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AN INTEGRATED EXPERIMENTAL – NUMERICAL APPROACH TO PREDICT STRAIN DEMAND FOR BURIED STEEL PIPELINES IN GEO-HAZARDOUS AREAS

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Abstract

In the course of a strain-based design framework, the evaluation of buried steel pipeline integrity in challenging geo-hazard areas, an accurate prediction of strain demand is required, accounting for the interaction between the pipeline and the surrounding soil. Finite element models have been widely recognized as a rigorous tool, capable of describing with significant accuracy large deformation and strains developed in buried steel pipes, including the effects of soil-pipe interaction, towards evaluating pipeline strain demand subjected to ground-induced actions. The simulation of the pipe-sol interaction is a key point and requires a complete mechanical characterization of the soil parameters, especially at the soil-pipe interface. For this purpose, the calibration of the finite element tools by means pipe-soil full-scale tests is necessary. The present paper describes a joint research effort within GIPIPE, a European research project sponsored by the European Commission, proposing an integrated numerical-experimental approach. In particular, a rigorous finite element model of a buried pipeline is presented, and the development of a new experimental full-scale device is described, devoted at the investigation of the mechanical interaction of the pipeline-soil system.

1. Introduction

Geo-hazards constitute a threat for the structural integrity of buried pipelines. Recent observations from pipeline damages have demonstrated that the majority of damages to continuous oil and gas steel pipelines were caused by permanent ground deformations such as fault movements, landslides, liquefaction-induced lateral spread. For the particular case of earthquake action (e.g. 1971 San Fernando earthquake, and, more recently, the 1995 Kobe earthquake, the 1999 Kocaeli earthquake and the 1999 Chi-Chi earthquake), permanent ground deformations, applied on the pipeline in a quasi-static manner, are not necessarily associated with high seismic intensity, but may result in serious damage of oil and gas steel pipelines, whereas only few pipelines were damaged by wave propagation.

The present work examines on the mechanical response of continuous (welded) buried steel pipelines subjected to horizontal quasi-static permanent ground-induced actions, with emphasis on strike-slip seismic tectonic faults. Other ground-induced actions such as landslides or liquefaction-induced lateral spreading can be treated in a similar manner. Pipelines subjected to such a horizontal action are subjected to an imposed deformation pattern, associated with axial, shear and bending loads, and develop high stresses and strains in critical locations, which are well into the inelastic range of pipe material and may cause pipeline failure. In particular, high tensile stresses may lead to fracture of the pipeline wall, which is the principal ultimate limit state of the pipeline. Fracture occurs mainly at welds or defected locations or welds. In addition, high compression stresses may cause buckling, either in the form of beam-type (global) instability or in the form of pipe wall wrinkling, a shell-type instability, sometimes referred to as "local buckling" or "kinking". This is also considered as an ultimate limit state, given the fact that the buckled area is associated with significant stress and strain concentrations that may lead to fracture under repeated operational loads. Furthermore, a serviceability limit state may be reached in terms of the distortion of pipeline cross-section, in the form of ovalization or flattening.

The pioneering work of Newmark and Hall (1975) has been employed as a basis for pipeline analysis crossing tectonic faults. This work has been extended by Kennedy et al. (1977), Wang and Yeh (1985), Wang and Wang (1995) and Takada et al. (2001) through a beam-type approach for describing pipeline deformation. More recent works on this

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subject have been reported by Karamitros et al. (2007) Liu et al. (2008) and Trifonov & Cherniy (2010). In addition to the above analytical and numerical studies, notable experimental works on the effects of strike-slip faults on buried high-density polyethylene (HDPE) pipelines have been reported in series of recent papers by Ha et al. (2008) and Abdoun et al. (2009). The analytical works outlined above have modelled soil conditions based on a spring-type approach. A more rigorous approach has been followed by Vazouras et al. (2010, 2012), for buried steel pipelines crossing strike-slip faults at various angles, through a finite element modelling of the soil-pipeline system, which accounts rigorously for the inelastic behaviour of the surrounding soil, the interaction and the contact between the soil and the pipe (including friction contact and the development of gap), the development of large inelastic strains in the steel pipeline, the distortion of the pipeline cross-section and the possibility of local buckling, the presence of internal pressure. In those studies, the behaviour of buried steel pipelines has been investigated with respect to appropriate performance criteria, expressed in terms of local strain or cross sectional deformation, in the framework of a performance-based pipeline design and numerical results are presented in the form of diagrams, depicting the fault displacement corresponding to a specific performance criteria with respect to the crossing angle.

The present paper summarizes the first part of the work within the GIPIPE project, and has a dual purpose: (a) it offers a brief description of the numerical modelling tools and their capabilities in simulating the response of buried pipelines subjected to horizontal ground-induced deformation and (b) it describes the development of a novel state-of-the-art experimental facility, capable of testing buried pipe segments under horizontal ground-induced deformation, towards better understanding of soil-pipe interaction and calibration of the numerical models.

2. Numerical Simulation

Numerical simulation of the strike-slip fault is performed, employing rigorous numerical tools that simulate large displacements and strains, inelastic behavior of the pipe and soil material, as well as the mechanical interaction between the soil and the pipeline.

