Assessment of Impact of Earthquake Surface Fault Rupture on Buried Pipes Using Numerical Analysis

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Abstract

A new long pipeline was to be installed in the southern part of Australia. A desktop study conducted along the pipeline corridor identified multiple historical active faults which were presumed to have experienced seismic fault movement to the order of a few meters in the last 10,000 years to 1,000,000 years. Estimates of potential displacements up to a few meters were provided by the study, however, no reliable quantitative estimate on the likelihood of these displacements could be provided due to the lack of information available during the study period. A reverse engineering approach was alternatively adopted to evaluate the risk to the pipeline due to possible fault displacement following a seismic event by performing numerical analysis on pipe and fault rupture interactions. The approach adopted utilised three dimensional finite element modelling to evaluate the response of the pipeline to progressive displacement. The modelling simulated the deformation of the pipe in the event of permanent ground displacement due to an earthquake and permitted the maximum displacement to be identified at the moment immediately prior to rupture of the pipe.
The results of the analysis using ABAQUS identified that the pipe could be exposed to not less than 4 m displacement for a vertical fault, and where the fault is inclined, can be exposed to at least 1.5 m without structural failure resulting. Whilst the analysis does not permit the potential displacement of the proposed DLE event to be quantified, it identifies that the pipeline is tolerant of displacements of up to 1.5 m or greater where displacement is vertical.

Keywords: surface fault rupture, pipe-fault interaction analysis, reverse fault, finite element analysis

1. INTRODUCTION

A new long pipeline was to be installed in the southern part of Australia. As part of the early studies for the pipeline, a Probabilistic Seismic Hazard Assessment (PSHA) was undertaken to estimate the design seismic events and to identify possible active faults crossing the pipeline alignment. A desktop study conducted during the PSHA identified multiple historical active faults which were presumed to have experienced seismic fault movement in the last 10,000 years to 1,000,000 years. Estimates of potential displacements up to a few meters were provided by the study, however, no reliable quantitative estimate on the likelihood of these displacements could be provided due to the lack of information available by the time the study was conducted. Considering the expected impact s on the surrounding community by undertaking the site investigation works, a reverse engineering approach was alternatively adopted to evaluate the risk to the pipeline due to possible fault displacement following a seismic event by performing numerical analysis on pipe and fault rupture interactions.

The approach adopted utilised three dimensional finite element modelling to evaluate the response of the pipeline to progressive displacement. The purpose of this analysis is to assess the effects possible fault movements will have on the structural integrity of the DN 350 pipeline installed in an ordinary trench. Non-linear finite element analyses are employed to model the interaction between the pipeline and the surrounding soil during seismic displacement, and to identify the seismic fault displacement the pipeline can tolerate before undergoing plastic collapse. This paper presents the assumptions and analytical procedures adopted for this assessment as well as the summary of outcome from the analyses undertaken.

2. BRIEF DESCRIPTION OF PIPELINE SUBJECT TO FAULT MOVEMENT

This study aimed to identify the maximum seismic fault displacement the buried DN 350 pipeline can withstand before undergoing plastic collapse.

The initial stress conditions within the pipeline were calculated an operating temperature of 60ºC. An internal pressure of 4.635 MPa was assumed to act on the pipeline. Following generation of the initial stress conditions, the effects of progressive seismic fault displacement on the pipeline were calculated. The fault displacement was increased progressively until the occurrence of local plastic collapse in the pipeline wall. The collapse condition was assessed based on the plastic strain within the pipe wall and the resulting deformation. A localised plastic strain of approximately 5% was adopted as the initial collapse screening criterion. Additional investigation of the plastic strain and deformation conditions are then undertaken to determine the fault displacement at which progressive collapse occurs. The corresponding fault displacement is then identified as the tolerable displacement.

3. OUTLINE OF FINITE ELEMENT MODEL

Finite element analysis of the pipeline was conducted over a 360 m long straight pipe. The centreline of the pipeline is assumed to be located 1.5 m below the ground surface. The schematic diagram for the pipe modelled is shown in Figure 1.

