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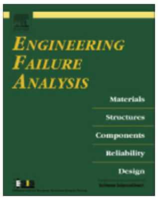

Nonlinear FEM strategies for modeling pipe–soil interaction

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ABSTRACT

This paper discusses the results of one finite element modeling strategy to assess the behavior of pipelines buried in rainy forest regions, which are prone to failures by axial stresses from land movement. Two failures had already been investigated; conclusions of Root Cause Analyses agree with numerical predictions. The model allows quantifying soil displacements that load the system, a parameter that could not be estimated by geotechnical specialists. The model also confirmed other facts suggested by different failure analysis with no trivial theoretical demonstration, such as the notable effect of pipe diameter.

The model is based on a three-dimensional simulation of the zone under analysis, which can be up to 1 km long. The finite element method is used for the resolution of partial derivative differential equations and incorporates complex nonlinear physical–mathematical models. A typical geometry considers a 20 m wide and up to 20 m deep right of way, supported in the solid rock layer. Two sufficiently documented events were used to verify if the tool really reproduces the stress state in the pipe due to soil movements. The model is properly adjusted using field instrument data and test results from the region under study, which include geotechnical measurements and pipe strains via vibrating wire strain gauges. The tool is meant to assist the Line Operators on the Integrity Management Policy.

1. Introduction

The system under study consists of two buried pipelines that share a common right of way that crosses the rainy forest and the Andes Mountains (4800 m over sea level) in South America. The “A” pipeline gradually changes diameters from 14″ to 10″, and the “B” pipeline begins in 32″ and telescopes to 24″ to finalize in 18″. The pipelines began in operation in 2004. Two incidents analyzed in this numerical model were located in the A pipeline (in the rainiest sectors of the forest within a year and at the end of the rainy season). No incidents occurred in the larger “B” pipeline.

Abundant rains (up to 7000 mm every year in the rainy season) create water flow along and traverse to the pipelines in the analyzed sections. The incidents investigated are related not only to the internal pressure, but also to combined bending and tension that are generated during the operation by ground movements – see Fig. 1.

Soil instability caused or substantially contributed to both incidents. Toward the end of 2006, after extraordinary efforts to stabilize geologic conditions throughout the right of way, the operator continued with the implementation of mitigation measures that perceivably reduced the risk by improving soil stability in the dangerous sites.

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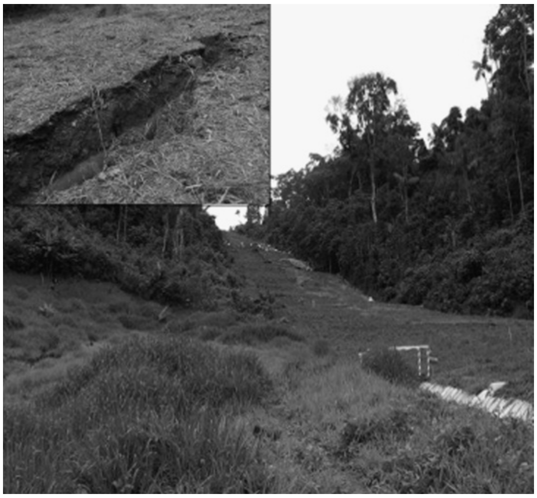

Fig. 1. Zone to model and escarps.

During 2006–2008 geological stabilization measures were constructed which showed reliable and robust. In the most critical areas, instrumentation (strain gauges, piezometers, clinometers and strain gauges) are being used to interpret and understand soil instability, allowing efficient and reliable repairs. On the basis of geological data a hybrid risk matrix was developed to determine suitable fault probability. This system was validated using the information of field inspection. Sites that have exhibited manifestations of ground instability were enumerated in the risk matrix, most of these potentially susceptible fault points are in the forest sector. The operatoŕs supervision system helps reduce failure risk as a result of early detection of instability signs a quantification. This program allows early detection and correction of potentially problematic areas.

As part of its pipeline integrity plan, the operator required to develop a reliable tool that allowed to know the stress state of the pipelines. Strain gauges, given their particularly complicated installation due to necessary logistic and lanḿs difficulties, are an expensive solution; nevertheless they offer very important information about the stress states of the pipes. One of their limitations is that they only allow to obtain conclusions on specific zones. The development of a reliable tool that a priori defines the most stressed points, would allow to optimize the location of strain gauges.

The operator and pipe integrity specialists set out to develop a model based in the finite elements method that allows simulating the stress state of pipelines as a result of imposed ground displacements. This model will be referred as “the tool” in the following. These located escarpments or landslides are detected by the geological team and serve as input data for the simulation.

Several projects and scientific publications address the computational simulation of the pipe–soil interaction during the last years. Proof of this is “Extended Model for Pipe Soil Interaction” prepared by C-Core and Honegger Consulting for Pipelines Research International Council [1]. This project compiles the state-of-the-art in the matter, including several standards that treat the problem, the last techniques and advances in numerical simulations and laboratory tests until 2003. Fredj A. et al. [2] presented several three-dimensional models of small straight and curved pipeline sections subject to lateral displacements. This way, a useful tool for the forensic analysis or special designs was developed. At the same time Mahdavi [3] and collaborator investigated the mechanical behavior of a small section of pipe subject to a large lateral soil motion until a wrinkle forms. They developed laboratory tests to calibrate the finite elements model until obtaining good agreement between both. Thus they consider the ultimate sustainable load.

