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SEISMIC HAZARD ASSESSMENT AND DESIGN METHODOLOGY FOR STEEL BURIED PIPELINES

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SUMMARY

For gas transmission pipeline operators, assessing their pipeline resistance to permanent ground displacements (PGD) triggered by earthquakes can be of great importance both at design stage and for rehabilitation programs. Whereas modern pipeline resistance to travelling ground waves is quite obvious, both theoretically and from field experience, issues like the resistance to permanent ground deformations are more complex to handle, for at least two reasons: there is a significant uncertainty in evaluating the possible amplitudes and directions of PGD, and no simple yet realistic enough methods seem available to allow performing extensive sensitivity studies. The field feed back tends to show that modern lines behave also well under quite severe straining conditions. Unfortunately, it is not easy to define precisely what preventing measures to take for each type of situation. In addition, there is no straightforward explanation for the general good behavior of buried pipelines subjected to fault displacements. Therefore, we decided to undertake a comprehensive finite element parametric study of the pipeline mechanical behavior when subjected to faults. This work enabled us to set firm foundations for identifying situations when constructive measures are needed, and help specifying them. A practical case study illustrates the approach, ranging from the geotechnical survey that helped identify the sensitive areas, to the choice of specific constructive measures when needed. How all this information helped draft an application guide to implement the general methodology is also described shortly.

INTRODUCTION

For gas transmission pipeline operators, assessing their pipeline resistance to permanent ground displacements (PGD) triggered by earthquakes can be of great importance both at design stage and for rehabilitation programs. Concerning the general frame for assessing pipeline resistance to earthquakes, some reference documents are available in countries exposed to strong seismic activity [1], [2]. In the last three years, the French Seismic Design Society (AFPS) organized a working group (AFPS-CESS) in order to update and adapt to the French context existing knowledge and undertake new work when necessary. This paper presents the general results of this group's work and an example of practical application to a 1000 mm diameter gas transmission pipeline.
Methods to assess pipeline resistance to travelling ground waves and to PGD are covered in the above-cited reference documents. For modern pipelines, both theoretical methods and field experience indicate that resistance to travelling ground waves does not modify the current design and construction practices. Issues like the resistance to permanent ground deformations are more complex to handle, for at least two reasons: there is a significant uncertainty in evaluating the possible amplitudes and directions of PGD and no simple yet realistic enough methods seem available to allow performing extensive sensitivity studies.

The most relevant phenomena, which might produce PGD under seismic loads and must be specifically detailed, are:

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- active faults;
- local sharp transitions in geomecanical properties, like between rock and soft soils, giving rise to large amplifications;
- liquefaction-induced lateral spreads;
- earthquake-induced landslides.

Nevertheless, the field feed back tends to show that modern lines behave also well under quite severe straining conditions. Unfortunately, it is not easy to define precisely what preventing measures to take for each type of situation. In addition, there is no straightforward explanation for the general good behavior of buried pipelines subjected to fault displacements. Therefore, we undertook a comprehensive finite element parametric study of the pipeline mechanical behavior when subjected to faults.

This general approach will be illustrated on a practical example. Gaz de France, presently the major natural gas transmission operator in France, started to build a new pipeline (named "Les Marches du Nord-Est") linking the North of France to the Swiss border, in order to supply North Sea gas to SNAM, natural gas transmission operator in Italy. This 500km-long, 36-in pipeline will reinforce the gas transmission network in the north-east part of France (see figure 1), and will be connected to the Trois-Fontaines underground gas storage. Depending on the section, gas transmission operations will begin in the second half of 2001 and in the fourth quarter 2002.

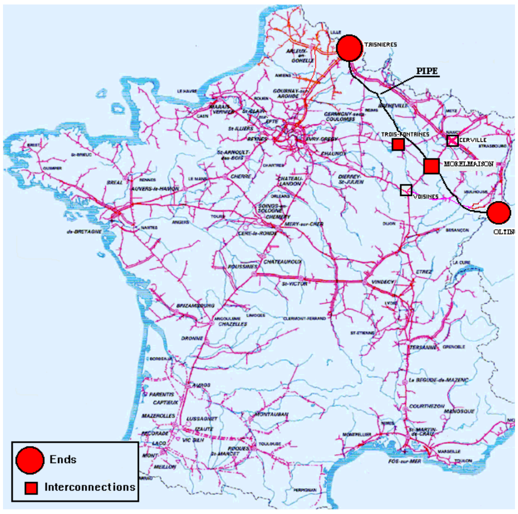

Figure 1: Gas transmission network in France

GDF entrusted BRGM with the task of performing the seismic hazard assessment study. Recently, the Natural Risks Department of BRGM was involved in three different studies relative to steel buried pipelines under seismic loads: one in Myanmar (former Burma) and two in France.

