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SEISMIC ANCHORS MOTION FOR PIPING SYSTEMS IN BURIED GALLERIES – STATIONARY WAVES METHOD

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ABSTRACT

Piping systems installed in buried galleries are subjected during an earthquake to both inertial effects and anchors motion effects. Inertial effects are generated by accelerations, and are usually considered in engineering practices by ground or floor response spectra, or acceleration time histories.

Anchors motion effects are generated by the propagation of seismic waves in the soil, around the buried structure housing the piping system. The consideration of this phenomenon in engineering practices is well described for buried piping systems, pipelines or buried structures.

Civil standards and codes provide the maximum axial strain and curvature generated in buried structures and displacements at movement joints, given the seismic motion parameters, and apparent wave velocity, for compressional, shear and Rayleigh waves.

However, the displacement communicated by the buried structures to the system supports requires further assumptions.

This paper aims to present the different options available for a mechanical engineer to introduce the seismic anchor motions in piping systems analyses, and compare them in terms of consistency with buried structures response, complexity and degree of margin introduced.

The main issue seems to be the definition of a load case in the piping analysis which can as far as possible:

- respect the rules and hypotheses and physics applicable to galleries or buried structures housing this piping system under earthquake;
- include the complex geometry of industrial piping systems such supports location, functions and orientations;
- reflect the position of the galleries sections crossed which may be complex, and takes into account the location of building interfaces;
- remain practical and easy to introduce in current engineering practices, in industrial softwares.

This paper also presents developments about an industrial approach called here by the authors “Stationary Waves Methods” usable in piping analyses, requiring a reasonable engineering efforts compared to current common practices, and including all the criteria presented above.

This method allows an interesting optimization of forces and moments communicated to the pipe and its supports at galleries movement joints and galleries/buildings interfaces.

HISTORICAL METHOD

Historically, the evaluation of Seismic Anchor Movements (SAM) applied to in-galleries piping systems were based on civil engineering methods used to calculate galleries motion at movement joints location.

One difficulty is that those methods describe the movements of buried structures themselves, but not directly the equipment anchors motion inside those structures. Therefore, the link between buried structures movements and SAM applied to equipments must be detailed.

Seismic Waves Modelling for buried structures movement joint displacement evaluation

During an earthquake, it can be assumed that soil particles are moved by several longitudinal and transverse waves described by the following formula:

$$U = D \sin\left(\omega t - \frac{\omega x}{c}\right) \quad (1)$$

Where U is the absolute displacement for a given wave, D the maximal particles movement generated for this wave, c is the apparent wave velocity, ω the wave pulsation , t the time and x the position of the particle towards wave propagation direction.

Particles speed V and acceleration A are given by derivation, detailed in Equations 2 & 3:

$$V = \omega D \cos\left(\omega t - \frac{\omega x}{c}\right) \quad (2)$$

$$A = -\omega^2 D \sin\left(\omega t - \frac{\omega x}{c}\right) \quad (3)$$

Maximum earthquake displacement D_{max}, velocity V_{max} and acceleration A_{max} should be linked to the idealized waves parameter in Equation 4:

$$\begin{cases} D_{max} = D \\ V_{max} = \omega D \\ A_{max} = \omega^2 D \end{cases} \quad (4)$$

However, due to the simplifications considered for the seismic wave modelling, D_{max}, V_{max} and A_{max} cannot be identified with a single (D, ω) couple of values. To address this difficulty, two waves can therefore be considered:

- A "Low Frequency" wave (LF) considering D_{max} and V_{max} and assuming

$$D = D_{max} \text{ and } V = \omega D = V_{max}$$

  and deducing

$$\omega = \frac{V_{max}}{D_{max}} \text{ and } A = \frac{V_{max}^2}{D_{max}}$$

- A "Medium Frequency" wave (MF) considering V_{max} and A_{max} and assuming

$$\begin{cases} A = A_{max} = \omega^2 D \\ \omega = \dfrac{A_{max}}{V_{max}} \\ A_{max} = \omega^2 D \end{cases}$$

$$V = V_{max} \text{ and } A = \omega V_{max}$$

  And deducing

$$\omega = \frac{A_{max}}{V_{max}} \text{ and } D = \frac{V_{max}^2}{A_{max}}$$

Those two waves can be considered to respect the parameters of the seismic movement D_{max}, V_{max} and A_{max}, considered to define the buried structures movements, and then, the SAM of in-galleries piping. Seismic calculations of those piping networks can rely on those two movements.

