Pragmatic method based on a refined computational approach to take into account external loads on PE pipes long term behavior

RAMCES PE v1.05 software

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ABSTRACT – ID 590 : Over the past few years, the number of polyethylene buried distribution pipelines in the gas industry has increased because of the numerous advantages that material presents such as easier field operations and very good resistance to earthquakes (like stated in the Japanese Gas Association Seismic Guidelines).

However, predicting the behavior of PE pipes subjected to external loads is much more challenging than for steel pipes, for which elasticity can be assumed under most acceptance criteria. Some formulae from empirical field tests results are often used and can be overly conservative. For example, the IOWA formula using the Ring Stiffness Factor allows to take into account soil weight and surface loads over plastic pipes. Even if it is not refined, this formula gives some pragmatic results for the deflection of the pipe without taking explicitly into account viscosity. It is understood today that viscosity and plasticity can play a major role over the pipe long term behavior.

This paper presents a combination of this empiric approach with a realistic elasto-visco-plastic law for the behavior of the PE material. That 6-parameter law has been developed at GDF SUEZ – CRIGEN with the Solid Mechanics Laboratory of Ecole Polytechnique and has been validated with laboratory experiments. It is available for computational models and allows the prediction for long-term behavior of PE pipes.

The main interest of such an approach is to give a more reliable prediction of the PE pipes behavior than that derived from the IOWA formula wherein some empiric extrapolations are used. Indeed, we can update the numerical model with the 6-parameter law finite element approach and then perform an extensive automated parametric study for various resins, diameters, thicknesses, soil and surface loads (permanent or temporary), etc.

This approach has been coded in a software by CRIGEN: RAMCES PE. The gas operator is then provided with fast and more accurate answers when studying the behavior of its PE pipes subjected to external loads.

KEY WORDS: Polyethylene pipeline integrity; Overload; Modeling; Finite element modeling; ElastoViscoPlastic rheology.

1 INTRODUCTION: NEED FOR A TOOL

The gas distribution operator has to meet new challenges regarding the increasing urbanization phenomenon (for example, the “Grand Paris” project aimed at building new suburbs train lines around the metropolis). Safety has to be justified both for new and old pipelines in an ever changing environment.

A pipeline laid in nominal conditions can be, for example, submitted to an overload due to a larger depth when an embankment is built. The same pipeline can be submitted to heavy rolling loads (new highway, tramway, civil engineering vehicles, etc.).

Temporary structures such as tower cranes, mobile cranes, etc. can be installed over the buried network. Vibrating civil engineering vehicles can produce vibrations around the buried pipelines. Therefore, the Distributor has to justify to the Regulator, that all pipelines are safely operated regarding these external loads.

Until recently, the operator didn’t have any tool to justify quickly such solicitations. Now, the RAMCES PE v1.05 software allow the operator to perform easy-to-use computations compatible with the delays generally observed in civil engineering works near buried distribution pipelines.

This application has been developed by the Center of Research and New Innovation for Gas and New Energies (CRIGEN).

This paper is aimed at presenting the first module of this software: Overload Module.

The first part is an introduction to the context. The second part presents the physical model which is used in the software. The third part presents the numerical approach based on mixing simplified models (IOWA and PPI) with the realistic long-term behavior law for the HDPE used in gas pipelines (Elasto-Visco Plastic law developed by CRIGEN). The fourth part gives insights on the experimental and numerical validation of the model.

The fifth part shows the software interface.

This papers gives eventually a conclusion and some perspectives of development for the software, meeting new challenges for the gas distribution operators: Vibrations due to civil engineering vehicles and safety distances regarding blasting detonations.

2 HYPOTHESIS

2.1 *Two external loads*

The following assumption is made for the considered pipeline:

- Existing or project pipeline made of HDPE;
- Straight pipeline without singularity (i.e. bend, tee, etc.) and without defect;
- Soil is made of earth, is homogeneous and has no hard point;
- Temperature range varies from 10 to 20°C;
- Loads are
  - Internal pressure;
  - Soil weight;
  - Overload due to vehicles, embankment, etc.

The behavior of the pipeline under these assumptions is then considered in order to evaluate if the loads are damageable to the pipeline.