Two basic schemes are used historically for the numerical simulation of buried pipes: (1) the habitual practice, using a special type of beam elements to model pipeline and the model of Winkler to represent the surrounding ground (materialized through springs with corresponding ground stiffness), and (2) the advanced method, using continuous finite elements for soil and pipe.

The first scheme demands considerably less calculation than the one that incorporates continuous solid elements. However, the representation of the ground by means of nonlinear springs lacks physical meaning and has serious limitations related to elastic–plastic behavior of the ground and interaction between diverse ground layers throughout the pipeline. The models that incorporate plasticity in a continuous scheme, explain the real three-dimensional stress state of the ground.

2. Developed model

A nonlinear finite elements pipe soil interaction model was developed. Software Abaqus was used for this purpose. A hybrid method (between the structural and the continuous one) was the goal of this investigation. This model includes the “pipe” element type (a special beam element for this intention) to model the pipe. The ground is simulated with continuous solid elements, whereas the interaction between both is modeled by a shared node. This system, internally known as “solid-beam model” works as a compound material and demonstrated good agreement with the real physical behavior of the pipeline in the field.

Another alternative, internally known as “solid-shell model” includes shell elements for the pipeline, solid elements for the ground and an algorithm of contact to model the interaction. But the computational time was not compatible with one of the most important conditions of the project: achieving a useful tool to contribute to decision making by the integrity team. For this reason this model was left at this stage of the project.

The developed model has the following characteristics:

The pipeline and the different layers of surrounding ground are generated, with data from ILI (in line inspection). This is one of the distinctive characteristics of this model that simulates real geometry with curves and slopes in the three coordinate planes, whereas most of other studies approach simple geometries.

The general dimensions and the material behaviors are:

Length: between the KP (Kilometric Progressive) 126 + 436 and 125 + 407 that includes both incidents (break and wrinkle).

Width: between both pipes the average distance is 5 m. The ground model wide is of 20 m coinciding with the right of way of the pipeline.
Depth: The average depth of this section is 20 m until solid rock. Diverse soil studies allow defining four layers with different mechanical characteristics shown in Table 1 and its distribution in Fig. 2. Mohr Coulomb model was used for soil.

Table 1
Materials characteristics soil layers.

Sensitivity analysis Imposed displacement		With gravity Max Stress (MPa)		Without gravity Max Stress (MPa)	
Longitudinal	Lateral	Pipeline “A”	Pipeline “B”	Pipeline “A”	Pipeline “B”
0	–	319,00	320,00	239,00	295,00
30	–	317,00	330,00	313,00	324,00
45	–	497,00	362,00	500,00	302,00
51	–	539,00	347,00	561,00	307,00

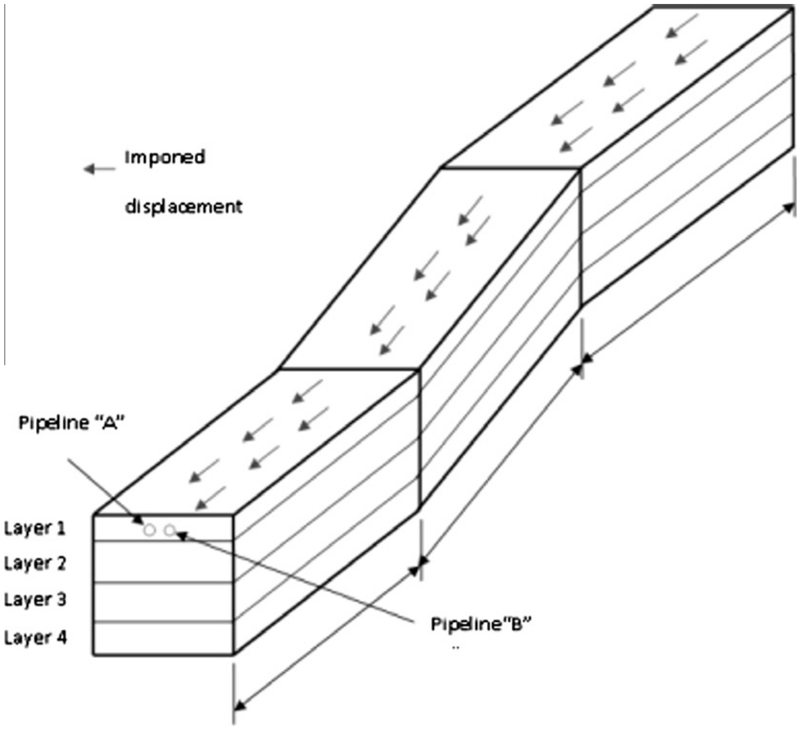

Fig. 2. Model scheme.

The drainage conditions of the ground are included in the analysis via the specific weight of the layer.

The full mesh of the ‘‘solid-beam’’ model incorporates near 50,000 elements whereas the full one of the ‘‘solid-shell’’ model approaches almost 500,000 elements. This is another reason for which the data processing time is several times greater.