Soil-Structure Interaction

When assessing the longitudinal response of buried galleries (and movement joints behaviour), it is commonly considered that SSI effects can be neglected, i.e. the galleries motion is identical to soil particles. However, it is important to identify the risk that the galleries sections could slide in the soil, that may increase the displacements at sections interfaces.

Considering that phenomenon, the maximal movement joint displacement can be estimated as the differential displacement of the two farthest extremities of two adjacent galleries sections, as follows in Equation 5:

$$\begin{aligned} &\delta = \pm 2D \sin\left(\frac{\omega l}{2c}\right) && \text{if } l \leq \frac{\pi c}{\omega} \\ &\delta = \pm 2D && \text{if } l > \frac{\pi c}{\omega} \end{aligned} \qquad (5)$$

Application for Piping Calculations

The equation 5 is generally used to define the SAM imposed to piping networks between galleries sections, considering that galleries can slide. Those values are then modelled using piping software (such as Pipestress from DST Computer Services S.A., Geneva, Switzerland) considering groups of piping supports corresponding to gallery sections. This application for piping is very similar to the one used for massive buildings motion, such as nuclear islands.

Figure 1 illustrates this “historical method” of design for piping networks in buried galleries:

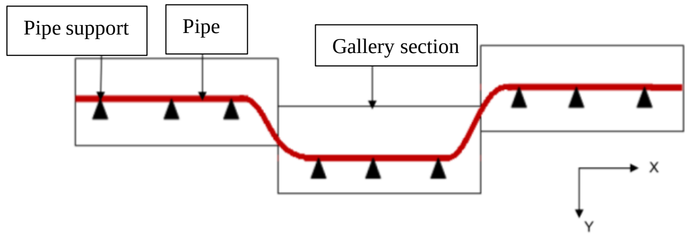

Figure 1: Illustration of the application of SAM on pipes in buried galleries – “Historical method”

Note: Z axis is note drawn, and is the upward vertical axis.

By considering LF and MF waves, figure 2 bellow illustrates how the SAM could be applied, and figure 3 shows distortion of a straight pipe for LF and MF waves.

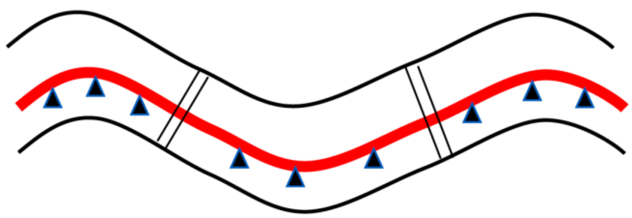

Figure 2: Illustration of the application of SAM following a sine wave – “Stationary waves method”

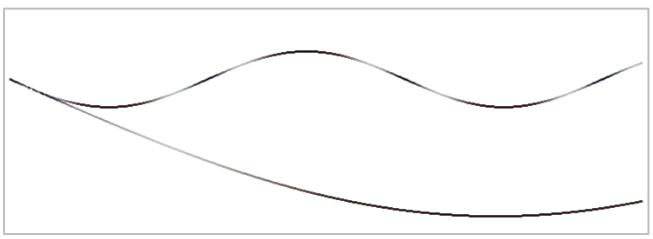

Figure 3: Amplified distortion of a piping in buried gallery for LF and MF wave

The use of this historical method in seismic piping studies implies:

- high curvature of piping near gallery movement joints, leading to high and maximized stress in pipes, and high reactions at supports;
- complex application of SAM, depending on the location and the functions of piping supports;
- different methods for Civil Works and housed mechanical equipment calculations.

Those elements have led EDF CNEPE to investigate the possibilities to perform optimizations in the seismic analysis of those systems, and to propose an evolution of the “Historical method” for studying piping networks anchored in buried galleries in order to apply SAM considering a method consistent with the one used to study the housing buried galleries.

"STATIONARY WAVES METHOD" APPLIED FOR PIPING

Description

This method aims to define SAM applied to galleries housed piping systems for LF and MF seismic waves. Figure 4 below is an example of situations to be studied.