Two different types of finite elements were used to model the pipe such that:

- A 30 m long section centred where the fault plane is supposed to intersect was modelled using second order shell elements to allow for the accurate calculation of spatially variant stresses and strains.
- The remaining length of pipeline at either side of the shell element section was modelled using first order beam elements suited for the modelling of straight piping sections.

The material of the DN350 pipeline is API 5L X60[2)]. The elastic properties of the material are shown in **Table 1**. Based on the soil strength parameters tabulated in **Table 2**, non-linear soil springs were assumed in the three directions to represent pipe-soil interaction when subject to fault movements with reference to the MCEER recommendations[4)] as depicted in **Figure 2**.

Table 1 Pipe material properties

Property	***Unit***	***Magnitude***
Density	t/m^3	7.86
Young's Modulus	MPa	200,000
Poisson's Ratio	-	0.3
Yield Stress	MPa	415

Table 2 Soil material properties

Property	***Unit***	***Backfill Sand***	***Natural Sand***	***Natural Clay***
Unit weight	kN/m^3	18	18	18
Friction angle	º	38	38	0
Friction factor at pipe surface	-	0.5	-	-
Undrained shear strength	kPa	-	0	150

Reverse fault movement was considered at dip angles of 90 and 45 degrees. The expression of fault movement at ground surface was assumed as shown in **Figure 3** with reference to Lee and Hamda[3)]. The analyses cases are shown in **Table 1**.

Table 1 ABAQUS analysis cases

Load case	***Scenario***	***Soil Type***	***Operating conditions***		***Seismic Fault Displacement Direction***		
			Temperature (m)	**Pressure (MPa)**	**Vertical**	**Axial**	**Lateral**
Load case 1	A	Clay	60	4.635	Yes	-	-
Load case 2	B		60	4.635	Yes	Yes	-
Load case 3	C		60	4.635	Yes	Yes	Yes
Load case 4	A	Sand	60	4.635	Yes	-	-
Load case 5	B		60	4.635	Yes	Yes	-
Load case 6	C		60	4.635	Yes	Yes	Yes

4. RESULTS AND DISCUSSIONS

The maximum tolerable fault movement identified out of ABAQUS analyses are summarised in **Table 2**. The critical fault movement appeared where both reverse (vertical) and strike (lateral) fault movement components are present that corresponds to Load case 3 in **Table 1**. The deformed pipe after the progressive fault movement at a dip angle of 45 degrees in clay is illustrated in **Figure 4** and **Figure 5**.
Table 4 shows the absolute pipe displacement, Δ_s, at the active side of the fault plane at which the onset of plastic collapse occurs. The absolute pipe displacement in the scenarios assumed is to be defined as follows:

- For Scenario A, the absolute pipe displacement is identical to a purely vertical upward movement of the pipeline on the active side of the trench.
- For Scenario B, the absolute pipe displacement is comprised of 1.2 m of purely vertical initial heaving plus the absolute pipe displacement in both vertical and axial direction.
- For Scenario C, the absolute displacement is comprised of the initial vertical heaving of 1.2 m plus the absolute displacement in vertical, lateral and axial direction.

The observation at each scenario is presented in the following paragraphs.

In Scenario A where the fault moves at a right angle, the pipeline can tolerate up to 4.4 m of displacement before plastic collapse occurs for a purely vertical movement of the underlying bedrock where the surrounding soil consists of clay. For this case, the initial plastic collapse appears to occur on the passive side of the fault in a region where high tensile and bending stresses combine. The pipeline appears to be able to tolerate at least 5.0 m of vertical displacement where the surrounding soil is sand. The plastic strain at the initial collapse location initially increases, then stabilises at around 3.5%. This behaviour is due to the progressive pulling-out of the pipeline from the trench on the passive side of the fault plane. The initial collapse condition is located on the active side (hanging wall) of the fault and is caused by high bending and shear stresses combined with local indentation of the pipeline by the underlying trench base material.