2.2 *Complex interaction between different physical phenomena*

The different loading presented above lead to consider that the stresses and deformations are in the cross-section plane of the pipe. The HDPE pipe ring model is then used and the following loads are considered :

- Vertical loading *p* (soil weight) or surface loading, see Figure 1. The Marston theory (see Ref. [1]-[3]) is used: the pipe is leaned in the ditch on a 2β angle area and the loading *p* is applied to all the above ring surface.
- Soil reaction (loading *q*).
- Soil lateral abutment exerted on the pipe contrary to the pipe deformation (horizontal pressure).
- Pipe internal pressure which induces a circumferential pressure (which "rounds back" the ring).

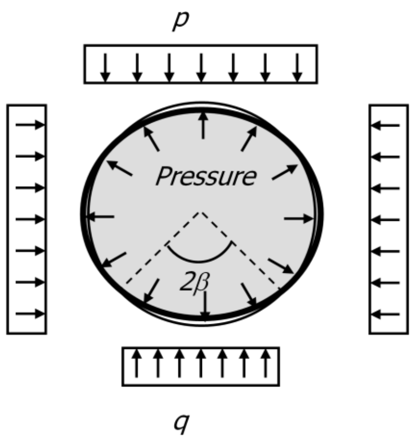


Figure 1. Ring submitted to a vertical crushing, horizontally restrained thank to the abutment effect and "rounded-back" thank to the internal pressure.

2.3 *Time scale*

Time scales are different regarding the different loadings. Soil weight is a long term loading whereas a vehicle will not be stationed for the same period, it is thus a short term loading.

The objective of RAMCES PE is to model the HDPE ring submitted to these different components and evaluate if the pipeline stays in a safe domain.

Indeed, as the material has elastic, viscous and plastic properties, its behavior strongly depends on the duration of the loading.

Both short term and long term are taken into account in the modeling.

3 PRAGMATIC APPROACH BASED ON INTERNATIONAL PRACTICE VALIDATED BY FINITE ELEMENT MODELING AND TESTS

3.1 *Simple soil mechanics*

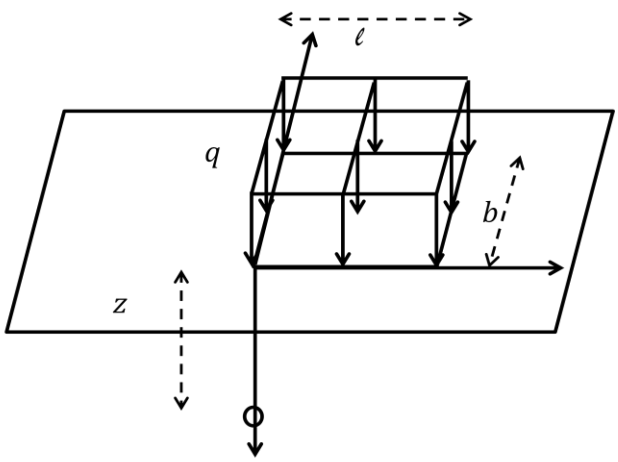


Figure 2. Uniform loading on a rectangle.

The first step consists in modeling the force due to the soil weight and surface loading on the ring.

Soil weight is considered to be a vertical pressure, given at the upper limit of the pipe,

$$P_{\text{soil}} = \rho_{\text{soil}} g H \quad , \qquad (1)$$

where ρ_{soil} is the soil density (kg.m^{-3}), g is the gravity constant and H is the soil depth to the pipe upper limit (in m).

A surface loading is modeled by a uniform distributed mass on a rectangle (see Figure 2). The Boussinesq theory (see Ref.[2]) is used to model the diffusion of the rectangular (l x b) loading q into the ground. The length is l, the width is b, and the solution at a depth z is written,

$$P_{\text{loading}} = \left(\frac{q}{2\pi}\right)\left(\tan^{-1}\frac{lb}{zR_3} + \frac{lbz}{R_3}\left(\frac{1}{R_1^2} + \frac{1}{R_2^2}\right)\right) \qquad (2)$$

with:

- $\mathrm{R}_1 = \sqrt{(\mathrm{l}^2 + \mathrm{z}^2)}$;
- $\mathrm{R}_2 = \sqrt{(\mathrm{b}^2 + \mathrm{z}^2)}$;
- $\mathrm{R}_3 = \sqrt{(\mathrm{l}^2 + \mathrm{b}^2 + \mathrm{z}^2)}$;
- $\tan^{-1}(\tan x) = \mathrm{x}$, for all $x \neq \pi/2\ [\pi]$.