2.1. Finite Element Modeling

The response of the pipeline under strike-slip fault movement is examined numerically using the finite element program ABAQUS. In particular, the mechanical behavior of a 36-inch X65 steel pipeline, crossing a strike-slip fault, is simulated, subjected to a permanent ground movement d in a direction that forms an angle β with the normal on the pipeline direction, as shown schematically in Figure 1, ranging from zero to 45°. The nonlinear behavior of the steel and the surrounding soil, as well as the soil-pipe interaction are modeled in a rigorous manner. Four-node reduced-integration shell elements (type S4R) are employed for modeling the cylindrical pipeline segment, and eight-node reduced-integration "brick" elements (C3D8R) are used to simulate the surrounding soil. The top surface of the prism represents the soil surface, and the burial depth is chosen equal to about 2 pipe diameters, which is in accordance with pipeline engineering practice. The prism length in the x direction is equal to more than 65 pipe diameters, whereas dimensions in directions y and z are equal to 11 and 5 times the pipe diameter, respectively. A large-strain von Mises plasticity model with isotropic hardening is employed for the steel pipe material. The mechanical behavior of soil material is described through an elastic-perfectly plastic Mohr-Coulomb constitutive model. The analysis is conducted by applying gravity first, then increasing internal pressure – if any – and, subsequently, applying a displacement-controlled scheme, in which the fault displacement d is increased gradually. The base and vertical-boundary nodes of the first soil block remain fixed in the horizontal direction, whereas the corresponding nodes of the second soil block are subject to a uniform displacement, in a direction parallel to the fault plane.

2.2. Numerical Results

Numerical results are obtained for the 36-inch buried pipeline. The pipeline has a diameter of D=0.914 m, thickness t=9.5 mm, Young's Modulus E = 210 GPa, Poisson's ratio ν=0.3 and yield stress σ_y = 448.5 MPa corresponding to an X65 steel material. The pipeline is buried in a cohesive soil, having a density ρ_s =2000 kg/m^3, cohesion c=50 kPa, friction angle ϕ=0°, Young's Modulus E_s=25 MPa and Poisson's ratio ν_s=0.5. The shear resistance at the pipe-soil interface is assumed to be of frictional nature, with a coefficient of friction μ=0.3.

Using the model above, Figure 2 plots the distribution of axial normal strain at the compression side of the pipeline respectively for a crossing angle $\beta = 0^\circ$, for different values of fault displacement d close to the displacement that causes local buckling. The buckling shape is shown in Figure 2 and Figure 3, its formation is gradual and occurs at fault displacement equal to d_{cr} =0.43 m; this is the most critical performance criterion for the present case. At the location of buckling, a significant increase of local strain can be observed. Furthermore, Figure 3 shows that local buckling is associated with significant cross-sectional distortion.

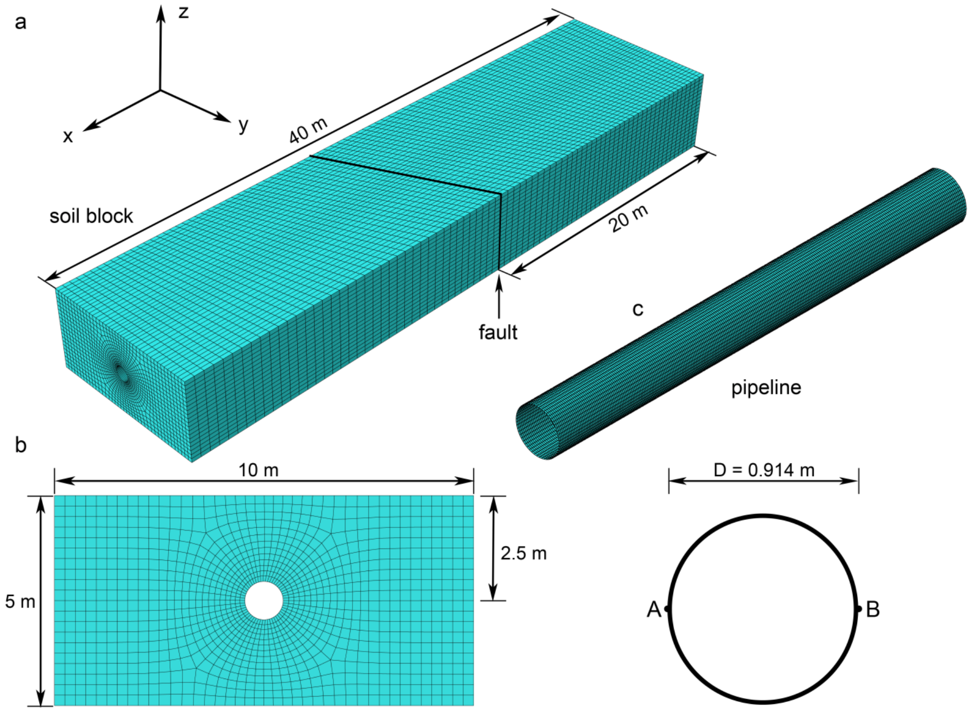


Figure 1. Finite element model of buried steel pipeline crossing oblique strike-slip fault.

