earthquake report; December 1999

[5] Japan Society of Civil Engineers. The 1999 Kocaeli earthquake, Turkey, investigation into the damage to civil engineering structures, JSCE earthquake engineering committee; December, 1999

[6] Ayala AG, O'Rourke MJ. Effects of the 1985 Michoacán Earthquake on Water Systems and Other Buried Lifelines in Mexico, NCEER-89-0009; 1989.,136 p.

[7] Joshi S, Prashant A, Deb A, Sudhir K. Jain., (2011), "Analysis of buried pipelines subjected to reverse fault motion," Soil Dynamics and Earthquake Engineering, Vol. 31, pp. 930–940

[8] Fadaee M, Anastasopoulos I, Gazetas G, Jafari M.K, Kamalian M, (2013), "Soil bentonite wall protects foundation from thrust faulting: analyses and experiment", Earthquake Engineering and Engineering Vibration, Vol.12, pp. 473-486

[9] Fadaee M, Ezzatyazdi P, Anastasopoulos I, Gazetas G, (2016), "Mitigation of reverse faulting deformation using a soil bentonite wall: Dimensional analysis, parametric study, design implications", Soil Dynamics and Earthquake Engineering, Vol. 89, pp. 248–261

[10] Anastasopoulos I, Gazetas G, Bransby F, Davies MCR and El Nahas A (2007), "Fault Rupture Propagation through Sand: Finite Element Analysis and Validation through Centrifuge Experiments," Journal of Geotechnical and Geo Environmental Engineering, ASCE, 133(8): 943−958.

[11] Anastasopoulos I, Gazetas G, Bransby MF, Davies MCR and El Nahas A (2009), "Normal Fault Rupture Interaction with Strip Foundations," Journal of Geotechnical and Geoenvironmental Engineering, ASCE, 135(3): 359–370

[12] Bray JD (1990), "The Effects of Tectonic Movements on Stresses and Deformations in Earth Embankments," PhD Dissertation, University of California, Berkeley.

[13] Vazouras P, Karamanos SA, Dakoulas P. (2010) "Finite element analysis of buried steel pipelines under strike-slip fault displacements," Soil Dynamics and Earthquake Engineering,30 (11):1361–76.

[14] Yimsiri S, Soga K, Yoshiaki K, Dasari GR, O'Rourke TD. "Lateral and upward soil–pipeline interactions in sand for deep embedment conditions," J Geotech Geoenviron Eng 2003;130(8):830–41

[15] Hojat Jalali H, Rahimzadeh Rofooei F, Attari NKA, Samadian M. (2016), "Experimental and finite element study of the reverse faulting effects on buried

continuous steel gas pipelines," Soil Dynamics and Earthquake Engineering, Vol.86, pp.1-14