3.2 *IOWA formula: pragmatic but without plasticity and viscosity*

Next step consists to model the response of the HDPE ring. North American operators often use the IOWA formula (see Ref. [4]). This analytic-empirical method uses an apparent elastic modulus inherent to the material. This formula takes into account the long term and the short term loading thanks to the empirical coefficient L_{DL} and thus estimates the maximal ring deflection $\frac{\Delta X}{D_M}$:

$$\frac{\Delta X}{D_M} = \frac{K_{\text{BED}}}{144}\left(\frac{L_{DL}\,P_{\text{soil}} + P_{\text{loading}}}{\frac{2}{3}E\left(\frac{1}{DR-1}\right)^3 + 0.061\,F_S\,E'}\right) \qquad (3)$$

where:

- $D_M = D_{\text{ext}} - t$ is the pipe mean diameter, where D_{ext} is the external ratio and t is the thickness of the pipe (in inches, 100 in = 2.54 m),
- ΔX is the horizontal deflection (in inches),
- $\mathrm{K_{BED}}$ is the bedding effect coefficient (=0.1 in general),
- L_{DL} is an empirical coefficient for ‘deflection lag’ and is taken equal to 1.25,
- P_{soil} is the soil pressure in psf (pound per square foot, 10^5 psf ≈ 4.8 MPa),
- P_{loading} is the vehicle loading in psf,
- E is the HDPE apparent modulus in lb.in^{-2} or psi (10^5 lb.in^{-2} ≈ 689.5 MPa),
- E' is the soil reaction modulus in psi,
- $\mathrm{F_S}$ is the ‘soil support’ factor,
- DR = D_{ext}/t is the ‘dimension ratio’.

This formula is very easy to use but as a counter-part, there are two main limitations :

- The apparent modulus E is inspired from the elasticity theory encountered for steel pipelines. It is however well known that the HDPE is a visco-elasto-plastic material. Thus if one does not take correctly into account the plasticity and viscosity, non conservative results may appear.
- The same denominator in Eq. (3) makes hard to uncouple the HDPE behavior on two different time-scales (the IOWA formula inserts an artificial ‘lag factor’ before the soil loading).

For these reasons, the IOWA formula was modified in order to model in a more realistic way, the HDPE behavior.

3.3 *Modified IOWA formula*

The IOWA formula (see Eq. (3)) was modified as written below:

- there is no apparent modulus E, but rather a ring stiffness constant (*RSC*) (see Ref. [4]), which characterizes the ring diametrical stiffness and which is computed numerically,
- cut the loading in two separated terms, one for the soil loading and one for the vehicles loading.

The modified formula is written below as,

$$\frac{\Delta \mathrm{X}}{\mathrm{D_M}} = \frac{\mathrm{K_{BED}}}{144}\left(\frac{\mathrm{P_{loading}}}{1.24\ \frac{\mathrm{RSC_{fast}}}{\mathrm{D_M}} + 0.061\ \mathrm{F_S}\ \mathrm{E}'} + \frac{\mathrm{P_{soil}}}{1.24\ \frac{\mathrm{RSC_{slow}}}{\mathrm{D_M}} + 0.061\ \mathrm{F_S}\ \mathrm{E}'}\right) \qquad (4)$$

where the *RSC* coefficients represent the capacity of an HDPE ring to oppose its ovalization and are computed with the reaction force (in N.m^{-1}) of the ring when the deflection reaches 5 % (deflection in % = 100 $\Delta X / D_M$). In the approach described in this paper, two different coefficients are computed with a finite element analysis (Abaqus v6.12®):

- RSC_{slow} is computed with a deformation velocity so as the strain goes from 0 to 5 % in 40 years,
- RSC_{fast} is computed with a deformation velocity so as the strain goes from 0 to 5 % in 1 s.

The computations are performed with a realistic behavior law for the HDPE rings which is described below. This is step (I) in Table 4.

3.4 Realistic rheology for HDPE rings in the computation

The Figure 3 explains the ElastoViscoPlastic (EVP) rheological model used for HDPE pipelines modeled with a finite element approach (Abaqus V6.12®).