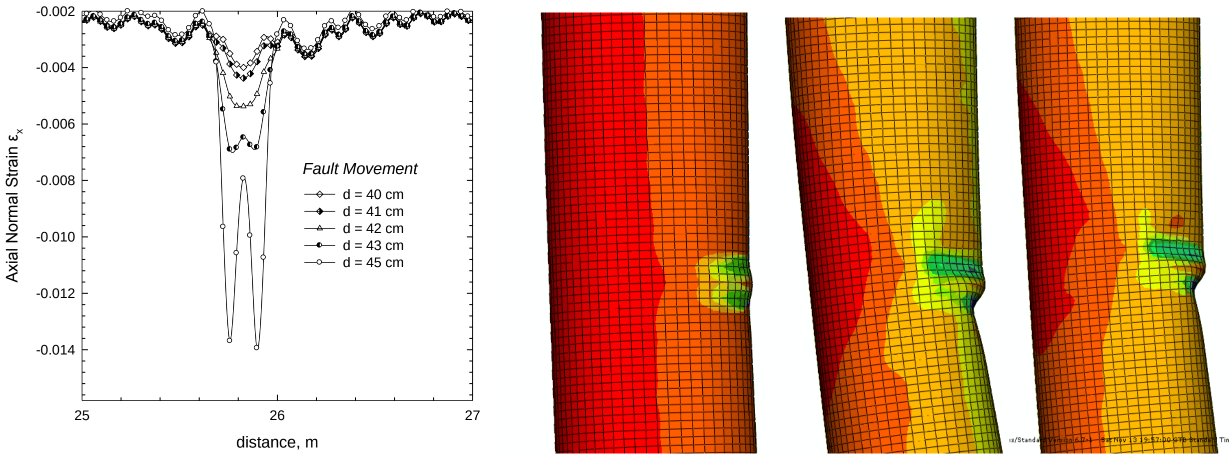
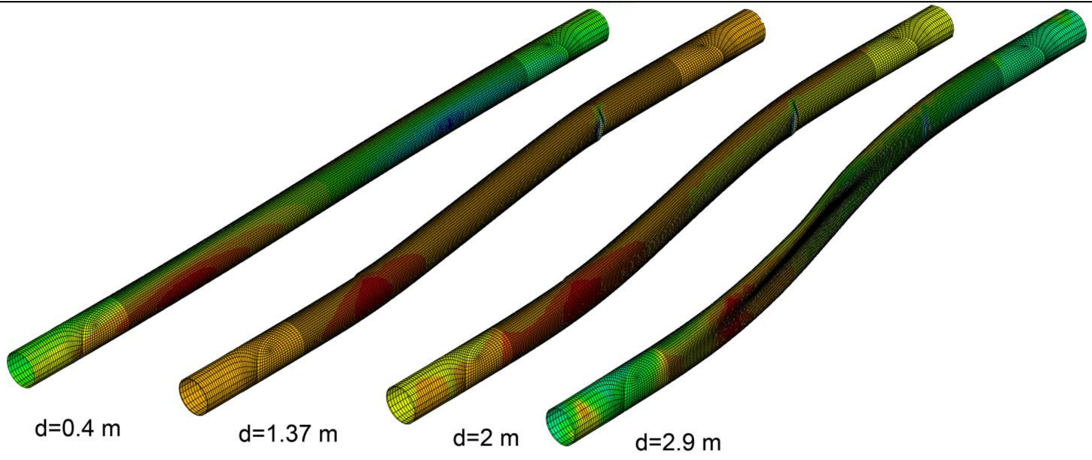


Figure 2. Finite element model of buried steel pipeline crossing oblique strike-slip fault.

Figure 4 plots the deformed shape of the pipeline and the distribution of the axial normal strain for a crossing angle $\beta = 25^{\circ}$ at fault displacements equal to d =1, 1.5, 2 and 2.5 m. In this case, additional pipeline extension equal to $d \sin \beta$ occurs, resulting in significant reduction of the compressive axial strains due to bending, and preventing the development of local buckling. Figure 4 also illustrates the ovalization of the pipe cross-section at the fault location ($x = 0$). At fault displacement equal to 1.28 m flattening (ovalization) reaches a value of 15%, which may be considered as a serviceability limit state.

Finally, Figure 5 shows the deformed shape of the pipeline and the distribution of the axial normal strain for a negative value of the crossing angle ($\beta = -10^{\circ}$) at 4 values of imposed fault displacement. In this case, pipeline is under significant compression, due to the direction of the $d \sin \beta$ component of the fault displacement, resulting in early development of local buckling.



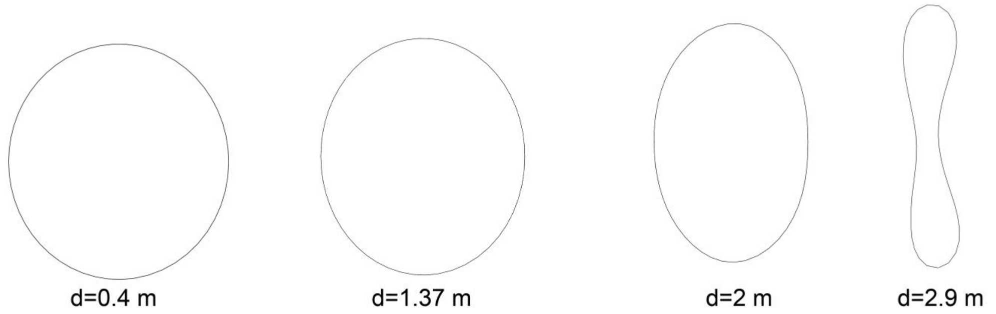
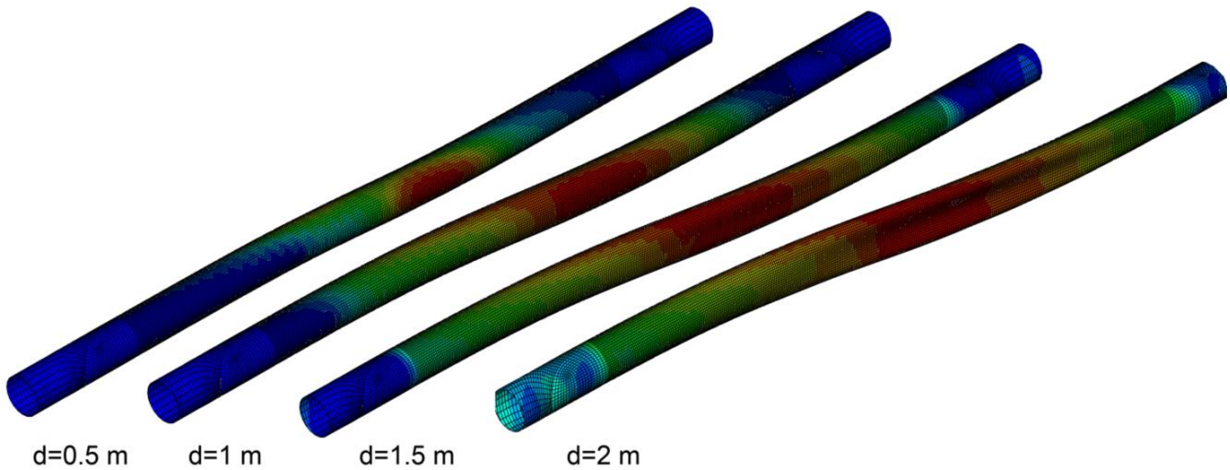