2. THE CONTRIBUTION TO THE AFPS-CESS WORKING GROUP

2.1. Effect of PGD on pipeline behaviour: literature review

A literature review about the effects of PGD on pipelines was performed for seven major earthquakes [6], [7], [8]: Kanto (1923), Long Beach (1933), Kern County (1952), Imperial Valley (1979), Loma Prieta (1989), Northridge (1994) and Kobé (1995). The main outcomes of this review are:

- Pre-world-war-II pipelines are often damaged by both PGD and travelling ground waves;
- Modern electric arc welded pipelines generally resist well to fault displacements or liquefaction, and are not sensitive to travelling ground waves.

2.2. The particular case of faults

2.2.1. *Parametric study*

Our previous work [3] concluded that finite elements (FE) analysis is best suited to realistically describe the mechanical behavior of a buried pipeline submitted to tension and/or shear by a fault movement. Although it is conservative at low and intermediate strain levels, FE calculations give realistic results at large strain values, whereas the simplified formulas become unrealistic. We used a screening procedure to combine parameter values in the below given parameters ranges in order to avoid unnecessary calculations. Overall, more than 200 FE computations were carried out. These results represent a quite thorough mapping of possible cases. We present here only a limited set of illustrative results. The range of our parametric study is defined in terms of:

- soil parameters for four types of extreme soils: dense and loose sand, soft and stiff clay;
- soil movements: strike slips and 60° inverse faults of various displacements: 0.1 to 1 m;
- pipe diameters: four pipeline diameter values were studied: 100, 150, 500, and 1000 mm;
- design factors: extreme values of 0.4 and 0.73 were covered;
- the angle of the pipe with respect to the fault plane was varied between 30 and 90°.

2.2.2. *Faulting*

Faulting is the deformation associated with the relative displacement of adjacent parts of the earth’s crust [1]. Two types of fault movements are studied: strike-slip fault in which the movement is a horizontal displacement, and reverse-slip fault (faults in which the overlying side moves upward). Only these two fault movements are studied because they are the most damaging for the pipeline. The normal fault is a less damaging version of the strike-slip fault. Moreover, several values of the angle between the pipeline direction and the strike line direction are studied.

2.2.3. *Model description*

This study was performed by using the ABAQUS STANDARD implicit finite element software. The model used to simulate the effects of a soil movement on pipe was a 200 m long model composed of 500 pipe elements (beam elements with internal pressure effect and elasto-plastic behavior). On these pipe elements, axial and lateral spring elements are connected. In order to reproduce the soil-pipe interaction, the behavior of these springs is piece-wise linearly elasto-plastic. The spring behavior is described in tension and compression.

2.2.4. *Main parameters explored by the parametric study*

Four extreme soils were studied: two clay soils (soft and stiff clay) and two sand soils (loose and dense sand). Sand and clay soils differ mainly by the axial friction between soil and pipeline. In this way, a bracketing approach is possible, for well-defined or unknown soils. Four pipe diameters and two pipe design factors were modeled. Pipe characteristics are summarised in table 1, and they are shown to cover largely the entire transmission pipe range in terms of diameters, thickness, steel grades, and load factors. As a first approximation, the strain for other pipe diameters can be estimated by interpolation from the values calculated for these four pipe diameters.

Table 1: Characteristics of studied pipes.

External diameter (mm)	**Design factor**	**Wall thickness** (mm)	**Specified minimum yield stress** (MPa)
114	0.73	3.2	250
	0.4	3.9	250
168	0.73	3.5	250
	0.4	5.0	290
508	0.73	5.7	415
	0.4	12.0	415
1016	0.73	9.9	480
	0.4	18.0	480

2.2.5. *Acceptance criterion*

Unlike mechanical criteria used in design and maintenance for current operations, which are based on elastic material behaviour, the extreme and occasional nature of earthquakes prompts for using an acceptance criterion based on plastic material behaviour. According to the ASCE guide, the pipeline strain must be limited, i. e. tensile strains should be less than 2 % to 5 %. In this study, we refined this criterion in order to distinguish between cases over such a large strain range [4]. We used a lower bound tensile strain criterion of 2% when the whole pipe section was plastified, i.e. a large volume fraction of the yielded zone of the pipe is plastically deformed. The upper bound of 5% was used for cases when only a « hot spot » is affected, i.e. the plastic strain is localised (see figure 2).

