Trench impact on lateral response of pipeline buried in sand

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ABSTRACT
Subsea pipelines may go under large lateral displacements due to ground movement and ice gouging etc. In practice, the backfilling material is significantly interacting with the pipeline and trench wall affecting the lateral response of the pipeline. The pipeline-backfill-trench interaction is not usually considered in design practice and has not been deeply explored in the literature. This paper presents the numerical modeling of centrifuge tests conducted at C-CORE to investigate the lateral response of a trenched pipeline backfilled with sand. The native soil bed in which the trench had been excavated was over-consolidated clay and also pure loose sand. Coupled-Eulerian-Lagrangian (CEL) analysis was performed using ABAQUS/Explicit to model the pipeline, trench, and backfill. A parametric study was conducted to investigate the influence of various parameters including the burial depth, and trench geometry on the lateral force-displacement (p-y) response of the pipeline. The results showed that the lateral p-y response of the pipeline is significantly affected by interactive failure mechanisms of the backfilling material and trenched native soil.

RÉSUMÉ
En pratique, le matériau de remblayage interagit de manière significative avec le pipeline et la paroi de la tranchée, ce qui affecte la réponse latérale du pipeline. L'interaction pipeline-remblai-tranchée n'est généralement pas considérée dans la pratique de conception et n'a pas été explorée en profondeur dans la littérature. Cet article présente la modélisation numérique des essais de centrifugation effectués à C-CORE pour étudier la réponse latérale d'une tranchée de tranchée remplie de sable. Le lit de sol indigène dans lequel la tranchée avait été creusée était de l'argile sur-consolidée et aussi du sable meuble pur. L'analyse Coupled-Eulerian-Lagrangian (CEL) a été réalisée en utilisant ABAQUS / Explicit pour modéliser le pipeline, la tranchée et le remblai. Une étude paramétrique a été menée pour étudier l'influence de divers paramètres, y compris la profondeur de l'enfouissement, et la géométrie de la tranchée sur la réponse latérale force-déplacement (p-y) du pipeline. Les résultats ont montré que la réponse p-y latérale du pipeline est significativement affectée par les mécanismes de rupture interactifs du matériau de remblayage et du sol natif de la tranchée.

1 INTRODUCTION

Trenching is one of the most practical physical protection methods for subsea pipeline transporting oil and gas. Lateral displacement of pipeline can be caused by ground movement, ice gouging etc. and consequently it is necessary to examine the force induced by the trench-backfill-pipeline interaction for the sake of the integrity of the pipeline. Experimental and numerical studies can be found in the literature with focus on the lateral displacement of a buried pipeline and the interaction between pipeline and backfilling material. But effects of backfilling material properties, trench geometry, and interaction rate have not been systematically examined before. Considering various backfilling materials used in practice, current design guidelines such as ALA-ASCE (2001), ASCE (1984), PRCI (2009, 2004) and O'Rourke and Liu (2012, 2010) do not make available specific recommendations with attention to the appropriate trench dimensions. Also, to estimate the ultimate soil reaction pressures, available methods do not take the effects of trench dimensions into accounts (Trautmann & O'Rourke 1985). To fill the knowledge gap and fully examine the trench-backfill-pipeline interaction and the resultant p-y response of the pipeline during large lateral displacement, a series of research work has been done. This paper specifically Focused on the experimental and numerical studies on trench-backfill-pipeline interaction that has been examined and presented with loose sand backfilled in the vertical trench excavated on native ground.

The centrifuge experiments were used to explore the pipeline loading in the mixed soil. To examine the soil interaction and the pipeline strains, the trench is backfilled with loose to medium dense sand in the state of permanent ground displacements and stiff natural soil conditions. An advanced numerical model was also developed for comparison with experimental tests and will be further calibrated using the test results.

2 LITERATURE REVIEW

Force-displacement response of pipelines in lateral pipe-soil interactions has been widely explored. But studies that specifically focus on trench dimension effects and failure mechanisms during the large displacement of pipelines are very limited. Phillips et al. (2004) examined the trench effects using numerical models (discrete nonlinear springs for cohesive soil around pipeline) and a centrifuge model (under an acceleration of 50 g). The results showed that the existence of a trench and increase in trench width mitigate the pipe response in lateral displacement.