Figure 3. View of deformed shapes for an X65 $D/t = 96$ pipeline in Clay I conditions and $\beta = 0$, for various values of fault displacement and correspoding cross-sectional deformation at 0.5 m from the fault.



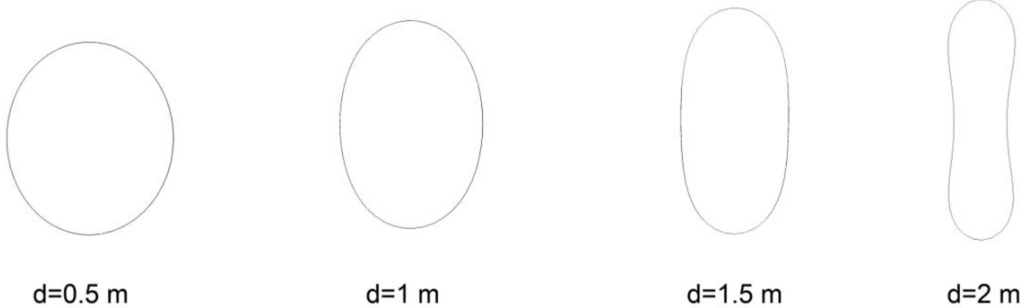


Figure 4. View of deformed shapes for an X65 $D/t = 96$ pipeline in Clay I conditions and $\beta = 25^{o}$, for various values of fault displacement and correspoding cross-sectional deformation at 0.5 m from the fault.

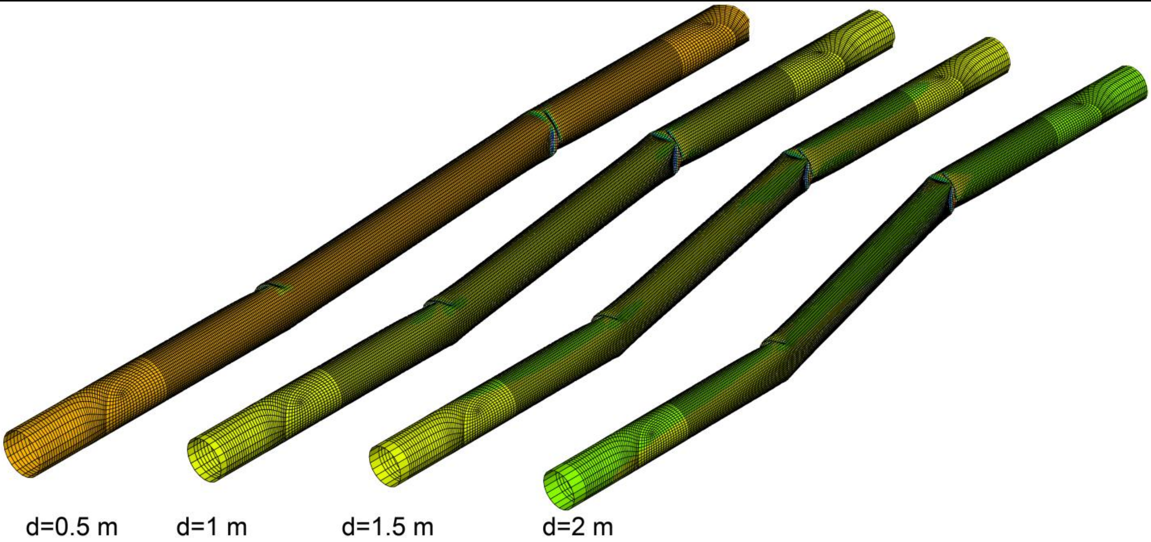


Figure 5. View of deformed shapes for an X65 $D/t = 96$ pipeline in Clay I conditions and $\beta = -10^{o}$, for various values of fault displacement.

3. Experimental Testing Program

Extensive full-scale experimental activity is planned in CSM full-scale test system in Perdasdefogu (Sardinia) using the bending machine for pipeline and tubular components. The system is capable of applying four-point bending loading on long pipeline specimens, through two parallel actuators of maximum capacity 4,000 kN each, and stroke equal to 14 meters. The tested pipes can be internally pressurized up to 2,000 bar. The main components are already fully operative, such as hydraulic actuators and data acquisition system, several modifications to the test area are required in order to perform the full scale test program.

Table 1. CSM full-scale testing program.