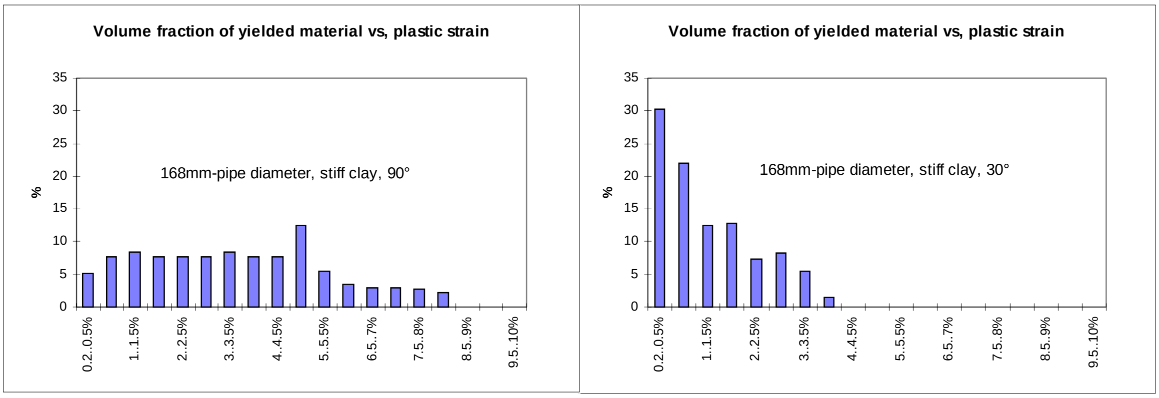

Figure 2: Two extreme cases of distribution for the volume fraction of yielded material:

- almost uniform yielding, which should be limited to 2 % of plastic strain ;
- localised « hot spot », which can be tolerated up to 5 % of plastic strain.

When the pipe is in compression, the limit of wrinkle initiation is given by the relation: $\varepsilon = 40.\frac{t}{D}$ where t is the wall thickness and D is the average pipe diameter.

2.2.6. *Order of magnitude of the fault displacement*

In addition to the feed back from past earthquakes concerning specifically pipeline performance, Wells and Coppersmith [5] related the magnitude moment M_w to the average and extreme fault slip displacements. According to [5], the average value Δ_m of the relative displacement and the extreme displacement Δ_e of the two ground slabs on each side of the fault are respectively given by:

Δ_m (m) = $10^{-4.8 + 0.69\ Mw}$ Δ_e (m) = $10^{-5.46 + 0.82\ Mw}$

The direction of displacements Δ_m or Δ_e is in principle determined by the type of movement, i.e. normal, strike-slip, or inverse fault. If the type of fault is not well established, it can be assumed that it is either strike-slip or normal fault type (if the regional tectonic context is dominated by tension), either strike-slip or inverse fault type, (if the regional tectonic context is dominated by compression). For the sake of simplicity, we consider here three values of moment magnitude which are representative of a wide seismic context range; for the metropolitan French area, only magnitudes 5.5 and 6 are relevant. The associated fault displacements are given in table 2.

Table 2: Average and extreme displacements for three moment magnitudes.

Magnitude M_W	Δ_m (m)	Δ_e (m)
5.5	0.10	0.11
6	0.22	0.29
6.5	0.48	0.74

Table 2 shows that below a moment magnitude of about 6, fault displacements are generally moderate to small - one to three decimetres -, while above 6, they can reach one half to three quarters of a meter. In the parametric study, we explore both ranges of displacements, and present here results for the first range.

2.2.7. Illustrative results for small and moderate strike-slips

This example, where thick and thin pipes (0.4 and 0.73 design factors) are submitted to a small or moderate strike-slip in stiff clay - sensitivity study with respect to the displacement - being typical of situations which are relevant for metropolitan France, is used to illustrate more precisely the use of the refined acceptance criterion. Small to moderate fault displacements corresponding to magnitudes about 5.5 and 6 are applied to four pipelines crossing the fault at an angle of 90°. The influence of the design factor is also tested. In table 3, the three numbers in brackets in the strain column are respectively the percentages of the most strained pipe cross-section for which strain is either less than 2%, between 2% and 5%, and larger than 5%. If the percentages are uniformly high, this means global plastic flow, limited around 2 % plastic strain, whereas a decreasing percentage means a less damaging « hot spot », limited at 5 % plastic strain.