Kouretzis et al. (2013) investigated quantitatively the size and the shape of the failure surface for laterally displaced pipelines in loose and medium dense sand backfill. It should be noted that in deep embedment conditions and under large relative displacement, the kinematic mechanism changes from a global-type failure to local shear soil failure (Yimsiri & Soga & Yoshizaki & Dasari & O'Rourke 2004).

Based on this literature review, there is not an adequate number of experimental and theoretical models in the literature to speculate the (p-y) and ultimate lateral resistance curve for pipelines. Most of the present models were based on anchor plates (Tschebotarioff 1973; Luscher et al. 1979; Rowe and Davis 1982; Das et al. 1985; Das et al. 1987; Rizkalla et al. 1992; Ranjani et al. 1993; Merified et al. 2001). A large number of other solutions were proposed on the basis of the piles (Hansen 1948, Poulos 1995, Hansen and Christensen 1961, Matlock 1970, ALA 2005, Welch 1975, Reese and Bhushan et al. 1979, Edgers and Karlsrud 1982, Klar and Randolph 2008). Only a few models were developed on the basis of the lateral interaction of pipelines (Oliveira et al. 2010, Poorooshasb et al. 1994, Paulin 1998). Paulin (1998) conducted a group of lateral pipeline-soil interaction centrifuge tests (under an acceleration of 50 g) to investigate the impacts of trench effects as one of the primary that thoroughly investigates small-scale studies on the lateral response of completely buried pipelines in clay (Kianian M, Esmaeilzadeh M & Shiri H 2018). It was discovered that trench width had negligible impact on an undrained interaction, whereas as the burial depth increases the undrained load on the pipeline will increase. The authors concluded that the transferred load from soil to pipeline significantly affected by displacement rate of the pipeline. But the failure mechanism was qualitatively explained and there is no direct visualization data. The authors stated that the overall normalized interaction between the soil and pipeline may be influenced by backfill properties. However, they could not ascertain if this is caused by a change in the separation condition behind the pipe or a change in failure mechanism.

To better examine the trench effects and present the failure mechanism during the large displacement of the pipeline, the authors developed a series of experimental tests with a full set of monitoring and state-of-the-art equipment utilized on the backfill, pipeline, actuation system, native soil and whole test configuration. The authors used a digital camera, transparent acrylic sheet and particle image velocimetry (PIV) to attain interactive and progressive failure mechanisms. Furthermore, an advanced numerical model was developed and will be further calibrated according to the experimental results. Altogether, this study increased the current comprehension knowledge of the lateral response of entirely buried pipes to large deformations and offered a complete understanding into this important critical problem. Ongoing tests and simulations will further explore the effects of interaction rate. In real pipe-soil interaction circumstances both drained and partially drained states are very frequent. In these conditions the rate of relative displacement between soil and the pipeline is moderate. In such instance, during the displacement the soil surrounding the pipeline reaches some degree of consolidation. Besides, in many geographical locations, silt fragment is found in soft natural offshore clays (e.g., Gulf of Mexico, Schiffman 1982). The consolidation properties of clay tend toward partial drained or fully drained if silt presents in clay. Similar effects may be indicated by further compositional and depositional fragments. In clay, the drained response of the pipeline induced by large deformations has been less investigated (Paulin 1998).

3 CENTRIFUGE TESTS

The testing program contains five series of tests involving in the lateral interaction of pipe-backfill-trench in clay through large lateral movement at a centrifuge with 19.1 g acceleration. In each run, two pipes with different configuration were dragged in opposite directions. Additionally, three series of tests were carried out in the dry loose sand. Although, in this paper, the results of performed tests in clay with sand backfill (rectangular trench) were discussed. The author used the transparent observation window placed on the front side of test box in order to directly monitor the details of interactive failure mechanisms during the lateral displacement of the pipeline. High quality images were captured by digital cameras for particle image velocimetry (PIV) and post-processing. During the tests, the full equipped model sections of pipeline were placed on the bottom of excavated trenches and were buried with backfilling material. The pipes were pulled in opposite direction with fixed moving pace controlled by two vertical actuators which had pulleys and horizontal cables, while pipes were not constrained in the vertical direction.