<table>
<tr><th>Test Configuration</th><th>Number of tests</th><th>Pipe type</th><th>Steel grade</th><th>Soil</th><th>Pressure</th></tr>
<tr><td rowspan="3">“Axial Pipe Pulling Test”</td><td rowspan="3">3</td><td>8.625"OD × 5.6mmWT</td><td rowspan="3">X65</td><td>Sand, compaction level 1</td><td rowspan="3">P = 0</td></tr>
<tr><td>8.625"OD × 5.6mmWT</td><td>Sand, compaction level 2</td></tr>
<tr><td>8.625"OD × 5.6mmWT (WITH COATING)</td><td>Sand, compaction level 1 or 2</td></tr>
<tr><td rowspan="3">“Transversal Soil-Pipe Interaction Test”</td><td rowspan="3">3</td><td>8.625"OD × 5.6mmWT</td><td rowspan="3">X65</td><td>Sand, compaction level 1</td><td rowspan="3">P = 0</td></tr>
<tr><td>8.625"OD × 5.6mmWT</td><td>Sand, compaction level 2</td></tr>
<tr><td>8.625"OD × 5.6mmWT (WITH COATING)</td><td>Sand, compaction level 1 or 2</td></tr>
<tr><td rowspan="4">“Landslide/Fault Test”</td><td rowspan="4">4</td><td rowspan="4">8.625"OD × 5.6mmWT</td><td rowspan="4">X65</td><td rowspan="2">Sand, compaction level 1</td><td>P = 0</td></tr>
<tr><td>P > 0</td></tr>
<tr><td rowspan="2">Sand, compaction level 2</td><td>P = 0</td></tr>
<tr><td>P > 0</td></tr>
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3.1. Experimental program

The first set of tests concerns axial-pulling tests, and the load configuration is depicted in Figure 6. The pipe is contained within a box and buried by sand soil with a specific compaction level. The pipe is pulled through openings in the soil boxes. Pipe pulling forces and displacement are measured, in order to determine the pipe-soil friction coefficient evolution. In this test the pipe surface will be “bare”, no instrumentation will be placed over, in order avoid any alteration of the test conditions. Applied load and displacements on pipes will be recorded. Two pipes specimens will be buried in the box so that the two test with different surface condition (coated and uncoated) could be performed in a short time period and under the best possible soil compaction level uniformity conditions (compaction will be obtained by mechanical tamping). In this way differences of the two pipes will be associated uniquely to "pipe surface condition". The boxes employ concrete walls in order to contain the soil and the pipes. After a preliminary study on feasibility of steel boxes, it was decided to adopt 1.5m side cubic concrete blocks and 1.5m × 1.5m × 0.7m blocks, laid on the concrete testing area. This solution gives more flexibility for the test configuration as different box shapes and sizes could be adopted if required. In order to evaluate the horizontal load bearing capability of the blocks, preliminary concrete to concrete friction tests have been performed by dragging the block with the actuator while recording the force with the load cell, and a force of approximately 6 tons has been measured.

Figure 7 reports the load configuration adopted in the second set of tests, which refer to transverse soil-pipe interaction. The pipe specimen is contained in a box and buried with sand under controlled compaction conditions (obtained by mechanical tamping) and pulled by means of steel bars through openings in the soil boxes. Pipe pulling forces and displacement are measured, in order to determine the pipe-soil lateral interaction evolution. Tactile forces transducers will be placed over the pipe in order to measure the soil-pipe normal contact forces distribution around pipe. This data will be also employed to compare the experimental and FE model results.

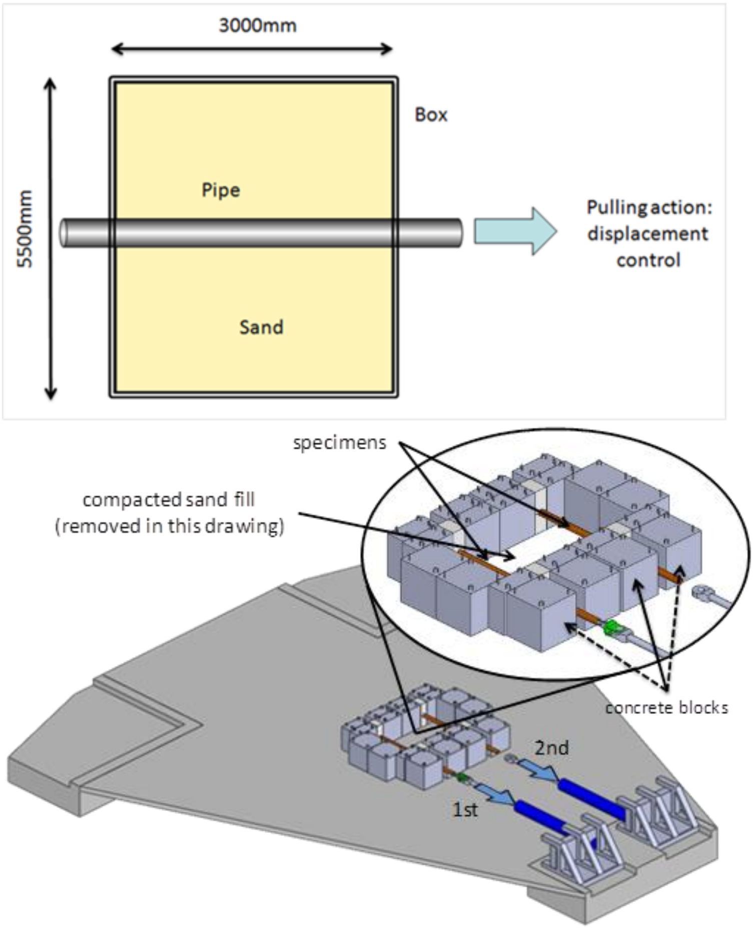

Figure 6. Axial pull-out tests

In the test configuration, one pipe specimens will be buried in the box. The pipe specimen will be pulled by simultaneous action of the two actuators under displacement-controlled conditions, so that pipe axis is maintained always perpendicular to displacement direction. In order to prevent vertical upward or downward displacements, the pipe will be guided by rails close to its ends. In this type of test significant bending load is expected to be applied on the pipe in its central section, this can cause deformation or buckling. To avoid this occurrence which could invalidate the test results, the specimen will be internally reinforced by concrete filling.