In Scenario B where the fault moves at a dip angle of 45 degrees without the horizontal (transverse) component of fault movement, the onset of plastic collapse will occur at a pipe displacement of 1.9 m where the pipe buried in clay. The initial point of plastic collapse is located at the passive side of the fault where the pipeline is subjected to high compressive and bending stresses. As can be expected the plastic collapse mechanism involves local wrinkling of the pipe wall, and the collapse develops rapidly as the pipeline displacement increases. The pipeline buried in sand appears to behave very similar to that in clay. The tolerable displacement is found to be 1.9 m in sand where the point of initial collapse is now on the active side of the fault as a result of the combination of compressive and bending stresses as well as the local indentation resulting from the high vertical stiffness of the pipe trench base.

In Scenario C where the fault moves at a dip angle of 45 degrees with the increasing horizontal (transverse) component of fault movement in the direction at 45^0 strike angle, the tolerable pipe displacement appears to markedly decreases 1.5 m at 45^0 strike angle from 1.9 m at 90^0 strike angle in Scenario B. The primary reason for this marked reduction is considered relating to the effective pipe - soil interaction stiffness at the initial collapse point that significantly increases where the fault orientation changes to a strike angle of 45^0. This stiffness increases for clay, which is readily apparent in **Figure 2,** results in the onset of plastic collapse at a smaller pipeline displacement. The maximum lateral reaction stiffness of the clay is greater than its maximum vertical reaction stiffness in the upward direction. When the pipe is simultaneously pulled out of the trench and pushed against the trench wall, the effective interaction stiffness is greater compared to the other scenario where upwards pulling alone was considered.

On the contrary, the tolerable pipeline displacement in sand appears to slightly increase with a change in the fault strike angle from 90^0 to 45^0, which is contradictory given the earlier observation for the case in clay. This observation is attributed to the difference in pipe - soil interaction between clay and sand. The increase in the effective pipe - soil interaction stiffness acting at the initial collapse location is significantly smaller in sand compared to that adopted for clay as seen **Figure 2**.

Table 2 Maximum tolerable fault movement

Load case	***Scenario***	***Soil Type***	***Pipe displacement at onset of plastic collapse***				***Maximum Plastic Strain***
			Absolute **$\|\Delta s\|$ (m)**	**Vertical** **Δs_y (m)**	**Axial** **Δs_x (m)**	**Lateral** **Δs_z (m)**	**e_p (-)**
Load case 1	A		4.4	4.4	0.0	0.0	0.045
Load case 2	B	Clay	1.9	1.8	0.6	0.0	0.045
Load case 3	C		1.5	1.5	0.3	0.3	0.044
Load case 4	A		5.0	5.0	0.0	0.0	0.035
Load case 5	B	Sand	1.9	1.8	0.6	0.0	0.044
Load case 6	C		2.0	1.8	0.6	0.6	0.048

5. CONCLUSIONS

The FE analysis performed using ABAQUS in the present study simulated the deformation of the pipe in the event of permanent ground displacement due to an earthquake and permitted the maximum displacement to be identified at the moment immediately prior to rupture of the pipe.

The results of the analysis identified that the pipe could be exposed to not less than 4 m displacement for a vertical fault, and where the fault is inclined, can be exposed to at least 1.5 m without structural failure resulting. Whilst the analysis does not permit the potential displacement of the proposed Ductile Level Earthquake event to be quantified, it identifies that the pipeline is tolerant of displacements of up to 1.5 m or greater where displacement is vertical.

In an environment where evidence of historical seismic displacement is absent and current seismic activity along the identified faults is appreciably sparse, it is considered that the interactions between pipe and surface fault rupture numerically estimated could be provide an useful indication on the risk management of the proposed pipeline.

6. REFERENCES

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2. API. (2007) API 579 *Fitness For Service*
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4. O'Rouke, M. J. and Liu, X. (2012) Seismic Design of Buried and Offshore Pipelines, MCEER.