Principal objectives of the experimental tests are:

- Failure mechanisms in both trench wall and backfill;
- P-y response of pipeline and peak resistance for both drained and partially drained tests;
- Interaction properties of the pipe-back-trench;
- Impact of backfilling properties, trench geometry, interaction rate, suction force mobilization and soil stress history;
- Development of analytical models for both ultimate soil resistance and lateral p-y curve;
- Assessment and development of this study for lateral interaction of pipeline-soil;
- Comparison between experimental results and previous studies without trenches

The primary objective of this paper is a general review of instrumentation, test configuration, observation and the primary results which were acquired from testing procedure in clay. Additional analysis of these data is proceeding, and the outcomes will be released accordingly. Failure mechanisms instances and proportional PIV analysis is produced. Testing program clarified to maximize the achieving high quality data. A summary of performed testing procedure is shown in Table 1.

Table 1. Sand backfill testing program

Characteristics	DETAILS
Test bed	cohesive
Pipe diameter	31.7 mm
Scale	19.06
Model cover depth	99 mm
Embedment ratio (H/D)	4.12
Trench backfill type	Loose Sand
Trench wall	vertical
Modified displacement rate	0.00929 mm/s
Normalized velocity (vD/c_v)	0.422
Normalized pulling distance	3.60
T-bar site backfill S_u	2-3.7 kPa
Native S_u at pipe depth	16-19.5 kPa
Native soil water content after consolidation (%)	30.81
Native water content after test at pipe depth (%)	31.11
Native soil void ratio	0.815
Saturated unit weight (Υ_{sat})	18.56 kN/m^3

In order to derive the profiles of undrained shear strength in both backfilling and native material, a T-bar penetrometer (Stewart and Randolph 1994) was employed. For deep penetrations, 10.5 T-bar bearing factor was selected. On the other hand, for shallow depths, a decreased bearing factor due to buoyancy of the soil and shallow failure mechanism mobilized prior to soil full flowing throughout the bar (White et al. 2010) was employed to convert the calculated bearing resistance to undrained shear strength.

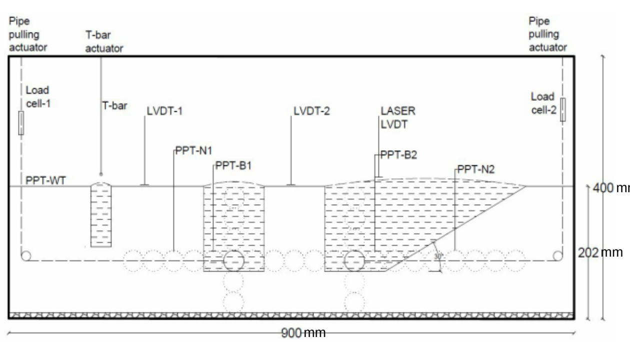


Figure 1. Configuration of experimental test

4 NUMERICAL MODELLING

4.1 Development of CEL model

A coupled Eulerian Lagrangian (CEL) model was developed in ABAQUS/Explicit to explore the backfill-trench-pipeline interaction. CEL has advantage in overcoming the mesh distortion problem compared with the conventional Lagrangian mesh. The large deformation of soil caused by the laterally displaced pipeline can be well represented using Eulerian elements. Pipeline has been modelled as a discrete rigid body with Lagrangian mesh. According to the geometry of the experimental tests (see Figure 1), the CEL model configuration was set in ABAQUS/Explicit (see Figure 2). The whole Eulerian domain has been separated into 4 parts: (1) initial void part (void above the initial soil surface), (2) native clay soil seabed, (3) trench with sand backfilling, (4) initial void part in trench taken by pipeline (no soil particles). Different parts were assigned with multi-material representing different types of soil.