The third set of tests consists of the landslide/fault experiments. Three boxes will be employed, as depicted in Figure 8. The pipe specimen will cross the three boxes and will be buried by sand at specified compaction level obtained by mechanical tamping. Pipe ends extend out of the soil boxes and will be constrained in order to prevent rotation on around vertical axis, while leaving axial displacements free.

Both pressurized and unpressurized tests will be performed Once test conditions are obtained the central box will be displaced by simultaneous action of the hydraulic actuators controlled in displacement mode. The action exerted by the sand fill on the pipe in the central box, and the constraint provided by the sand on the lateral boxes will cause a realistic bending deformation on pipe which could result in local buckling or tearing on the tensile part of the specimen. The setup configurations before and during test execution are reported in Figure 9. Concrete blocks will be employed for construction of lateral fixed boxes, while for the central box it was decided to employ a combined steel structure composed by steel pipes for the walls, beams for the frame, and plates for the floor. Welded and bolted connections are employed in the joining of various parts, bolted connections were chosen in order to simplify construction and to allow for possible future enlargement of the box, by inserting floor extensions.

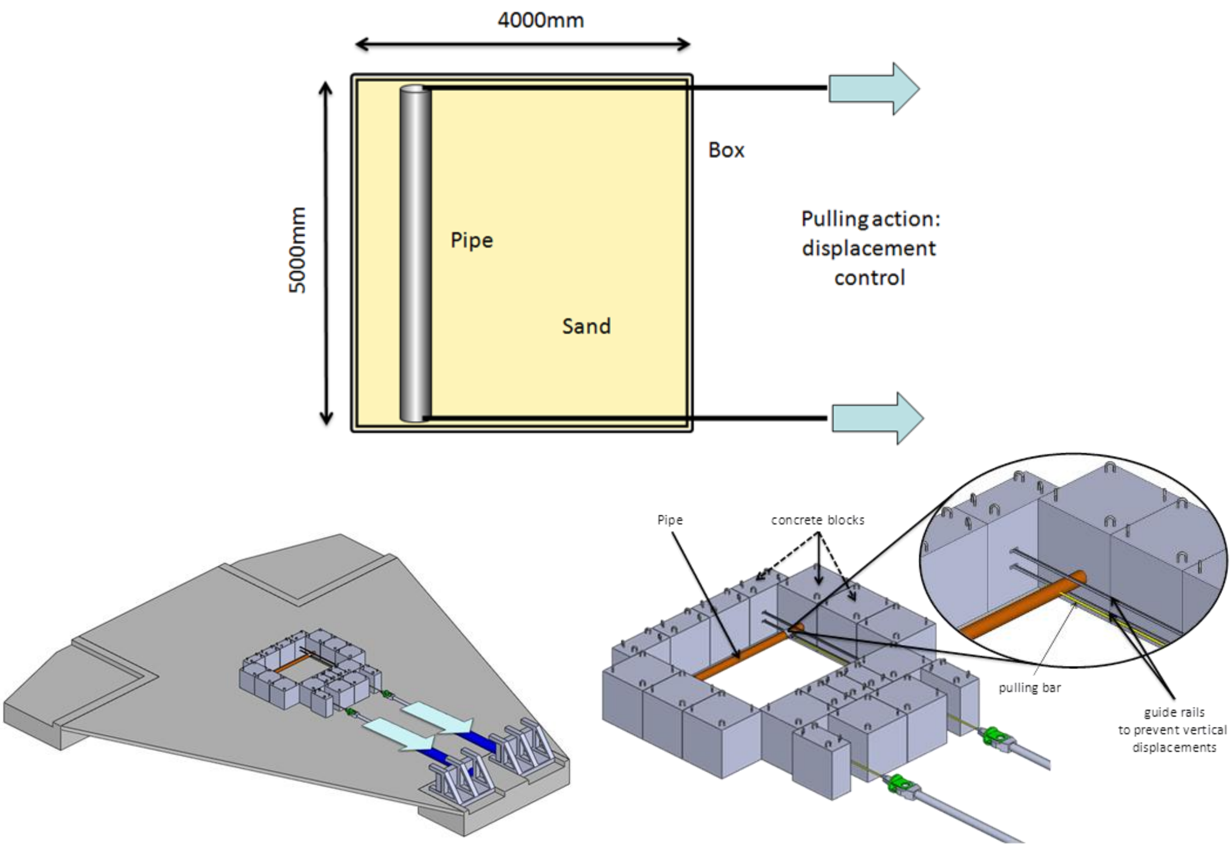

Figure 7. Transverse soil-pipeline interaction tests.

3.2. Instrumentation

During testing relevant test instrumentation is required in order to measure parameters that describe the pipeline-soil interaction phenomena:

- Pipe internal pressure monitored and controlled within specified values;
- Temperature;
- Sand compaction level, verified during box filling;
- Hydraulic jack displacements: monitored and controlled;
- Hydraulic jack loads: monitored;
- Soil displacement, by means of video recording of the position of grid markers placed over the soil surface, to compare with results of full scale test with FE model results (Figure 10);
- Local strains on pipe with strain gauges;
- Pipe deformed configuration displacements, by means of strain gauges and wire LVDTs. LVDT will measure the global pipe displacement at mid length and pipe ends, while will global displacements along the pipe will be calculated by measuring the local strain distribution through the strain gauges (Figure 11);
- Contact pressure at pipe-soil interface, by means of flexible tactile force transducers (Tekscan) model 3150 that will be wrapped around pipe as shown in Figure 12.