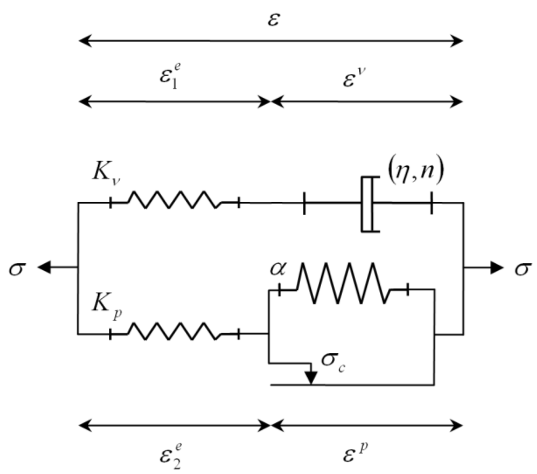


Figure 3. ElastoViscoPlastic (EVP) rheological model developed for HDPE (from Ref. [5]-[6]).

In Figure 3:

- K_p (MPa) is the elastic modulus of the plastic branch,
- K_v (MPa) is the elastic modulus of the viscous branch,
- σ_c (MPa) is the plastic threshold,
- α (MPa) is the linear kinematic hardening,
- η (MPa.s^n) is the viscosity coefficient,
- n (-) is the viscosity exponent,
- σ (MPa) and ε are the total stress and strain of the model,
- ε_1^e and ε_2^e are respectively the elastic strains for the viscous and respectively the plastic branch,
- ε^v and ε^p are respectively the viscous strain and respectively the plastic strain.

The governing equations of this model are described in Ref. [5] and are not reminded here for the sake of brevity.

The final results of the computation (described below) consists in a database:

- for 3 kinds of HDPE (PE50, PE63 and PE80),
- both the corresponding RSC_{slow} and RSC_{fast}.

Nota Bene: it is considered that the initial ovalization is zero, which in reality is not the case because the ovalization percentage can reach up to 6% when unrolling the pipeline in the ditch. Nonetheless, the approach is conservative.

3.5 Deflection threshold

Ring deflection has to be limited for two reasons:

- **Geometrical stability**, because the overweight can lead to flatten the ring which can then collapse due to the inflection in the curvature;
- **Bending deformation**, additional deformation can lead to traction or compression in the pipe wall (depending of the clock position).

The thresholds are taken accordingly to international guidelines and state of the art (see Ref. [4], [7]-[9]), they are gathered in Table 1.

Table 1. Deflection threshold in function of the pipe DR.

Dimension ratio (D_{ext}/t)	**Deflection threshold (%)**
11	5 %
7.4	3 %

Nota Bene: the thresholds presented above cannot be compared with the deflection thresholds used when the pipe is rolled up because in this case, the pipe is not loaded with pressure and is submitted to imposed displacements.

3.6 Factor K_{BED}

The bedding factors are taken from manufacturers catalogues (see Figure 4 for the geometry and Table 2 for the values).

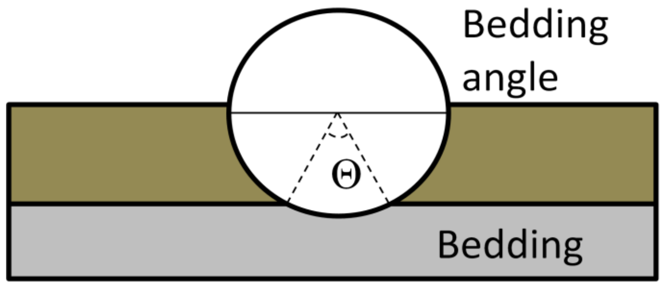


Figure 4. Bedding angle geometry.

When the pipe is laid down in the ditch, the vertical reaction is amplified when the angular sector is small (see Figure 4). This phenomenon is traduced in IOWA formula (see Eq. (3)) by the KBED factor which is empirically known by manufacturers (see Table 2).

Table 2. Values of K_{BED}.

Bedding angle (Degrees)	K_{BED}
0	0.110
30	0.108
45	0.105
60	0.102
90	0.096
120	0.090
180	0.083

3.7 Soil stiffness: E'

The soil is opposed to the ring ovalization. Thus the stiffer the soil is (i.e. *E'* value is high), the less the ovalization appears. This parameter can be of great importance for big diameters but for gas distribution pipes it is very often less predominant than the RSC coefficients. For this reason, it is decided in the RAMCES PE software to take a conservative "soft" E' = 551 psi (≈ 3.8 MPa). In practice, soils are very often stiffer.

The different values of soil moduli are given in Table 3.

Table 3. Values of *E'* (from PPI, see Ref. [4]).