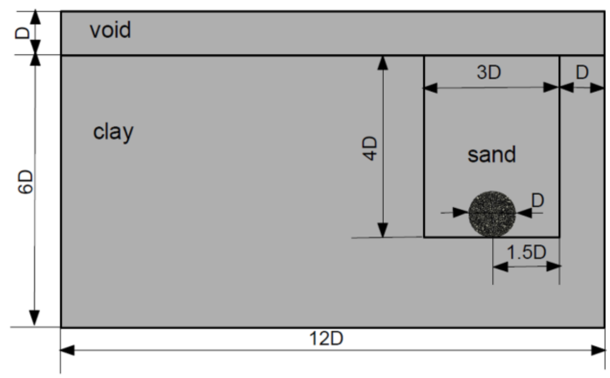


Figure 2. configuration of numerical model

To model the native ground clay behavior, the cam clay constitutive model is used, and parameters of clay are selected based on the experimental test (see Table 1), Paulin's thesis (1998), and Chen's thesis (2013).

Table 2. Characteristics of native clay ground

Characteristics (%)	Vancouver
Density	1800
Stress ratio at critical state	0.8
Peak strength parameter	0.5

Linear hardening rule of Cam-clay model requires the relation between yield stress values and plastic natural volumetric strains (Tekeste et al. 2013) and this needs to be input as tabular mode since this is the only option for ABAQUS/Explicit (ABAQUS 2012a). With tests conducted (oedometer test etc.) for required parameters, the plastic volumetric deformation, elastic natural volumetric strain, and therefore the plastic natural volumetric strain can be calculated according to equations listed as below (Tekeste et al. 2013, ABAQUS 2012b):

$$\bar{\varepsilon}_v = \ln\left(\frac{v_i}{v_o}\right) \quad (1)$$

$$\bar{\varepsilon}_{ve} = \ln\left(\frac{v_i}{v_e}\right) \quad (2)$$

$$\bar{\varepsilon}_{vp} = \bar{\varepsilon}_v - \bar{\varepsilon}_{ve} \quad (3)$$

where

$\bar{\varepsilon}_v$ is the total natural volumetric strain

v_i is the specific volume at the maximum stress value

v_o is the specific value at the preload stress

$\bar{\varepsilon}_{ve}$ is the elastic natural volumetric strain

v_e is the specific value at lowest rebound stress

$\bar{\varepsilon}_{vp}$ is the plastic natural volumetric strain.

To model the backfill sand behavior, the Mohr-Coulomb model is used, and sand parameters are selected according to the loose sand backfill properties in Paulin's thesis (1998). Therefore; the sand unit weight was set to γ=14.8 kN/m^3 for the loose sand and other properties are listed in Table 3.

Table 3. Characteristics of backfill sand

Characteristics (%)	Value	Unit
Density	1480	kg/m^3
Poisson's ratio	0.33	-
Young's modulus	5	MPa
Friction angle	31	degree

4.2 Simulation steps

4.2.1 First step for geostatic stress and multi-material assignment

Set geostatic stress for soil models via predefining conditions. To specify different types of soil in native ground and trench backfill (consider the room taken by buried pipeline), trench geometry and seabed ground geometry were created as reference regions and EVF tool was adopted to assign different materials into different reference regions (see Figure 2). With gravity load executed on whole model, the stress (S33) in the soil can be observed in Figure 3.

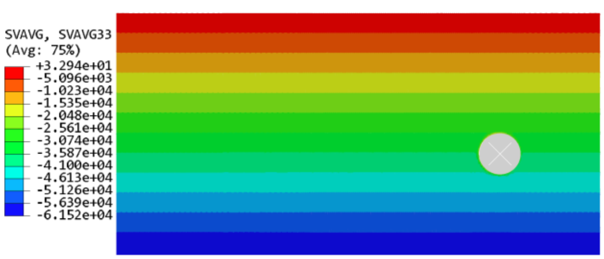


Figure 3. Stress levels in soil

4.2.2 Second step for lateral displacement of pipeline

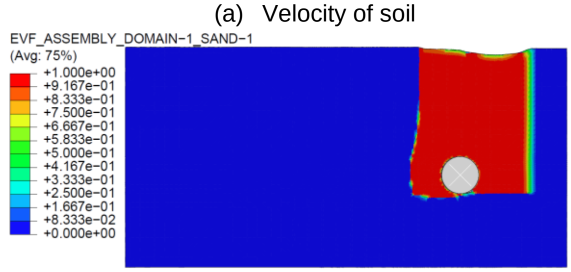
Velocities normal to all surfaces of the whole Eulerian domain were set as zero to prevent the flow out and flow in of materials during the analysis. The pipeline was displaced laterally by a distance of 4D with constraint in vertical direction. During the large lateral displacement of pipeline, the failure of trench wall was observed, and this will be discussed in next section.