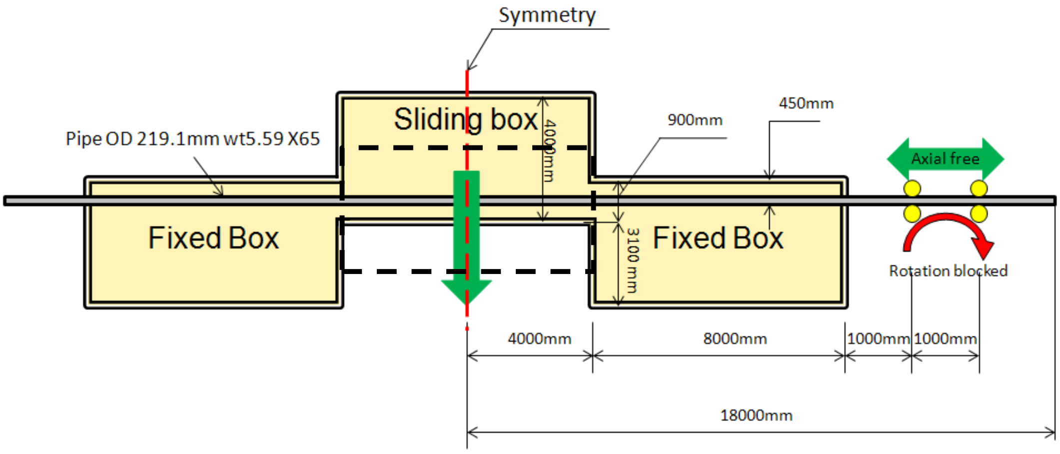

Figure 8. Schematic representation of landslide/fault tests.

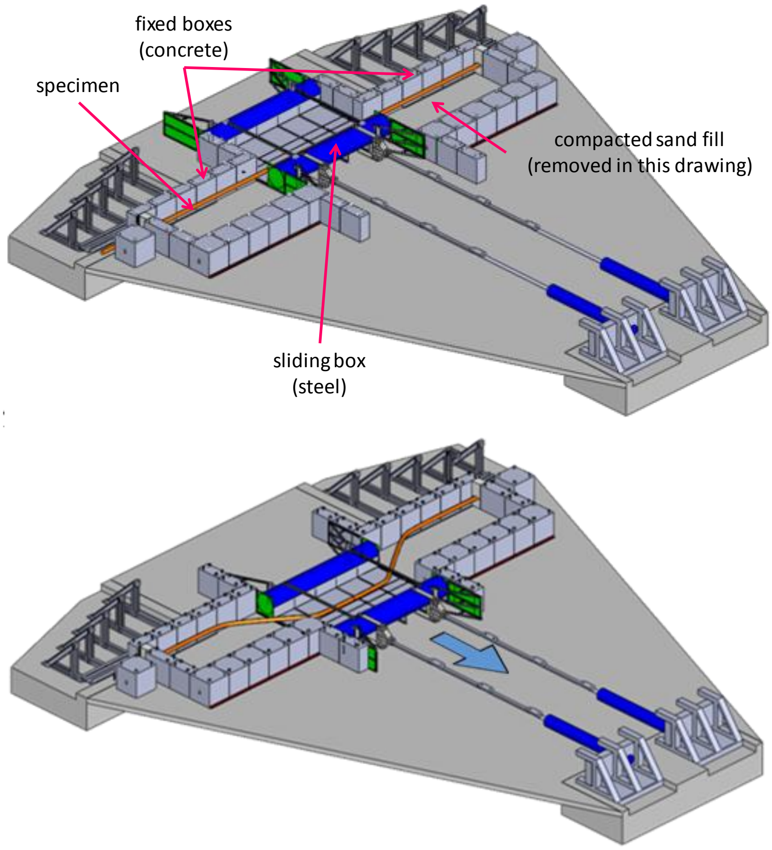

Figure 9. Configuration for landslide/fault testing; before (top) and after (bottom) the application of displacements.

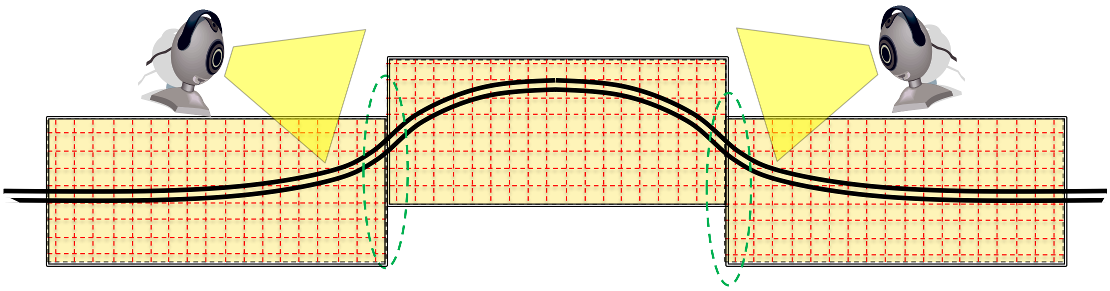

Figure 10: Grid marking and video recording of sand surface, to evaluate surface deformation.