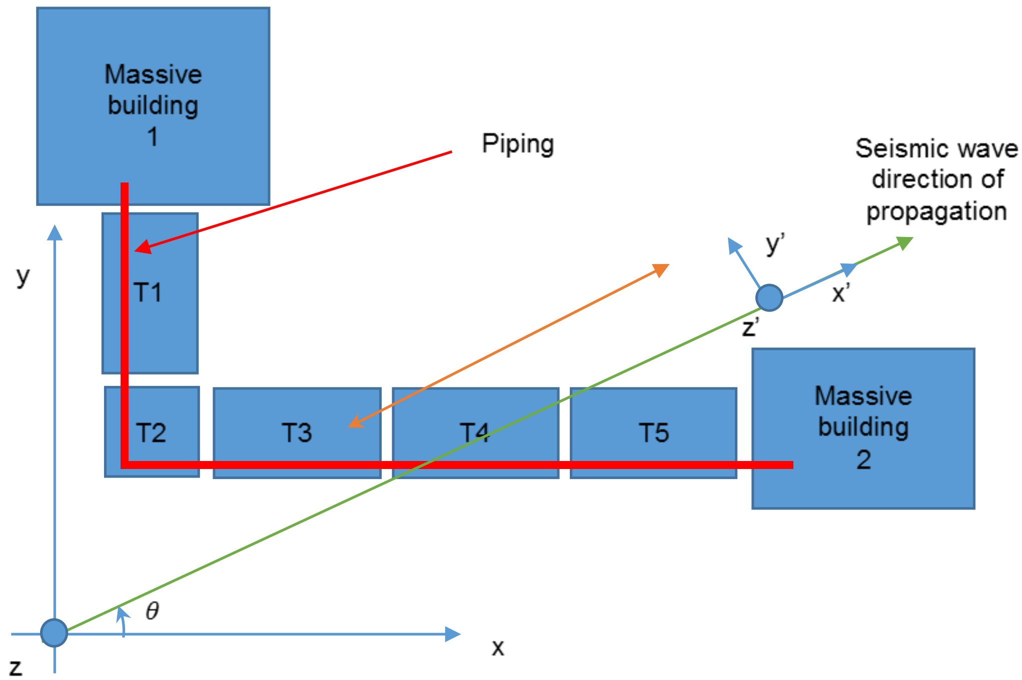

Figure 4: Typical case to study – Piping system connected to 2 buildings, and crossing several buried galleries sections.

On figure 4 it is assumed that the earthquake generates, for a given propagation direction in the horizontal plane (X, Y) and an angle θ, three independent waves:

- a pressure wave "P", inducing movements in the direction of propagation;
- an horizontal shear wave "Sh", inducing horizontal movements perpendicular to the direction of propagation;
- a vertical shear wave "Sv", inducing vertical movements perpendicular to the direction of propagation.

Those waves are a simplified modelling of the projection of a wave traveling from the bedrock to the surface, with its own incidence, and inducing surface seismic movements defined with the additional parameters D_{max}, V_{max} and A_{max}.

The θ angle must describe the $[0° - 180°[$ interval.

A point M described by (x', y', z') coordinates in the local wave propagation coordinates system will move accordingly to the Equations 6, 7 & 8, for the three "P", "Sh" and "Sv" waves:

"P" wave:

$$D\_P_{x',y',z'} = \begin{pmatrix} D\sin\left(\omega t - \frac{\omega x'}{c}\right) \\ 0 \\ 0 \end{pmatrix} \tag{6}$$

"Sh" wave:

$$D\_Sh_{x',y',z'} = \begin{pmatrix} 0 \\ D\sin\left(\omega t - \frac{\omega x'}{c}\right) \\ 0 \end{pmatrix} \tag{7}$$

"Sv" wave:

$$D\_Sv_{x',y',z'} = \begin{pmatrix} 0 \\ 0 \\ D\sin\left(\omega t - \frac{\omega x'}{c}\right) \end{pmatrix} \tag{8}$$

The MP matrix between (X, Y, Z) and (x', y', z') coordinates systems is given by Equation 9:

$$MP = \begin{bmatrix} \cos(\theta) & \sin(\theta) & 0 \\ -\sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{9}$$

Then, M coordinates in (x', y', z') system are defined by Equation 10:

$$M_{x',y',z'} = \begin{bmatrix} \cos(\theta) & \sin(\theta) & 0 \\ -\sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} x' = X\cos(\theta) + Y\sin(\theta) \\ y' = -X\sin(\theta) + Y\cos(\theta) \\ z' = Z \end{pmatrix} \tag{10}$$

The MP' matrix between (x', y', z') and (X, Y, Z) coordinates system is defined in Equation 11:

$$MP' = \begin{bmatrix} \cos(\theta) & -\sin(\theta) & 0 \\ \sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{11}$$