Type of Soil	Depth of Cover, ft	E' for Standard AASHTO Relative Compaction, lb/in^2			
		85%	90%	95%	100%
Fine-grained soils with less than 25% sand content (CL, ML, CL-ML)	0-5	500	700	1000	1500
	5-10	600	1000	1400	2000
	10-15	700	1200	1600	2300
	15-20	800	1300	1800	2600
Coarse-grained soils with fines (SM, SC)	0-5	600	1000	1200	1900
	5-10	900	1400	1800	2700
	10-15	1000	1500	2100	3200
	15-20	1100	1600	2400	3700
Coarse-grained soils with little or no fines (SP, SW, GP, GW)	0-5	700	1000	1600	2500
	5-10	1000	1500	2200	3300
	10-15	1050	1600	2400	3600
	15-20	1100	1700	2500	3800

3.8 Other variables

The soil density is fixed conservatively at $\rho = 2000$ kg.m^{-3}.

The F_s coefficient (in Eq. (3)) is aimed at correcting the embankment soil stiffness compared to natural soil stiffness which has to be taken into account in case, for example, the ditch is very thin. In that case, the natural soil stiffness is preponderant on the embankment soil stiffness. For a softer natural soil than embankment soil, $F_s < 1$ and for a stiffer natural soil, $F_s > 1$.

In practice in the RAMCES PE software, its value has been fixed to 1 because, on the one hand, it is difficult to evaluate it precisely regarding the real ditch conditions and on the other hand, it's not a preponderant factor with the previously fixed value for *E'*.

The deflection are then computed with the modified IOWA formula (part of step (II) in Table 4).

4 EXPERIMENTAL TESTS AND NUMERICAL COMPUTATION

4.1 Laboratory tests

Lab tests were performed to empirically validate the computed *RSC* values. A piece of HDPE pipe was crushed between two stiff steel plates with a traction/compression device.

The inferior plate was fixed and the superior plate was able to go down with a controlled velocity. The pipe was then ovalized with controlled loading velocity and controlled-deflection.

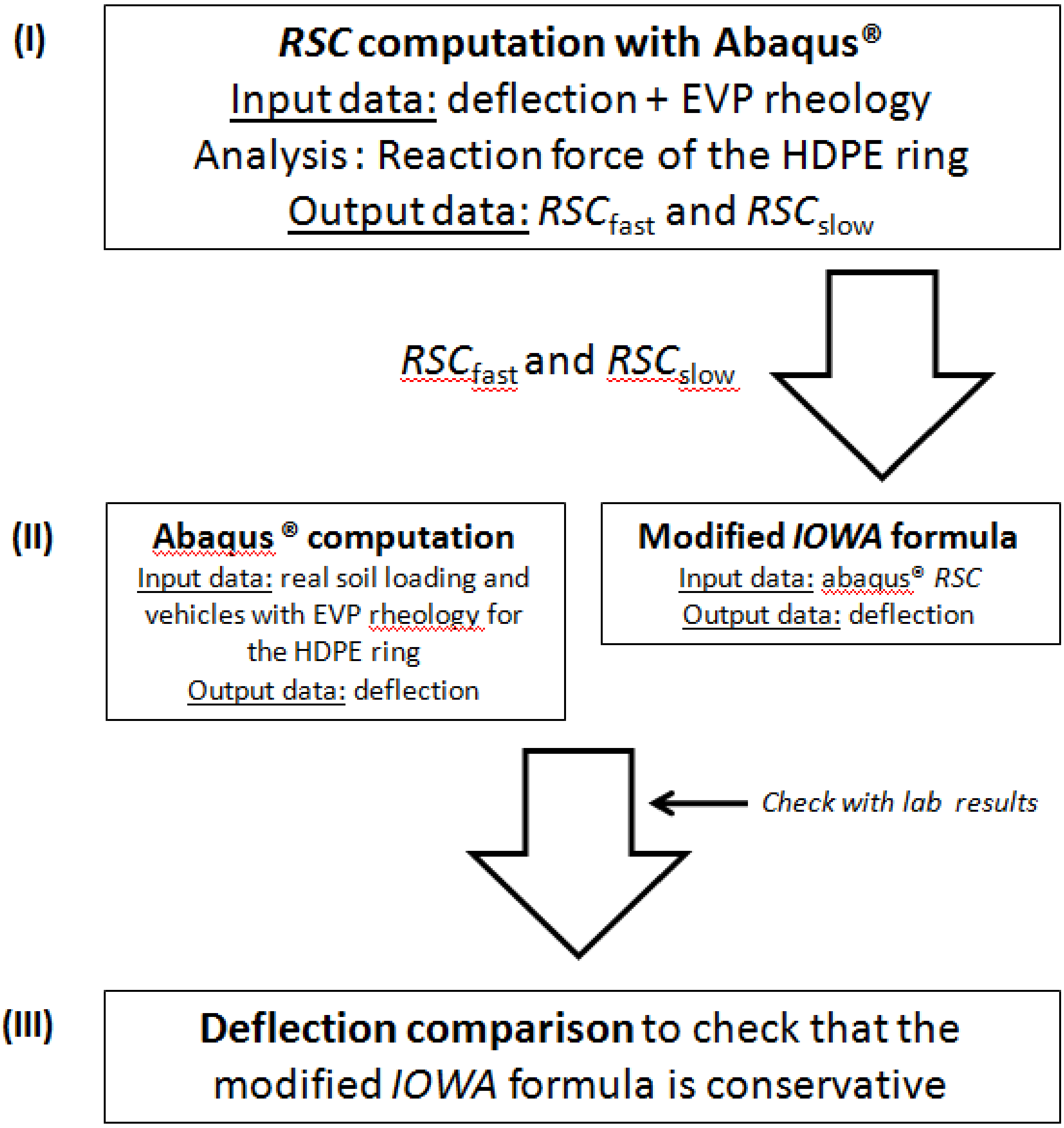
Each test provides an "Applied Force" versus "Displacement" curve which leads to the intrinsic stiffness of the HDPE ring. The values can then be compared to the computations.