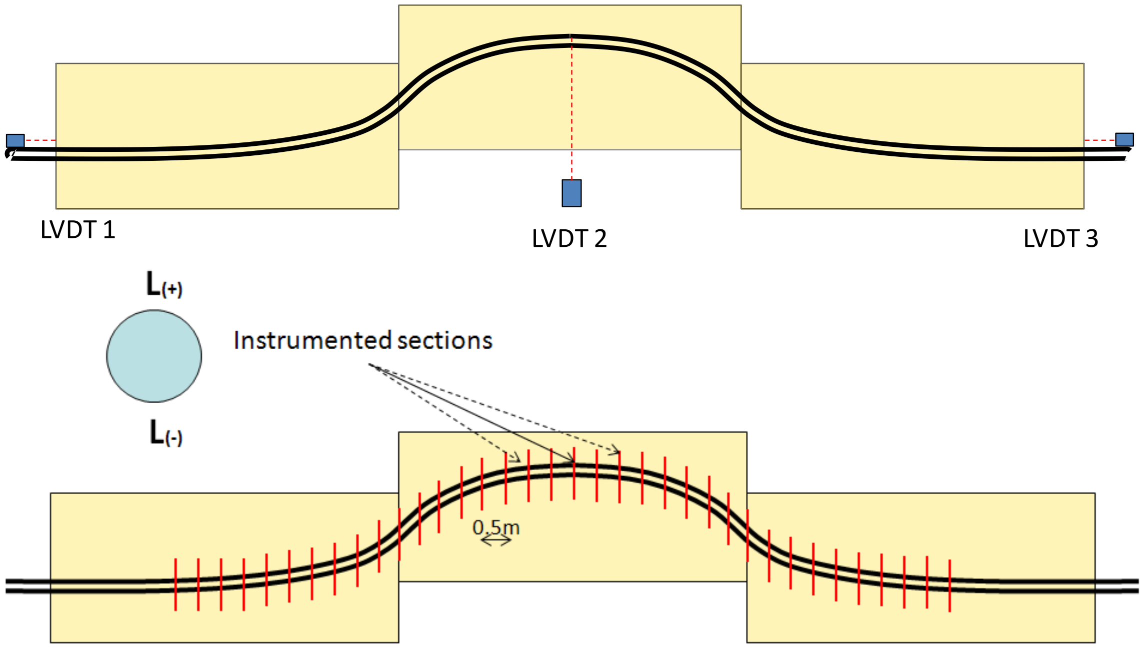

Figure 11: (top) LVDT positioning to measure pipe displacement at symmetry section and pipe ends, and (bottom) strain-gauge positioning to evaluate pipe displacement along its length during landslide/fault bending test.

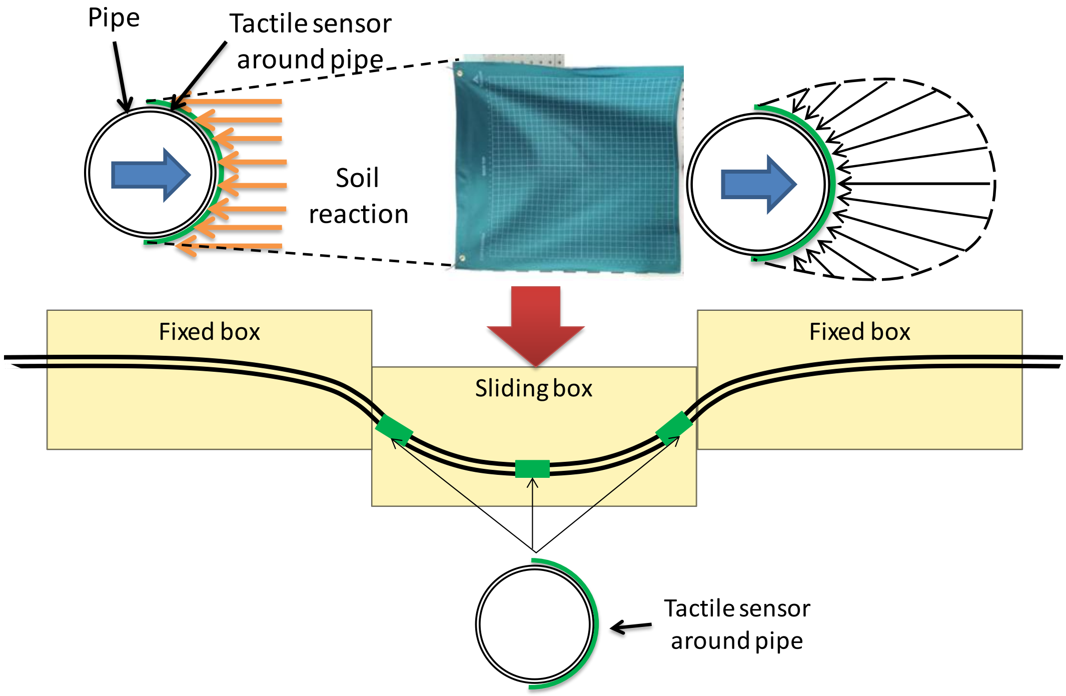

Figure 12: Tactile sensor around pipe and sensor positioning for landslide/fault testing

4. Conclusions

The need for assessing buried steel pipeline integrity against geo-hazards motivates the development of advanced numerical finite element tools, capable of describing large deformations of pipelines against ground-induced actions. Nevertheless, those models require calibration through special-purpose experimental testing. The present paper, motivated by this need, describes the first part of a combined numerical-experimental research effort, aimed at investigating in detail interaction between soil and pipe in the course of significant ground-induced deformations.

5. Acknowledgements

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