Finally, M movements in (X, Y, Z) system are given by Equations 12:

$$D\_P_{X,Y,Z} = \begin{bmatrix} \cos(\theta) & -\sin(\theta) & 0 \\ \sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{pmatrix} D\sin\left(\omega t - \frac{\omega x'}{c}\right) \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} D\sin\left(\omega t - \frac{\omega x'}{c}\right)\cos(\theta) \\ D\sin\left(\omega t - \frac{\omega x'}{c}\right)\sin(\theta) \\ 0 \end{pmatrix}$$

$$D\_Sh_{X,Y,Z} = \begin{bmatrix} \cos(\theta) & -\sin(\theta) & 0 \\ \sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{pmatrix} 0 \\ D\sin\left(\omega t - \frac{\omega x'}{c}\right) \\ 0 \end{pmatrix} = \begin{pmatrix} -D\sin\left(\omega t - \frac{\omega x'}{c}\right)\sin(\theta) \\ D\sin\left(\omega t - \frac{\omega x'}{c}\right)\cos(\theta) \\ 0 \end{pmatrix} \tag{12}$$

$$D\_Sv_{X,Y,Z} = \begin{bmatrix} \cos(\theta) & -\sin(\theta) & 0 \\ \sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{pmatrix} 0 \\ 0 \\ D\sin\left(\omega t - \frac{\omega x'}{c}\right) \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ D\sin\left(\omega t - \frac{\omega x'}{c}\right) \end{pmatrix}$$

To study a piping network, all θ azimuths between 0° and 180° will be considered in order to cover all incident angles of the seismic waves impacting the line.

For each θ azimuth, displacements have to be calculated for pseudo time-steps describing $[0, T]$ with T the wave period in order to take into account the maximum curvature for all the model nodes. Both LF and MF waves have to be studied.

Given the three moments components (Equations 13, 14, 15) in the pipe at node M, for a wave $Wave_i$, an azimuth θ, and pseudo time-step t, the equivalent moment is described in Equation 16:

$$\Gamma_{1}\_OS(M, Wave_i, \theta, t) \quad (13)$$
$$\Gamma_{2}\_OS(M, Wave_i, \theta, t) \quad (14)$$
$$\Gamma_{3}\_OS(M, Wave_i, \theta, t) \quad (15)$$
$$\Gamma_{eq_{OS(M, Wave_i, \theta, t)}} = \sqrt{\Gamma_{1\_OS}^2 + \Gamma_{2\_OS}^2 + \Gamma_{3\_OS}^2} \quad (16)$$

Then, the equivalent moment used in mechanical codified verification of the pipe is given by Equation 17:

$$\Gamma_{eq_{OS(M)}} = \max_{0 \le \theta \le 180°} \sqrt{\max_{0 \le t \le T} \Gamma_{eq}(M, Wave_P, \theta, t)^2 + \max_{0 \le t \le T} \Gamma_{eq}(M, Wave_{Sh}, \theta, t)^2 + \max_{0 \le t \le T} \Gamma_{eq}(M, Wave_{Sv}, \theta, t)^2} \quad (17)$$

Using Equation 17, it is assumed that seismic waves components “P”, “Sh”, and “Sv” are statistically independent.

Combination with Massive Buildings Movements

Massive buildings movements have to be taken into account by applying their displacements to all the piping supports housed. Each direction of displacement Dir_j is to be considered independently.

Given the three moments components in the pipe at node M when the building BAT_i generates the displacement in direction Dir_j (Equation 18), the equivalent moment at the node M is defined by Equation 19 below:

$$\begin{array}{c} \Gamma_{1}\_BAT_i(M, Dir_j) \\ \Gamma_{2}\_BAT_i(M, Dir_j) \\ \Gamma_{3}\_BAT_i(M, Dir_j) \end{array} \quad (18)$$
$$\Gamma_{eq}(M, BAT_i, Dir_j) = \sqrt{\Gamma_{1\_BAT_i}^2 + \Gamma_{2\_BAT_i}^2 + \Gamma_{3\_BAT_i}^2} \quad (19)$$

Then, the equivalents moment to consider for the three displacements of the building is obtained by a Square Root of the Sum of the Squares (SRSS) of equivalent moments for three directions X, Y and Z as described in Equation 20 below:

$$\Gamma_{eq}(M, BAT_i) = \sqrt{\Gamma_{eq}(M, BAT_i, Dir_X)^2 + \Gamma_{eq}(M, BAT_i, Dir_Y)^2 + \Gamma_{eq}(M, BAT_i, Dir_Z)^2} \quad (20)$$

The total response of the piping network to the SAM is given by an SRSS combination of the responses in massive buildings and the response in buried galleries, as described in Equation 21:

$$\Gamma_{eq}(M) = \sqrt{\Gamma_{eq\_}OS(M)^2 + \sum_i \Gamma_{eq}(M, BAT_i)^2} \quad (21)$$

METHODS COMPARISON

This part presents a margin assessment in piping studies by comparing the "Historical method" results to the "Stationary waves method" results on a simple case that assumes the effects of Sh wave only.