The pipeline material is API 5L X70 with an elastic module of 2.1 e^{11} Pa and a Poisson coefficient of 0,3. The elastic–plastic behavior is defined from tensile testing according to Report INTEMA 070605 [5]:

Boundary conditions are imposed according to physical reality. Both longitudinal movements are fixed on the deepest soil layer. Vertical movements are fixed in the lower face of the deepest layer, where solid rock exists. Finally both lateral movements of the model are fixed to avoid a fictitious overturn (since in fact there is the rest of the ground that borders the sector under analysis). In some cases a careful hydrostatic distribution was applied to model the surrounding absent ground, but this requires a careful calibration that takes much time.

Internal pressure and dead loads of the pipe and the first soil layer are included in the model. Diverse ground movements observed by geologists are modeled as imposed movements.

3. Results of finite element models

Two sufficiently documented events were used to verify if the tool really reproduces the stress state in the pipe due to soil movements. The first event is known as ‘‘Incident KP 125 + 950’’. Geological specialists indicated that the rupture was caused mainly by two soil movements lateral to the pipe. These displacements are applied in the model. This situation is identified in the following as scene ‘‘A1-f’’. The purpose is to verify if the model reproduces what really happened in the field and, in such a case, to specify the magnitude of the soil motion that caused this failure in the ”A” pipeline. The displacements are applied in the 1st and 2nd soil layers as it is shown in Fig. 3. The maximum equivalent Von Mises stress levels in both pipelines are indicated in Table 2 for increasing magnitudes of displacement.

The failure criterion was defined considering the results of the full scale biaxial tension tests carried out at CFER, Canada. The region indicated corresponds to a deformation of 3%. In the region of plastic deformation of this API 5L X70 the slope of the stress–strain curve is very small, so a small change in strength or thickness would imply a great difference in the

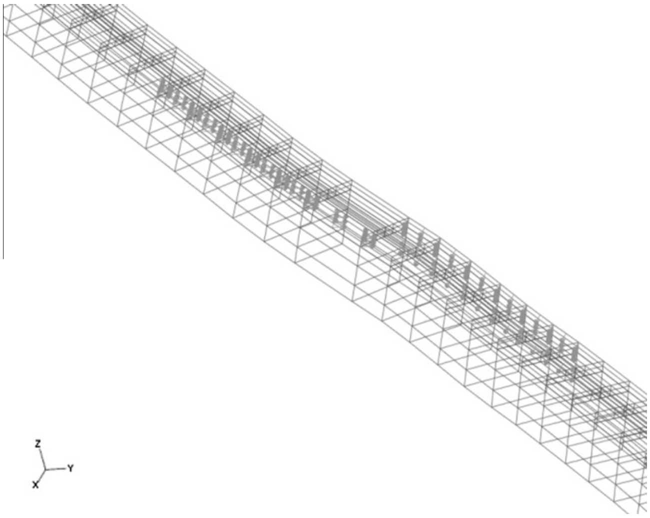

Fig. 3. Boundary conditions applied to reproduce Incident KP 125 + 950. Scene ‘‘A1-f’’.

Table 2
Results validation scene A1-f with increasing displacements until the rupture (Incident KP 125 + 950).

Max Stress (MPa)		Validation case
Pipeline ‘‘A’’	Pipeline ‘‘B’’	
3.29E+08	3.18E+08	A1-f-10 cm
3.06E+08	3.20E+08	A1-f-25 cm
3.28E+08	3.31E+08	A1-f- 50 cm
3.58E+08	3.48E+08	A1-f-75 cm
3.94E+08	3.69E+08	A1-f-100 cm
4.82E+08	4.21E+08	A1-f-150 cm
5.84E+08	4.37E+08	A1-f-177 cm

accumulated deformation for any load applied during the test. That is why it is possible to consider that a (biaxial) fracture stress of the order of 500–600 MPa is a proper failure criterion for this material.

According to Table 3, results of the load scene A1-f (Fig. 4) show that stress values become critical for accumulated displacements larger than 150 cm. It must be noticed that stresses keep moderated and comparable between both pipelines for small displacements. As the displacements increase, stresses sharply increase in the"A" pipeline. For displacements larger than 150 cm, the"A" pipeline takes stresses of the order of failure whereas the "B" pipeline remains in the elastic regime. This confirms that the model predicts the failure of the "A" pipe, and also justifies the integrity of the "B" pipeline. In addition, it quantifies the displacement, which ratifies and complements the conclusions of the geotechnical specialists.

The location of KP 126 and KP 125 + 950 are shown in Fig. 4, where the described displacements in Table 2 were applied. The displacement gradient in the soil is shown in the lower part of Fig. 4. Finally, Fig. 5 shows the agreement between the predicted critical point of the "A" pipeline with land records. It was demonstrated, as concluded the geotechnical specialists, that failure stress is obtained when applying soil displacements of 180 cm. Failure stress in the "A" pipeline is 584 MPa, whereas the "B" pipeline remains in elastic regime. This justifies the field behavior: the "A" pipeline is more susceptible to soil displacements than the larger "B" pipeline.

The second validation is reproducing a ground movement which produced the formation of a wrinkle in the "A" line identified in April 2007 in KP 125 + 487. The results of MFL (Magnetic Flow Leakage) tool allow to assure their existence (Fig. 6).