5 RESULTS

5.1 FAILURE MECHANISM

During the lateral displacement of pipeline, different flow trends of soil occurred in different locations. As shown in Figure 4, before the pipeline enters into the native soil (see Figure 4 (b)), load has been transferred to native ground by the backfilling sand and the clay soil in the front side of pipeline was forced to start moving (see Figure 4 (a)). Also, it was observed that the backfilling sand began to fall downward especially sand in approximate a curved band on the rear side while the pipeline moved forward.

(a) Velocity of soil

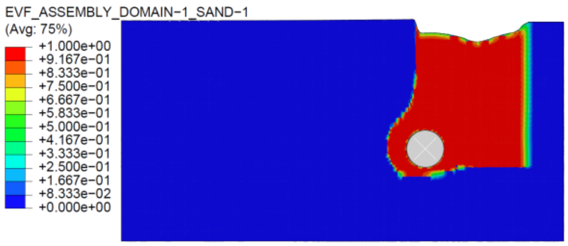


(b) Distribution of soil

Figure 4. Pipeline laterally displaced by 0D-0.5D.

While the pipeline further displaced and arrived at the trench wall (see Figure 5 (b)), a similar curved band of falling sand can be observed in Figure 5 (a) and this time, left part of backfilling sand showed larger velocity in flowing. It can be observed that backfilling sand in front of the pipeline has been somewhat pushed into the native ground and in that region soil particles have higher magnitude of velocity compared with shown in Figure 4 (a).

(a) Velocity of soil



(b) Distribution of soil

Figure 5. Pipeline laterally displaced by 1D-1.5D.

Failure of trench wall showed while the pipeline further entered into the native ground as shown in Figure 6. Instability of the trench wall caused by the interaction can be directly observed in Figure 6 (a) since the velocity of the native ground soil near to the trench wall increased significantly compared with Figure 4 and Figure 5. Indications of cracks in clay can also be observed at the surface of native ground (see Figure 6 (b), vertically above the pipeline) between the actively moving clay part and the relatively stationary clay part (see Figure 6 (a)).

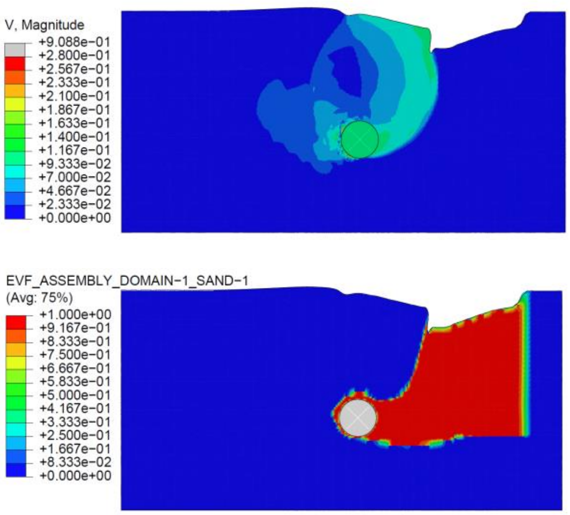
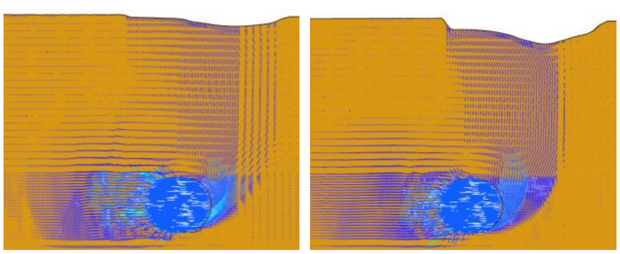
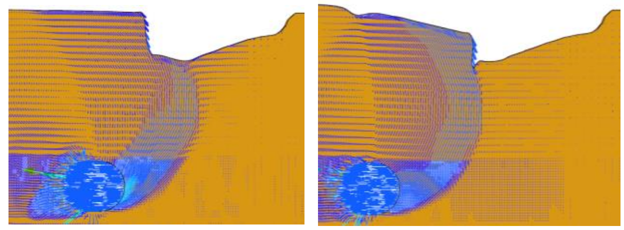


Figure 6. Pipeline laterally displaced by 2D-3D.