The test-case piping line is described in table 1 and in figure 5:

Geometry	Straight pipe Beam model
Length	300m
Piping Supports	31, from N10 to N40 3 translations restraints 3 rotations free
Outer diameter	0.7112 m
Thickness	0.00792 m
Young's Modulus	204E9 Pa
Poisson's ratio	0.3
Steel density	7.85

Table 1: Test-case piping description

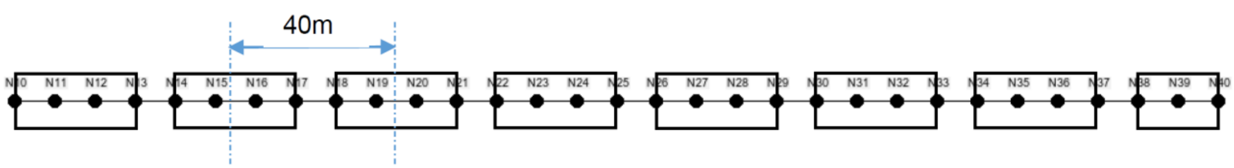

Figure 5: Test-case model, with galleries sections

Seismic movement parameters and "historical method" waves are described in table 2:

Earthquake parameters				"Low Frequency" wave (LF)					"Medium Frequency" wave (MF)					Waves length	
Amax	Vmax	Dmax	c	w_{LF}	f_{LF}	A	V	D	w_{MF}	f_{MF}	A	V	D	λ_{LF}	λ_{MF}
(m/s²)	(m/s)	(m)	(m/s)	(rad/s)	(Hz)	(m/s²)	(m/s)	(m)	(rad/s)	(Hz)	(m/s²)	(m/s)	(m)	(m)	(m)
1.913	0.084	0.034	175	2.474	0.394	0.208	0.084	0.034	22.746	3.620	1.913	0.084	0.0037	444.5	48.3

Table 2: Seismic waves parameters and displacements values

Historical method" leads to 19 mm displacements at galleries movement joints interface assuming l = 40m in equation 6.

Figure 6 below presents the piping line distortion for three load cases:

- 19 mm displacement perpendicular to the pipe, "DEP_OLD" – "Historical method";
- "Sh" displacement for MF wave (3.70 mm amplitude, 3.620Hz frequency), "DEP_SMF" – "Stationary wave method";
- "Sh" displacement for LF wave (34.00 mm amplitude, 0.394Hz frequency), "DEP_SBF" – "Stationary wave method".

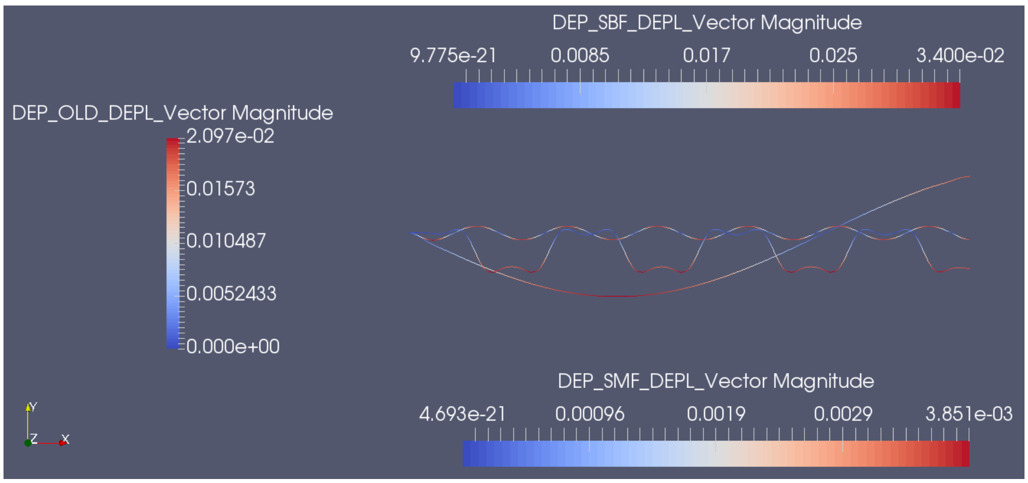

Figure 6: Distortions for 3 load cases

Figure 7 below compares reactions at piping supports for the 3 investigated load cases:

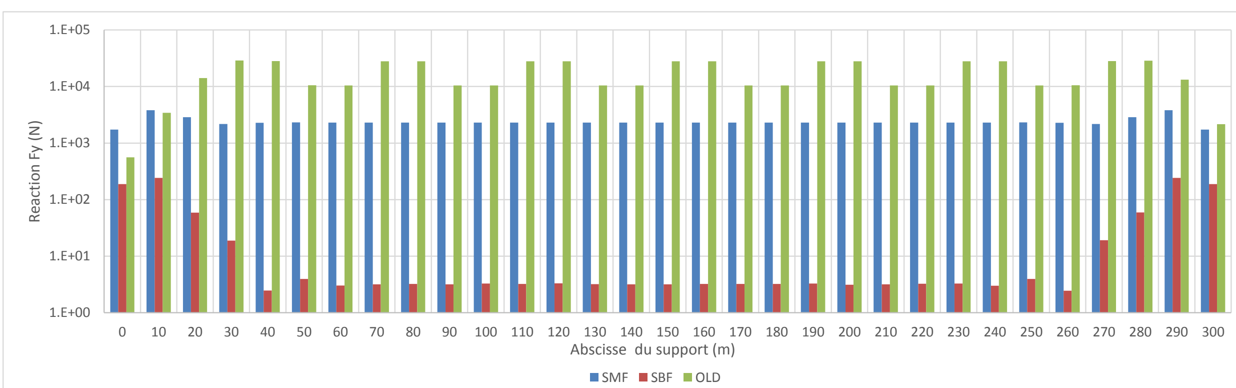

Figure 7: Pipe supports reactions – Logarithmic scale

In this simplified test-case, the “Stationary waves method” enables reactions reduction between 70% and 90%, or shows margin factors between 3.5 and 11.2.

Figure 8 presents the comparison of equivalent moment between “Historical method” and “Stationary waves method”:

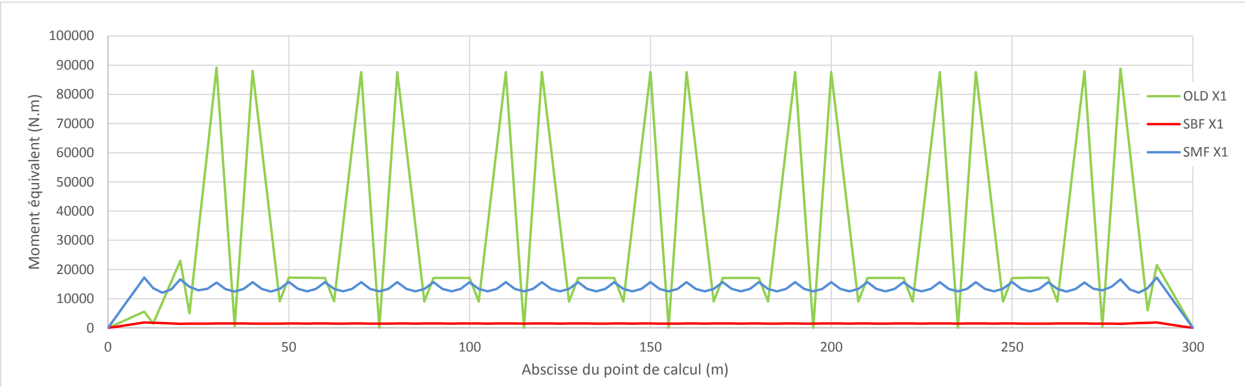

Figure 8: Equivalent moment comparison between methods

Those results can only be considered as an illustration of the possible margins to be shown using the “Stationary waves method” instead of the “Historical method”. As a matter of fact, those results cannot be definitive as the study did not take all the seismic waves into account, and a real piping network configuration would impact them.

Moreover, it may be assumed that the “Historical method” leads to high stress levels, especially on pipe sections and pipe supports located near galleries movement joints.

CONCLUSION

This paper presents thoughts about an optimization of current method for studying, towards seismic loadings, piping systems located in buried galleries and submitted to seismic anchor motions.

With the first test-cases (simple, and more complex ones) results, the “Stationary wave method” shows great margin factors compared to “Historical method”, both for pipe stresses and pipe support reactions, and so confirm an interest for further efforts and developments in the field of the seismic analysis of galleries housed piping systems.