This is confirmed in the field geologic reports and the strain gauge readings previously installed by the operator. Next paragraphs are transcribed to understand the ground and pipeline kinematics.

Table 3
Results of the models to validate "the wrinkle".

Row	Max stress (MPa)		Displacement		Wrinkle localization	Gravity
	NGL pipeline	NG pipeline	Longitudinal	Lateral		Layer 1
1	239,00	295,00	–	–	No	No
2	319,00	320,00	–	–	No	Si
3	313,00	324,00	30	–	No	Si
4	500,00	302,00	45	–	Si	Si
5	624,00	316,00	60	–	Si	Si
6	647,00	334,00	69	–	Si	Si
7	337,00	324,00	30	20	No	Si
8	492,00	310,00	45	20	Si	Si
9	627,00	326,00	60	20	No	Si
10	644,00	247,00	71	10	Si	Si
11	317,00	330,00	30	–	Si	No
12	497,00	362,00	45	–	Si	No
13	539,00	347,00	51	–	Si	No

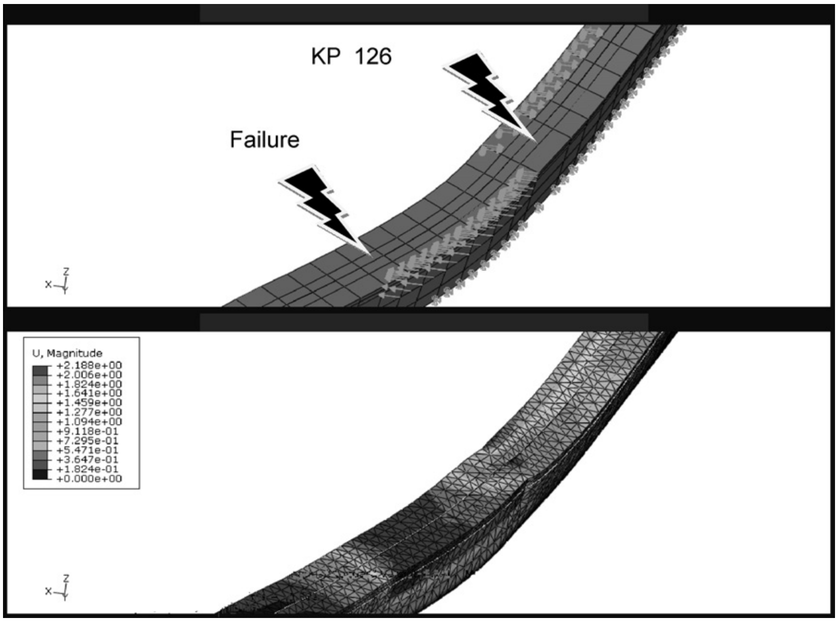

Fig. 4. KP 125 + 950, site of incident and boundary conditions. Underneath, displacement gradients.

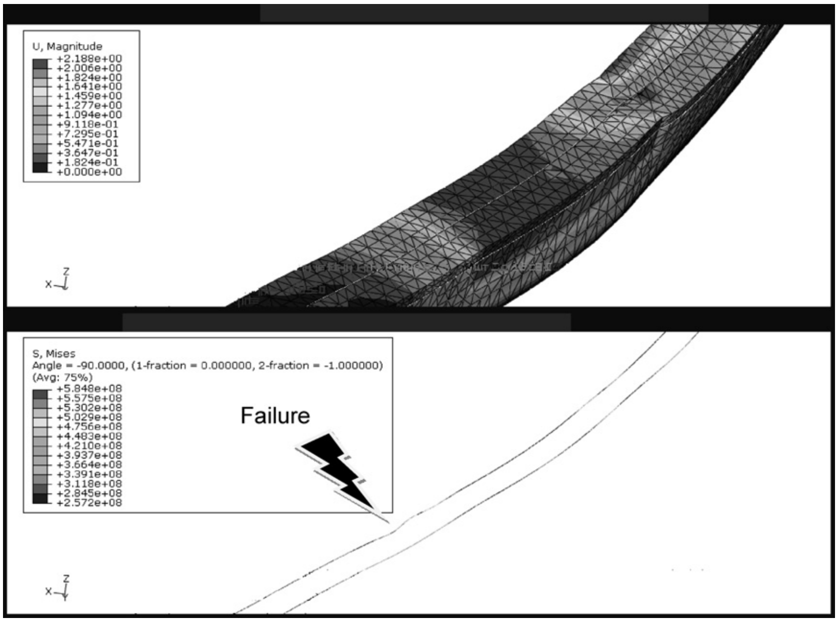

Fig. 5. Critical point location in "A" pipeline (584 MPa).