The tests show that the empirical RSC values are conservative with a safety factor of about 1.5 for the fast loading (the computed HDPE pipe is deformed more easily than the real one).

It appears that the slower the loading, the more predictive the model is. This remark can be correlated with the equations of the model presented in Figure 3 because, this model is used for long-term predictions.

Even if the validation is not so straightforward (loading time of 40 years), the numerical RSC values for slow loading are quite close to the tests values.

Table 4. Methodology of computation in order to validate the modified IOWA formula.



4.2 Abaqus® computations

In order to validate the approach, two hundred computations were performed and compared to the modified IOWA formula results.

Half a ring was modeled in 2D with the finite element method (the model is symmetrical). HDPE behavior laws were the same as previously used (PE50, PE63 and PE80). The loading were discretized along the border of the ring thanks to soil mechanics hypothesis (see Marston theory, Ref. [1]). The FE model computes the ring deformation and thus the deflection.

The FE-computed deflection is then compared to the modified IOWA formula-computed (step (II) in Table 4) and the results are presented in .

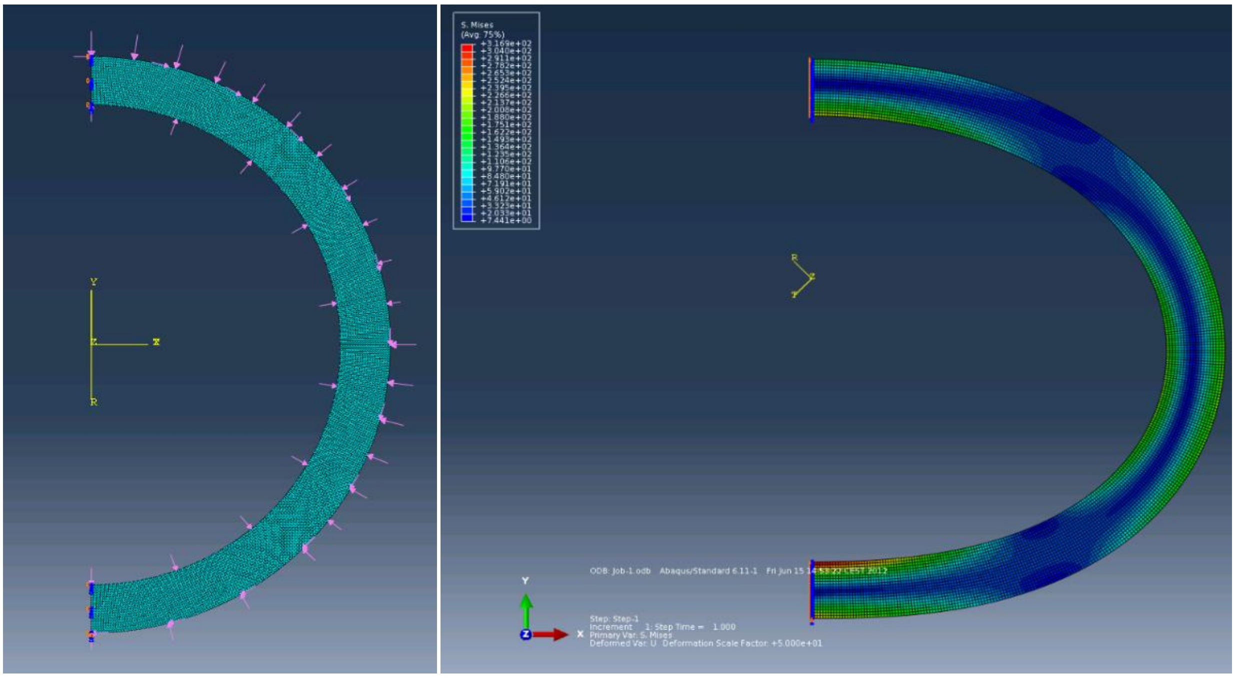


Figure 5. Complex EVP FE-model performed with Abaqus®.

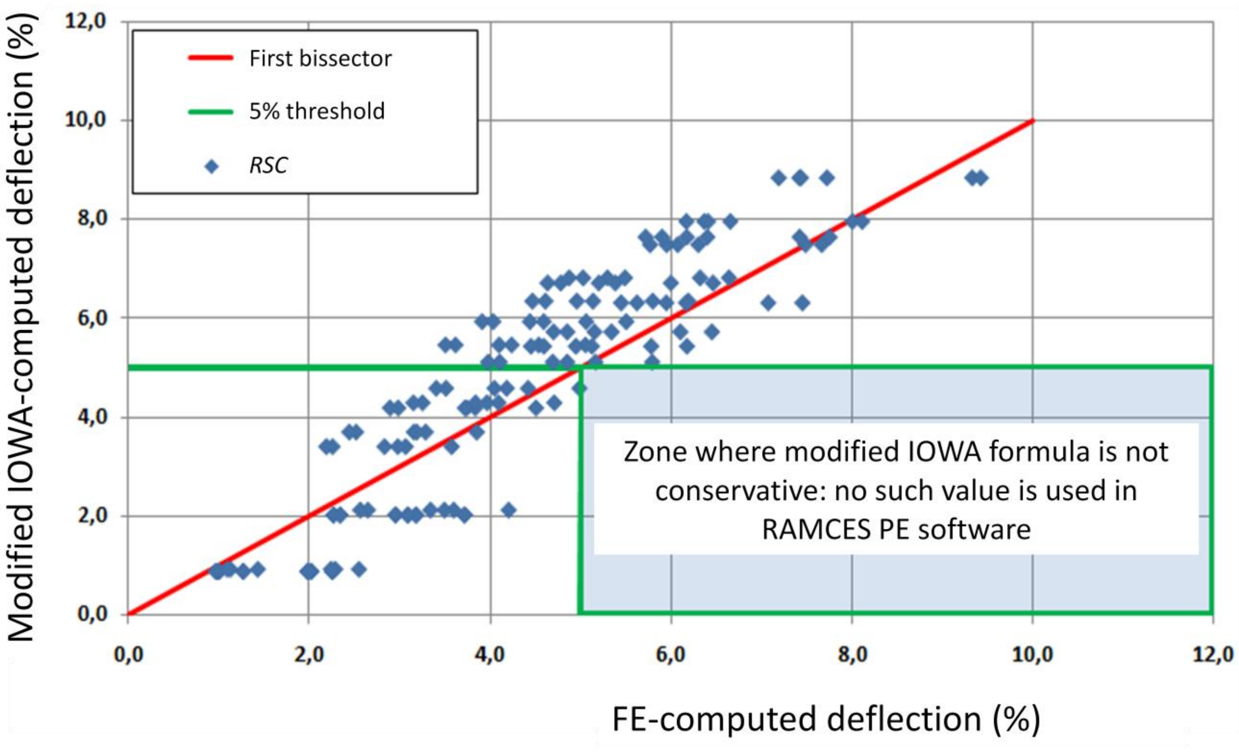


Figure 6. Comparison between FE-computed and modified IOWA-computed deflection (step (III) in Table 4).

The comparison in Figure 6 shows that the analytico-empirical results obtained with the modified IOWA formula are coherent with the 6 parameters EVP-FE simulation: all the dots are close to the first bisector and the model is conservative.