Table 3: maximum longitudinal pipeline strain in stiff clay (90° angle between pipeline and slip line)

Diameter (mm)	Design factor	Fault displacement (m)	Maximum strain (%)
114	0,73	0,3	4,5 (59,41,0)
		0,2	4,35 (77,22,0)
		0,1	2,40 (88,12,0)
114	0,4	0,3	3,89 (75,25,0)
		0,2	3,69 (77,23,0)
		0,1	2,2 (88,12,0)
168	0,73	0,3	4,67 (64,36,0)
		0,2	3,56 (70,30,0)
		0,1	2,03 (96,4,0)
168	0,4	0,3	3,94 (71,29,0)
		0,2	3,23 (84,16,0)
		0,1	1,78
508	0,73	0,3	2,8 (85,15,0)
	0,4	0,3	1,02
1016	0,73	0,3	1,7
	0,4	0,3	0,4

According to this refined strain criterion, all pipelines can resist to strike-slip and normal fault displacements up to 0.3 meters. The design factor has to be decreased for the small diameter lines, but the medium and large diameter pipelines resist well even with a high design factor value. This example shows that current practice does not have to be modified, except for adapting the design factor in some small diameter cases. This data was then used as a basis to define when constructive measures are needed, and what they should be, like the example given in table 4. The general results cover obviously the entire range of studied displacements.

Table 4: Constructive measures for pipelines crossing faults.

Fault displacement d (m)	Pipe load factor and orientation (angle between pipeline direction and slip line direction)	
	strike-slip, normal fault	Reverse-slip fault
0 < d ≤ 0,1	0,73	0,73
0,1 < d ≤ 0,2	0,73	0,73; crossing 30° if D≥508 mm
0,2 < d ≤.0,3	0,73	0,73; crossing 30° if D≥508 mm

These and other results, ensuring a broad coverage of the subject, were published by AFPS as methods to assess the seismic behaviour of steel transmission pipelines in seismic areas [9] and approved by French

Administration. The need for a guide helping in the practical application of these methods was expressed, so such a guide was drafted and will be published soon [10]. This guide uses the methods of [9] and their application on the « Marches du Nord-Est » project, particularly concerning the geotechnical survey [11].

3. APPLICATION TO THE "MARCHES DU NORD-EST" PIPELINE PROJECT

The aim of the geological and geotechnical survey performed by BRGM was both to assess seismic hazard along the pipeline and to develop a practical methodology in order to apply [9]; it was a qualitative approach, with an important methodological part.

The survey was based on a compilation and interpretation of existing information, (in particular from BRGM archives or databases, relative among others to historical seismicity, paleoseismicity and neotectonics, aerial photographs…). They were completed by detailed visual observations in the field. The four relevant phenomena which might produce large displacements under seismic loads, detailed in §1, were taken into account on eighty kilometres of the total pipeline route, according to the different seismicity zones defined by French regulations [12]. For each of the four previous phenomena, localisation, typology, severity and impact on the pipeline were successively determined. By a permanent dialogue with GDF, we tried to reach a balance between, on one hand, complementary site surveys (for instance geophysical investigations, or Cone or Standard Penetration Test and laboratory tests with regard to liquefaction), and on the other hand, adapted constructive measures.

- The potential activity of four faults was first discussed. Two active faults were finally kept, crossing with the pipeline route. BRGM characterised them with estimated length, type of mechanism, estimated magnitude, and associated displacements (a rough estimate is a decimetre).

- Nine zones were identified as exposed to local sharp transitions in geomecanical properties like between rock and soft soils, able to give rise to large amplifications of surface seismic motion. Four were characterised as clear (an enlarged excavation was then proposed), five as diffuse. In addition, all the river-crossings should be examined to verify if there are no alluvial deposits brought into contact with substratum.

- As regards to liquefaction, the following approach was developed. First, the geological age of the deposits, (from Antepleistocene to recent Holocene), and the water table are examined (four ranges were distinguished). These two factors determined an a priori susceptibility, as shown in table 5.

Table 5: A priori susceptibility to liquefaction

A PRIORI SUSCEPTIBILITY (Before Present)	Water table depth (m)			
Geological age of the deposits	0-3	3-10	10-15	> 15
Recent Holocene (<=500 years)	High to very high	Moderate	Low	Very low
Holocene (<=10 000 years)	High	Moderate	Low	Very low
Pleistocene (<=1 800 000 years)	Low	Low	Very low	Very low
Antepleistocene	Very low	Very low	Very low	Very low

Then, we used the symbol T if the pipeline is situated transversely to the considered river or to the topographic contour lines, which is a more favourable situation; the L symbol is used if the pipeline is parallel to the topographic contour lines. At the end, seven different situations are considered: if a river does exist or if it is a marsh, if there is a slope or not, according to the river width and the strength of the river current and to the possible lateral spread. It leads to a qualitatively induced impact on the pipeline ranging from zero to four. An example is given in table 6, corresponding respectively, from left to right, to seismicity zones defined by French regulations as Ib and II.