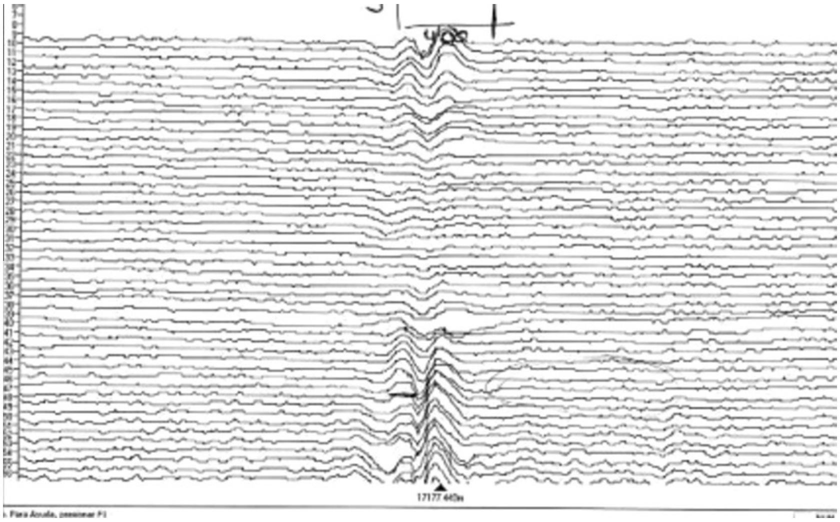

Fig. 6. Evidence MFL – May 2006.

From strain gauge report: "... For the monitoring points in KP125 + 418, KP125 + 555 and KP125 + 655 last readings are reflecting that pipeline was compressed between the KP125 + 418 and the KP125 + 555 at first moment (effect that produced the wrinkle in that zone) and when opening the zone was the pipe decompressed (increase in the 3 sensors)..."

Of the geologic report: "... It is considered that the ground push in very slow flow. This produce two effects throughout the ROW (main component of the movement in the direction in which the slope descends), like towards the left of this one (component imposed by the action of the gorges and the direction of the slidings and recognized. So earth flows are inferred, drawn in Fig. 7). This has generated important efforts on the pipe, as they are concentrated in the lowest part, in the crossing of the gorge, where pipeline finds a great restriction to the movement. In answer to these efforts and having the pipe a fixed point (the crossing of the gorge), pipeline rose and it was become deformed towards where it has weaker boundaries conditions, that is to say, in the concave curve downwards, in which finally the wrinkle formed...".

A section of pipeline was removed to reproduce the effect of Incident PK125 + 950 repair. Fig. 8 shows this detail. Fig. 9 shows the displacements imposed in the longitudinal axis of the pipelines and the small lateral component in the zone of the wrinkle. In this case the displacements are imposed on the upper face with increasing magnitudes according to the values

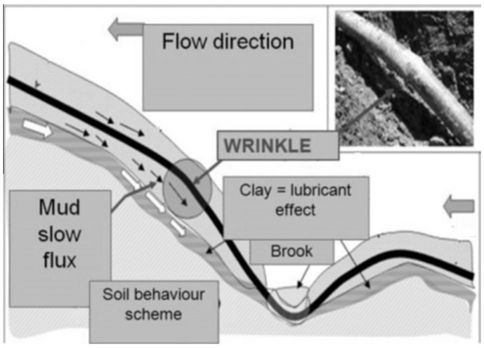

Fig. 7. Scheme of the pipeline and soil kinematics.

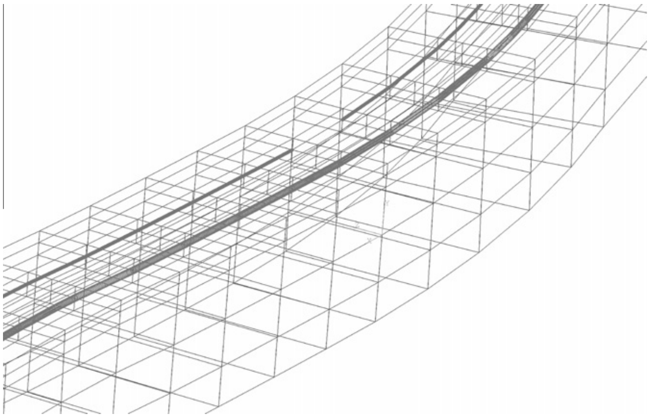

Fig. 8. "A" Pipeline cut during reparation of incident KP 125 + 950.

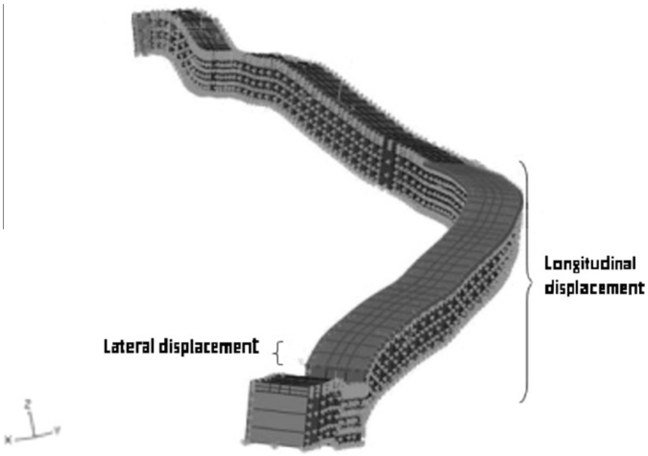

Fig. 9. Displacements imposed in the superior zone of ground layer 1.

reported in Table 3. The rest of the loads are the internal pressures of the pipelines (150 barg for "A" and 145 barg for "B") and the action of gravity in the pipelines and first soil layer.