As shown in Figure 7, with the vectors plotted for the soil materials, the backfill-trench-pipeline interaction can be better observed. The location of most active region of soil with high velocity moved laterally with the displacement of pipeline. Also, clear difference in moving trends of native ground can be found in Figure 7 (c) and Figure 7 (d) and indications of crack showed right in that area (see Figure 7 (d)).



(a) (b)



(c) (d)

Figure 7. Backfill-trench-pipeline interaction

5.2 Comparison with experimental test

As shown in Figure 8 and Figure 9, the results from experimental test and numerical model meet well. The ultimate lateral load per unit length is around 80 kN/m and the normalized lateral load is around 13-14. Slight differences showed in the 0D-0.5D on the magnitude of responses where the numerical model produced higher magnitude of p-y response. Also, the ultimate response magnitude in experimental test was arrived at 1D-1.5D while in the numerical model it was arrived later at round 2D-3D. Further enhancement can be made to overcome this defect by using finer mesh in the trench wall region to get more accurate material assignment (more accurate value of material volume fractions in boundary elements) and calibrating the numerical model parameters with the experimental results.

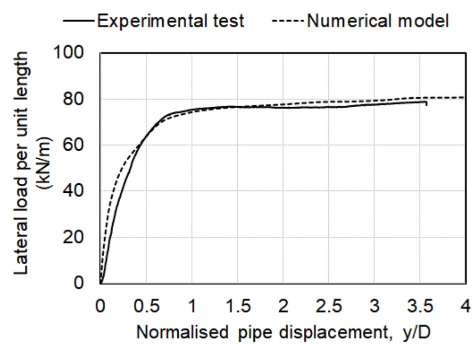


Figure 8. p-y responses of pipeline in numerical model and experimental test.

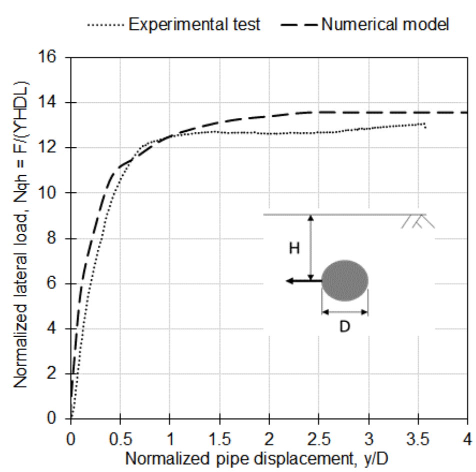
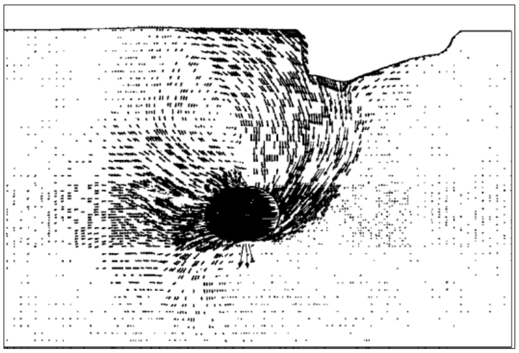
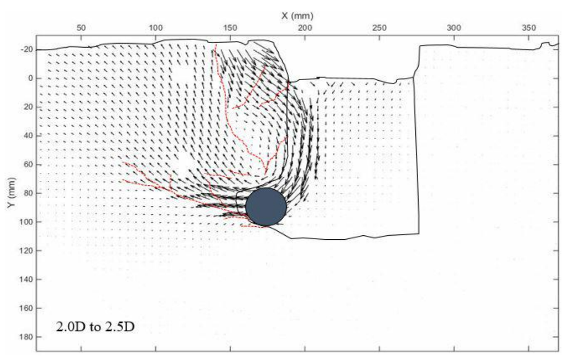


Figure 9. Normalised lateral load

While the pipeline entered into the native ground and the trench wall was about to fail towards the trench, the displacement trends of soil in native ground and backfilling sand showed good agreement in the numerical model (see Figure 10 (a)) and experimental test (see Figure 10 (b)). The trench wall began to lean towards the backfill and in following period cracks tended to show on the surface of native ground as we discussed in former section.