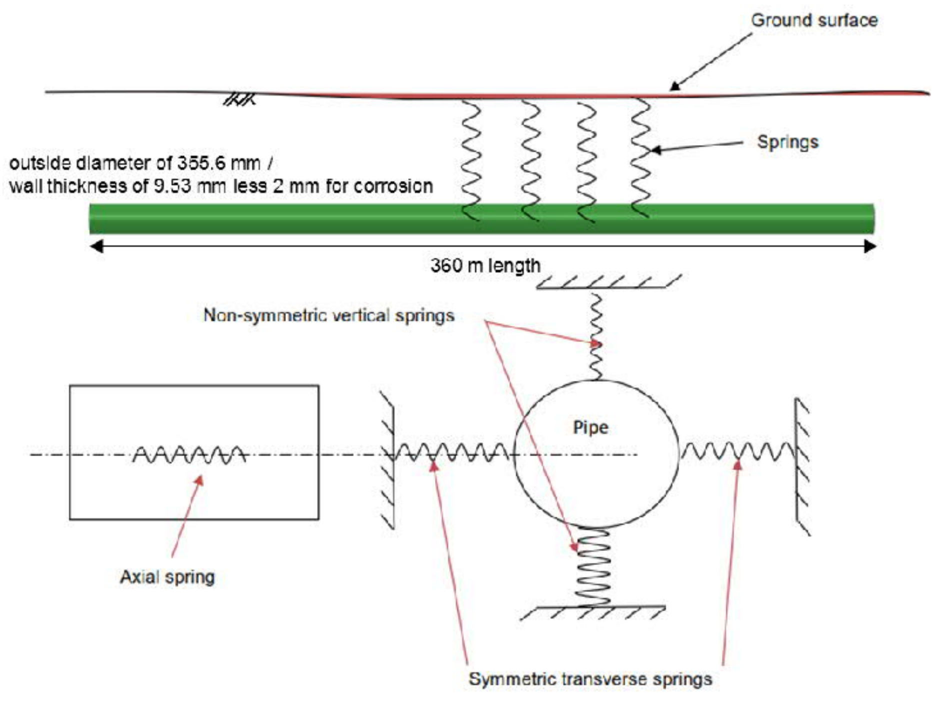
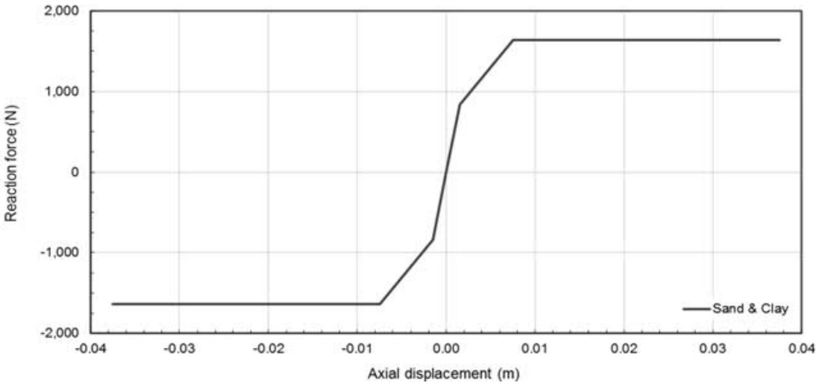
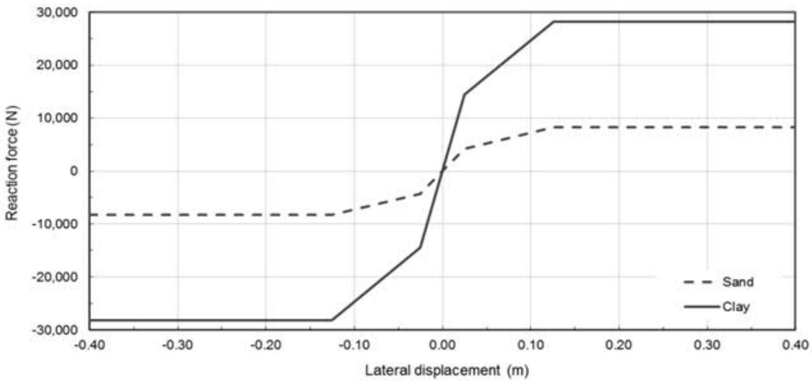