Obtained results are shown in Table 3. The first column is row number. Columns 2nd and 3rd display the equivalent Von Mises stress (MPa) for the most stressed point of each pipeline. Columns 4th and 5th display the magnitude of the displacements imposed upon the upper face of soil layer (see Fig. 9). Column 6th shows if the maximum equivalent stress is located in the wrinkle; the last column indicates if gravity in the first layer of soil is considered.

Shades in the table show different load conditions. Rows 1 and 2 show results not considering imposed displacements. The only difference among them is that row 1 does not include weight of first ground layer. Rows 3–6 increase magnitude of longitudinal displacement. Rows 7–10 incorporate the lateral displacement in the wrinkle zone (see Fig. 9). Rows 11–13 present increased longitudinal displacements not taking gravity into account.

The equivalent stress failure criterion was defined as 500–600 MPa. Rows 3–6 show that for small displacements (30 cm) maximum stress change between ducts. It was also observed in KP 125 + 950.

For increasing longitudinal displacements (45, 60 and 69 cm) the most critical section appears in the "A" pipeline. The "A" pipeline reaches the critical stress for displacements greater than 45 cm while the "B" pipeline remains near 300 MPa. The maximum stress location appears in the wrinkle zone. Thus, the model works correctly and agrees with the geological reports.

Rows 7–10 also include lateral displacement. For small displacements (30 cm) stresses are similar in both pipelines. For increasing displacements, stresses show a similar trend as with the longitudinal loading cases. The behavior was not so frank (only 2 of the 4 cases locate the wrinkle in the correct place).

Rows 1 and 2 and 11–13 display additional results for model sensitivity analysis purposes, regarding gravity incorporation in the first layer of soil. This is not trivial. Gravity inclusion requires greater calculation time and a careful adjustment process. For this reason, if this load may be omitted in future models, it would save great analysis time. This is one of the most important features when using this model technique as a management tool.

Rows 1 and 2 show some randomness, especially at small stress levels. Increasing longitudinal displacements are applied in rows 10–13. In fact, this are the results to be compared with those of rows 3, 4 and 5. Results show that gravity inclusion does not affect predictions about the occurrence of the wrinkle.

4. Analysis of predicted behavior of critical sections of the pipeline

The following results correspond to the model of row 5 (60 cm longitudinal displacement – Table 3), since it most faithfully reproduces the observed in-field behavior. Fig. 10 shows the displacement vector distribution. As it was indicated by geologists, the "anchorage" in the river bottom is observed. The maximum displacement is about 90 cm.

Fig. 11 (only the pipelines are displayed) shows the highest stresses in the wrinkle zone. Fig. 12 shows the evolution of the longitudinal displacement component in each "Pipe Section" point (1, 3, 5, 7). From Fig. 12 it can be concluded that point SP7 is the bottom point and the SP3 is the pipeline section top point. This reproduces the compression at lowest end of the pipeline section and traction at the upper one, which is coherent with the kinematics of wrinkle formation.

If the Z662-03 code [4,6] is applied, it is possible to obtain compression strain acceptable limits. C 6.3.3.2 paragraph establishes that the local wrinkles can appear if the longitudinal compression strain achieve:

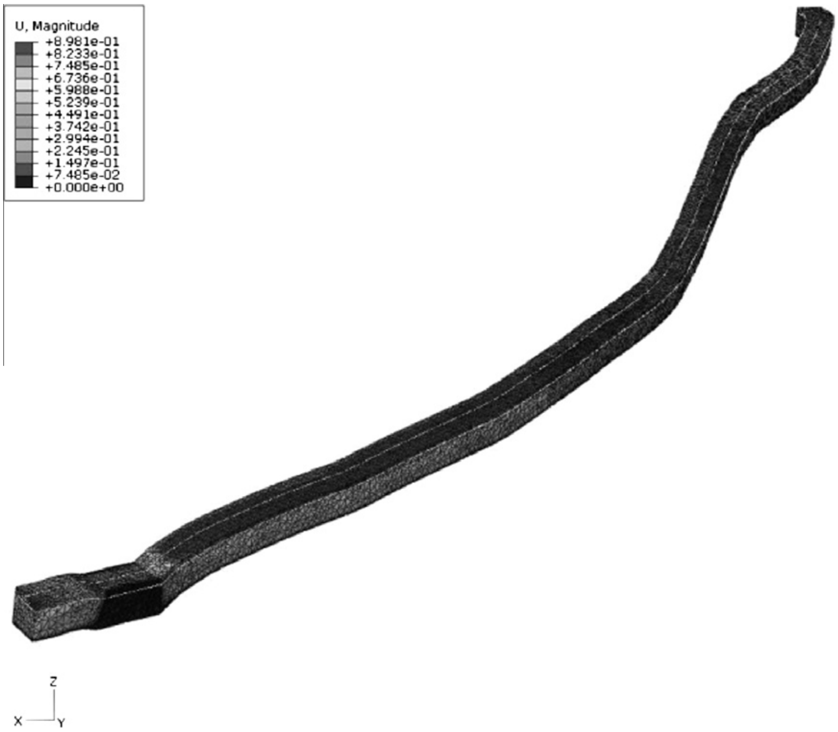

Fig. 10. Model displacements.