This approach is moreover easy to implement in a software and it was performed in the version 1.05 of RAMCES PE presented below.

5 RAMCES PE SOFTWARE V1.05

This software has been developed at CRIGEN. In this paper, the overload module is presented.

The interface is presented below in Figure 7.

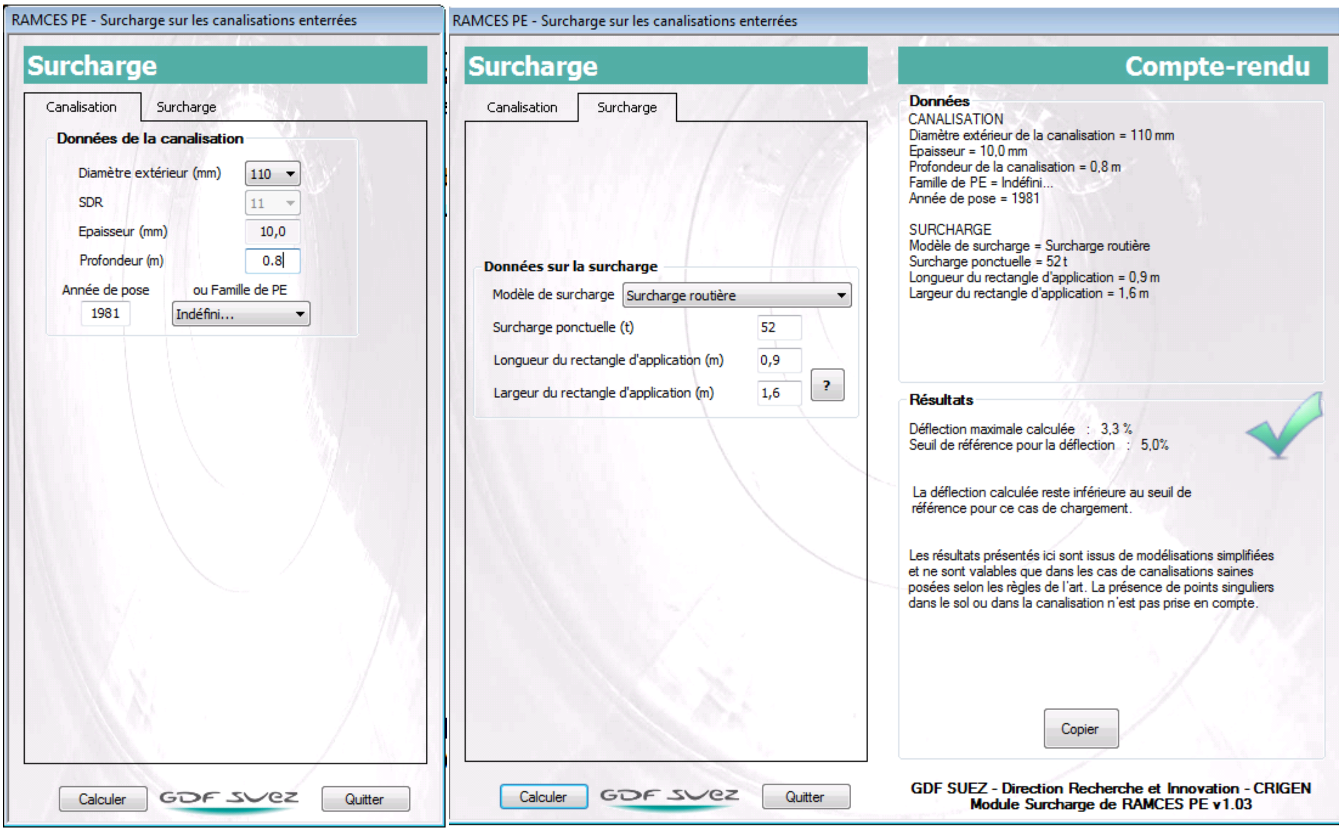


Figure 7. Easy-to-use interface for the module overload of RAMCES PE software v1.05.

CONCLUSION

In this paper, a simple and pragmatic approach to take into account external loads on PE pipes long term behavior has been presented.

This method combines both a modified analytic-empirical formula and complex elastoviscoplastic FE-computations.

Tests and computations were performed to update the model which has then been implemented in an easy-to-use software for the gas distribution operator.

This software is evolving and will be able to predict safety distances between buried HDPE distribution pipelines and various vibration sources like blasting, compaction or heavy jackhammers.

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