Table 6: Examples of impact indexes

French seismicity Ib Zone		
Impact Index	Pipeline position	
	T	L
No river	0	0
River of moderate width or/and current	1	2
Wide river or/and current	2	3
Topographical slope	1	3

French seismicity II Zone		
Impact Index	Pipeline position	
	T	L
No river	0	0
River of moderate width or/and current	1	3
Wide river or/and current	2	4
Topographical slope	1	4

Qualitatively, the simple following recommendations can be made in case of high impact indexes. In case of river crossing, it is possible to reduce the influence of potentially unstable riverbanks by increasing the burying depth. The most adequate angle for crossing non horizontal liquefiable areas is along the slope rather than along topographic contour lines. At last, if the pipeline is parallel to the topographic contour lines, either it can be buried below the liquefiable deposits, or it might be placed directly in the horizontal alluvial plain (slope less than 2%), if the expected displacements induced by lateral spreads or riverbanks rupture are not too large.

Six of the sixteen zones identified as a priori susceptible to liquefaction, were characterised by an impact index considered as large enough to require complementary field investigations and/or anticipate constructive measures.

Nevertheless we consider that, in general, part of liquefaction phenomena still remains difficult to evaluate, especially the determination of the distance to be used to prevent the pipeline from lateral spread or riverbanks rupture propagation. Modelling is suitable to improve this knowledge. In metropolitan France, taking into account the moderate seismic context, there is no evidence of recent liquefaction phenomena; this is not the case for French West Indies, whose seismic context is much more constraining.

- Twelve zones were identified as exposed to earthquake-induced ground movements: underground cavities (among others an old important coal mine), rockfalls, and landslides. For each, a methodology was defined to determine the typology, susceptibility, activity and impact on the pipeline; this impact is characterised by an estimate-induced displacement, connected to a theoretical safety factor.

In total, forty one zones corresponding to the four phenomena were localised on a 1/25 000 plan, connected with thirty eight synthetic cards. The overall results of the geotechnical survey performed by BRGM and the complementary field investigations led Gaz de France to the following conclusions:

- Faults: on the basis of the parametric study, no constructive measure is needed across the two faults identified during the geological survey. Moreover, one of these faults is crossed by a 0.4 load factor pipe due to an urban environment.

- Liquefaction: liquefaction susceptibility measurements were performed (Plasticity index, Atterberg limits and density) along several sections of the pipeline route. As the soil is not susceptible to liquefaction in these sections, only at one particular river crossing, a slight route modification was adopted even before measurements.

- Amplifications: according to [9], such a transmission pipeline can sustain sharp discontinuities.

- Others movements (rock falls, spreads): further investigations (drillings) were performed in order to check the stability of slopes, and no need for constructive measures evolved.

The experience gathered during this study and the practical methodology thus tested helped considerably to derive practical guidelines.

4. GUIDE FOR PRACTICAL APPLICATION OF THE SEISMIC ASSESSMENT METHODS

This guide covers the following seismic actions: travelling waves, particularly taking into account the amplification due to soil type discontinuities, faults, liquefaction, and other ground movements (landslides, settlements, etc.), and links their potential amplitude to the seismic zones existing in France. Its objective is to either conclude that the design covers the seismic hazard of the area, or to indicate constructive measures or additional investigations in order to reach the objective of resistance to seismic hazard.

This guide proposes three steps to conduct the analysis, each of which is presented as a set of flowcharts:

Step 1: Identification of potential seismic loads along the pipeline route;

Step 2: Choice of standardised seismic parameter values (or constructive measures) and first check of pipeline resistance to earthquake;

Step 3: Additional geotechnical investigations in order to check for actual seismic loads and/or constructive measures.

5. CONCLUSION

This paper presents part of the work done by the French Seismic Design Society (AFPS) in order to update recommendations published more than ten years ago in the United States and in Japan in the field of pipeline resistance to seismic loading. The results of this study are used to check pipeline design in seismic areas. It shows both with the feed back from the field and by theoretical means that in most cases, modern pipelines can cross strike-slip or normal faults without any damage in case of actual fault displacement.

These methods are illustrated on a practical case, a project of a large diameter pipeline, named "Les Marches du Nord-Est", to be constructed in France in the following years. This example study, performed by BRGM and GAZ DE FRANCE, was useful in establishing practical ways to address the issue of evaluating pipeline resistance to earthquakes. It shows both the usefulness of taking into account seismic resistance from the very design stage, and the very limited impact on the design choices which already integrate other constraints.

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