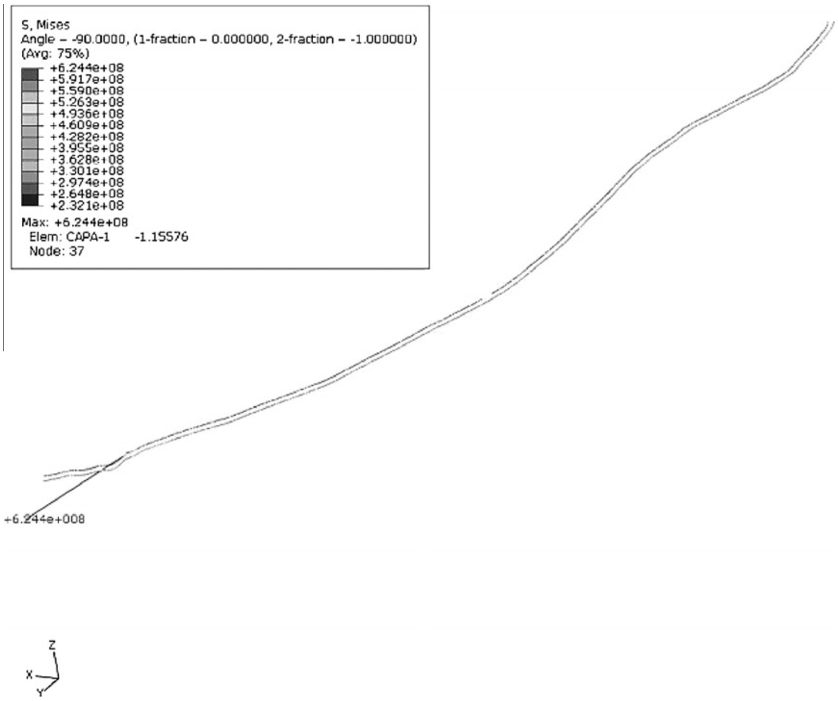

Fig. 11. Stress concentration in the "A" pipeline wrinkle zone.

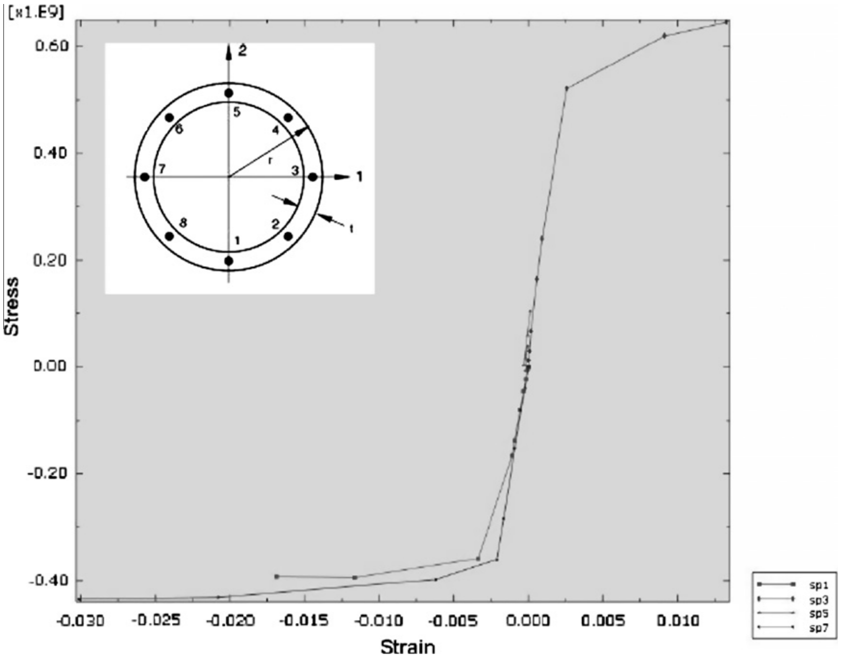

Fig. 12. Longitudinal stress S11 versus longitudinal stain E11 in each section point of the wrinkle.

$$\varepsilon_{cf} = \Phi_{ec} \times \varepsilon_c^{crit}$$

where ε_{cf} is the resistance factor and ε_c^{crit} is the compression strain capacity of the pipe wall. The Φ_{ec} value suggested by the code is 0,8 and the following formula allows to calculate ε_c^{crit}:

$$\varepsilon_c^{crit} = \frac{0.5 \times t}{d} - 0.0025 + 3000 \times \left[\frac{(pi - pe) \times d}{2 \times t \times Es}\right]^2$$

Table 4
Values according to Z662-03.

Internal pressure (barg)	Thicknesses of wall of the tube (mm)			
	5.56	6.35	7.14	9.53
1	0.0053 (−5300)	0.0064 (−6400)	0.0075 (−7500)	0.0109 (−10090)
100	0.0121 (−12100)	0.0117 (−11700)	0.0117 (−11700)	0.0132 (−13200)
150	0.0208 (−20800)	0.0183 (−18300)	0.0169 (−16900)	0.0162 (−16200)

0	Increment	0: Step Time=	0.0000
1	Increment	1: Step Time=	0.1000
2	Increment	2: Step Time=	0.2000
3	Increment	3: Step Time=	0.3500
4	Increment	4: Step Time=	0.5750
5	Increment	5: Step Time=	0.6594
6	Increment	6: Step Time=	0.7859
7	Increment	7: Step Time=	0.9125
8	Increment	8: Step Time=	1.0000

Fig. 13. Evolution of the load application proportionality factors.

where t is the thickness, d is pipeline external diameter, pi is internal pressure, pe is external pressure, E_s is the Young modulus.