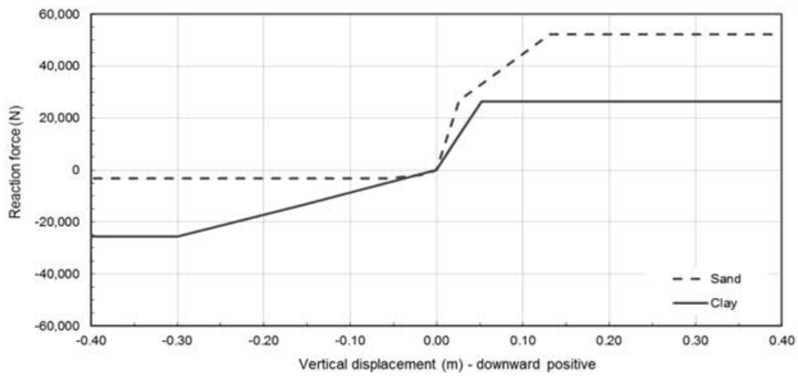
Figure 1 Geometry of the modelled pipeline (not to scale) with soil springs



(a) Soil springs for pipe-soil interaction in the axial direction

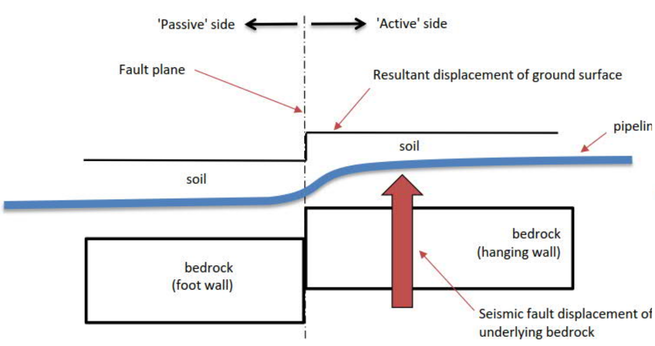


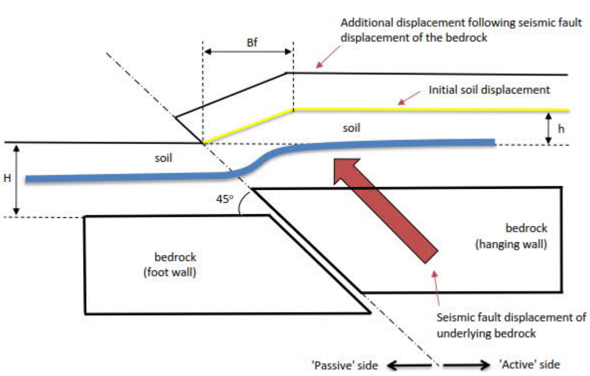
(b) Soil springs for pipe-soil interaction in the lateral direction



(b) Soil springs for pipe-soil interaction in the vertical direction

Figure 2 Soil stiffness for 100 mm pipe segment in vertical direction





(a) Dip angle at 90 degrees (Scenario A) (b) Dip angle at 45 degrees (Scenario B and C)