(a) Numerical model



(b) Experimental test

Figure 10. Vectorial displacement for pipe movement from 2.0D to 2.5D

In current testing procedure, it was noticed that various essential factors could control the lateral response of the pipe these parameters mostly including type and the strength of the backfilling material, geometry of trench, embedment depth and interaction rate (see Figure 11). Consequently, pipeline response and failure mechanism will be influenced by all of these crucial factors. Authors are now working on the postprocessing of the tests and calibration of current numerical model based on the conducted tests. Numerical modelling work will also be extended to conduct the parametric study of the key factors of backfill-trench-pipeline interaction.

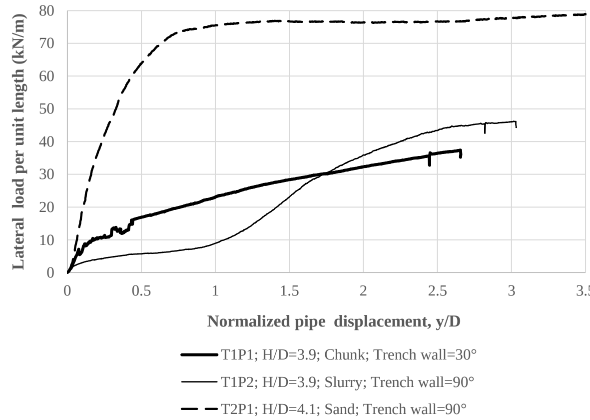


Figure 11. Effect of backfill type on force-displacement response (Kianian et al., 2018).

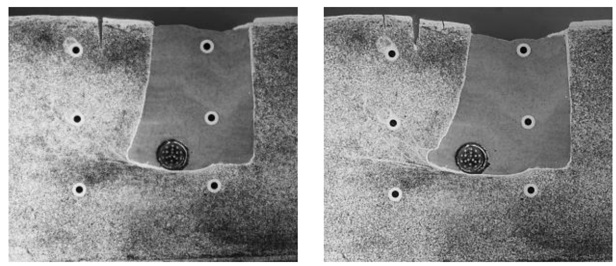


Figure 12. Crack shown in native ground

During the testing, cracks on the native clay ground surface can be observed with further penetration of the pipeline towards the trench wall (see Figure 12). Similar phenomenon can be observed in numerical modelling as shown in Figure 6 and Figure 7. Some differences could be found, and this further proved the importance of experimental tests, that is to say, experimental data will provide better assistance in setting parameters for numerical model. Then the calibrated numerical model will be adopted to conduct a series of simulations representing various backfill-trench-pipeline interaction cases to generate results for developing analytical design equations, which is one of the objectives of the whole research project.

6 SUMMARY AND CONCLUSION

In order to define the shape and mechanism of failure in loose sand backfill, the present study uses experimentally verified numerical analyses. The analyses results can be summarized as follows:

- The advanced CEL model gives direct view of the interaction between backfill material, native soil and the laterally displaced pipeline by generating the moving trends of soil during the analysis.
- Curved band of moving soil showed on the rear side of the pipeline and moved forward with the pipeline displacement.

- Experimental tests have shown the influence of type and the strength of the backfilling material, geometry of trench, embedment depth and interaction rate on the ultimate pipeline response. Numerical models are now under development for further exploration with systematic parametric study to providing strong basis for proposing analytical equations for backfill-trench-pipeline interaction.
- In view of above finding, to drive an approximate formula in order to the maximum horizontal force estimation on shallow pipelines installed in dry loose-to-medium sand, we can use the failure of backfill prism geometry and maximum forces developing on the pipeline.

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