Table 4 shows critical strain for a 356 mm (14″) diameter pipe. One Bar external pressure was consider, as when the pipe is out of service, since this is the worst condition for local buckling. The calculation is made for the different thicknesses of the pipeline. Results in parenthesis are expressed in microstrain.

For the thickness at the zone under study, the pipeline can support a 1% compressive strain before the wrinkle takes place, when it does not have internal pressure. Records by the operator indicate that in this zone pressure varies between 147 and 150 barg. The maximum compressive strain was also calculated for 100 barg, considered as the minimum possible pressure during operation, and for 150 barg.

The maximum soil displacement that would cause the critical deformation in agreement to Z662-03 was assessed using this information and results in Fig. 12 (the "Section Point" plot). In this case the "A" pipeline was at 150 barg. The critical strain – according to Table 4 – is 17000 microstrain for that pressure.

Interpolating linearly between the load application proportionality factors of the numerical model that appear in Fig. 13, it can be concluded 87% of the total applied displacement (60 cm), it produced a longitudinal strain of 17000 microstrain. Thus, the model allows quantifying the displacements observed by the geotechnical specialists. The model also shows good agreement with the limit values suggested by Z662-03.

5. Conclusions

A numerical model for integrity management of buried pipelines in unstable soils was developed. Two conceptually different models were presented. The "solid-shell" model uses solid elements for the soil and shell elements for the pipelines. The "solid-beam" approach maintains solid elements for the soil and beam elements for the pipelines. The solid-shell model presents greater versatility since it allows simulating different contact types between the soil and the pipeline and has an improved visualization capability, but calculation is excessively slow. The solid-beam approach requires short calculation (hours or minutes) due to its significantly smaller amount of elements. This approach resulted in a reliable and fast tool in the decision process of the integrity team.

The soil movements defined in-field as the main failure cause in the "A" pipeline were simulated. For small displacements, the stiffer "B" pipeline is more stressed than the slender "A" pipeline, but strains are far from critical for pipeline integrity (in the order of half the UTS). For larger displacements this tendency is reversed, the "A" pipeline is more stressed than the "B" one. The model for this specific geometric configuration predicts that a 70 cm longitudinal displacement produce failure of "A".

An equivalent stress in the pipeline between 500 and 600 MPa was adopted as the failure criterion. For maximum imposed soil slidings the model predicts 2–3% pipeline strains, similar to biaxial full scale tests carried out on the pipes at CFER. The numerical results predict the "A" pipe fracture for 178 cm of imposed displacement with the load scheme defined by the geotechnical study. The maximum stress (584 MPa) is for the “A” pipeline while, the “B” pipeline remains in elastic regime (437 MPa). These results agree with the geotechnical specialist’s conclusion that analyzed the events that lead to the failure.

For the second validation (wrinkle) it was demonstrated that the model not only predicts the failure of the “A” pipeline, but also justifies the integrity of the “B” pipeline. In addition it quantifies the displacement, which ratifies and complements the geotechnical specialists conclusions. It was demonstrated that when the longitudinal displacements grow in magnitude (45, 60 and 69 cm) the most critical section appears in the “A” pipeline. For displacements greater than 45 cm the “A” pipeline reaches the critical stress values (500–600 MPa) while the “B” pipeline remains in elastic stress values.

When the stress values are important and they approach the yield material stress, critical values are located in the wrinkle section. In a detailed cross-sectional analysis in the wrinkle zone, the model reproduces the compression on the pipeline lowest edge and traction on the upper one, which is coherent with the wrinkle mechanism kinematics. Thus, the model reproduces correctly the pipeline behavior and agrees with geotechnical reports.

Finally compatibility with Z662-03 standard of the Canadian Association for Gas and Petroleum Pipeline Systems was also demonstrated. In this way critical displacements can be defined to help to the integrity strategies decision. The model is operative for the section under study. Its present and future function is to collaborate in the decision process for pipelines operator integrity interventions.

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References

[1] Pipeline research council international. Inc., Extended model for pipe soil, interaction, PR-271-0184, 2003.
[2] Fredj A et al., A 3-Dimensional. Continuum ALE model for soil-pipe interaction. In: Proceedings of 7th international pipeline conference, ASME, IPC2008-64624.
[3] Mahdavi H. et al., Influence of geotechnical loads on local buckling behavior of buried pipelines. In: Proceedings of 7th international pipeline conference, ASME, IPC2008-64054.
[4] CSA Standard Z662, Oil and gas pipeline, System, June 2007.
[5] Report INTEMA 070605 Mar del Plata, Argentina, 2005.
[6] Report GIE 2801–06-07, Root cause analysis of failures 1 & 5, 14″ “A” pipeline, Camisea. GIE S.A., Mar del Plata, Argentina, 2007.