Figure 3 Fault movement expressions – reverse fault

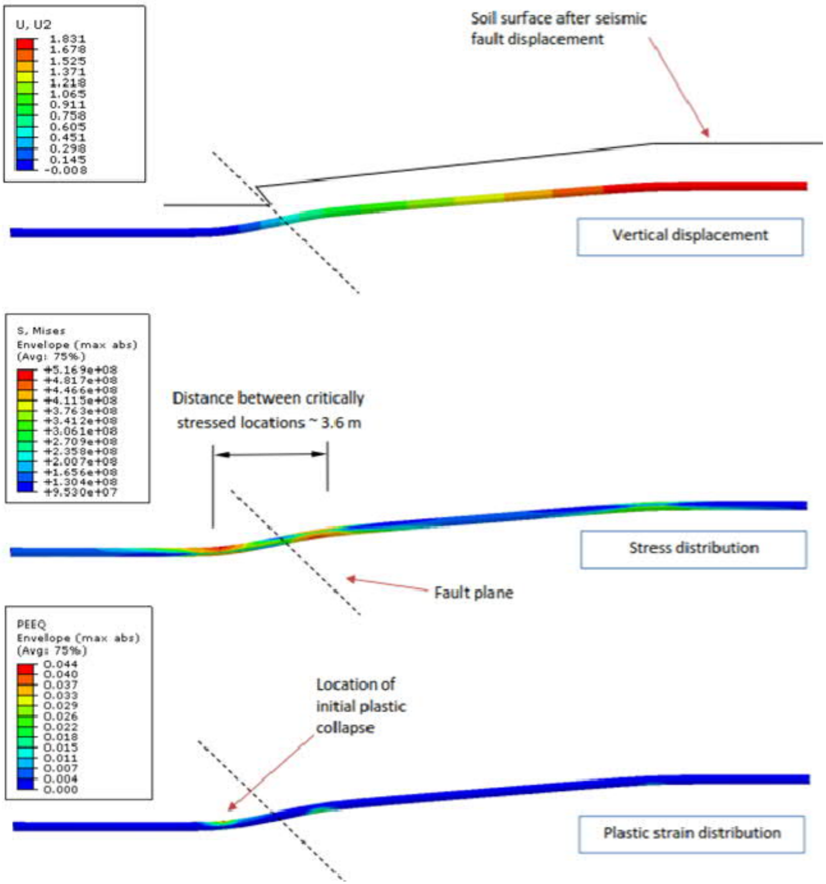


Figure 4 Point of initial collapse for load case 2 – Scenario B in clay

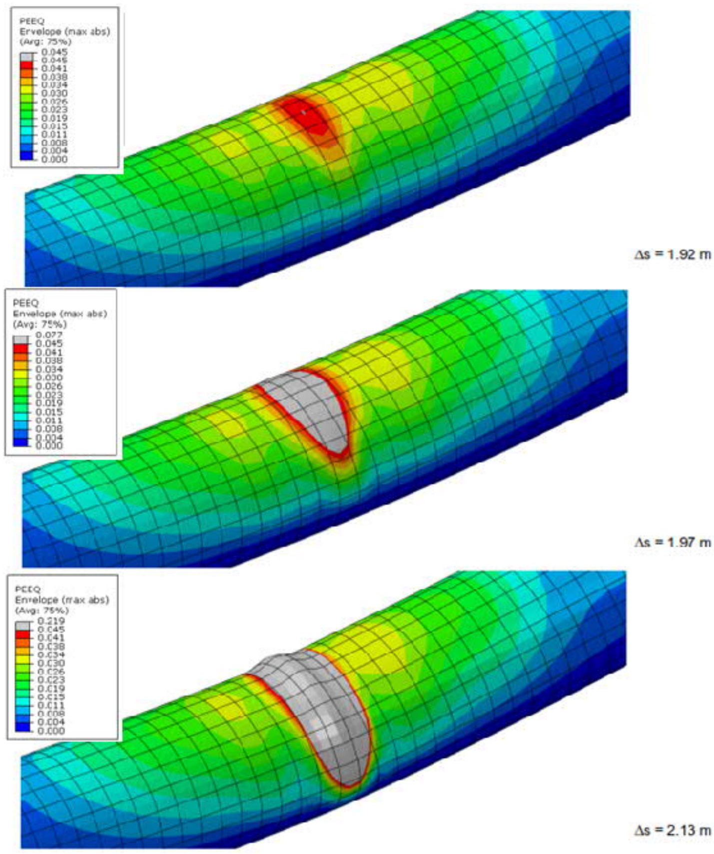


Figure 5 Progressive plastic collapses for load case 2 – Scenario B in clay