PIWG 15 033

Pipeline resistance to earthquakes – state of the art, lessons learnt and gap analysis

This paper presents results of the first phase of a research project funded by the European Pipeline Research Group (EPRG). The study is aimed at summarizing the state of the art of seismic design practices for buried steel transmission pipelines. It also shows that lessons learnt about pipelines' resistance to past (since 1923) to recent (2011) large American, Asian and European earthquakes support the presented assessment methods, which are widely used. A state-of-the-art based on ten relevant reference documents is provided, which covers: (1) guidelines for pipelines resistance to earthquakes; (2) an assessment methodology for pipeline resistance to permanent ground displacement; (3) some resistance criteria for pipelines as well as (4) a brief overview of mitigation techniques. A comparative study between the main current practices is summarized in a format where the ten main documents are classified in three categories: general seismic assessment (one document), general pipeline design and assessment (six documents) and specific seismic assessment for pipelines (three documents). The two main documents for seismic design and assessment of pipelines are the PRCI L-51927 Report Design and Assessment Guidelines [5] and the French Guidelines: Methods to Assess Pipeline Resistance to Earthquakes – AFPS (French Seismic Design Society) CT15 [3] (based on Eurocode 8). PRCI L-51927 Report guidelines provide a quite complete methodology for seismic design and assessment of pipelines, with extensive qualitative mitigation measures. Similar recommendations are also available in the AFPS CT15 guidelines, with the supporting extensive parametric studies for fault crossings, liquefaction-induced movements and vibration-induced strains. A practical issue is that of performing a post-seismic check of the pipeline system, and this is partly addressed by complying with the recommendations, but in some cases more specific checks might be necessary. The discussion is also open about the need for more in-depth comparison of strain-based criteria used in the different documents, or even further work on these subjects.

1. INTRODUCTION: OVERVIEW OF ASSESSMENT FRAMEWORKS FOR SEISMIC DESIGN AND ASSESSMENT OF BURIED STEEL TRANSMISSION PIPELINES

1.1 Overview

This paper presents the results of the first phase of a research project funded by the European Pipeline Research Group (EPRG). The study is aimed at summarizing the state of the art of seismic design and assessment practices for buried steel transmission pipelines. It also shows that lessons learnt about pipelines' resistance to large earthquakes support the presented methods, which were consolidated in the last decades.

A comprehensive past and recent seismic feedback is presented in § 2. Parameters describing seismic hazards for assessing pipelines are described in § 3. A general methodology for seismic assessment of pipelines is provided in a third part (§ 4). Some resistance criteria for pipelines (§ 5) as well as mitigation techniques (§ 6) are also proposed. A comparative study between the main current guidelines is provided in a summarized format (§ 3.4). Details for each methodology can be found in the references (a quite comprehensive yet not complete list is found at the end of this report). A discussion and gap analysis of the current guidelines is provided in the last section (§ 7).

Many documents are more or less relevant for seismic design of pipelines, and the summarized review of the ten main ones ambitions to map their respective positioning:

- PRCI: reference seismic design guidelines used in this report [5];
- EN 1998-4: European standard relative to seismic design of pipelines, applicable in each country of the European Union [7];
- EN 1594: European design and construction standard for pipelines [10];
- B31.8-2010: American design and construction standard for pipelines [14];
- ALA - American Lifelines Alliance: Guidelines for the Design of Buried Steel Pipe, Section 11.0 Earthquake [4];
- AFPS CT15-2013: French guidelines relative to seismic design and construction for transmission pipelines, regulatory document ([16] as an update of [3]);
- ISO 13623: Petroleum and natural gas industries-pipeline transportation systems [12];
- BS-PD 8010-1:2004 Code of practice for pipelines. Part 1: steel pipelines on land. Annex G (Normative) loads [6];
- IGEM/TD/1 Edition 5. Steel pipelines and associated installations for HP gas transmission. Section 6 "Design of pipelines" – seismic activity ([18]);

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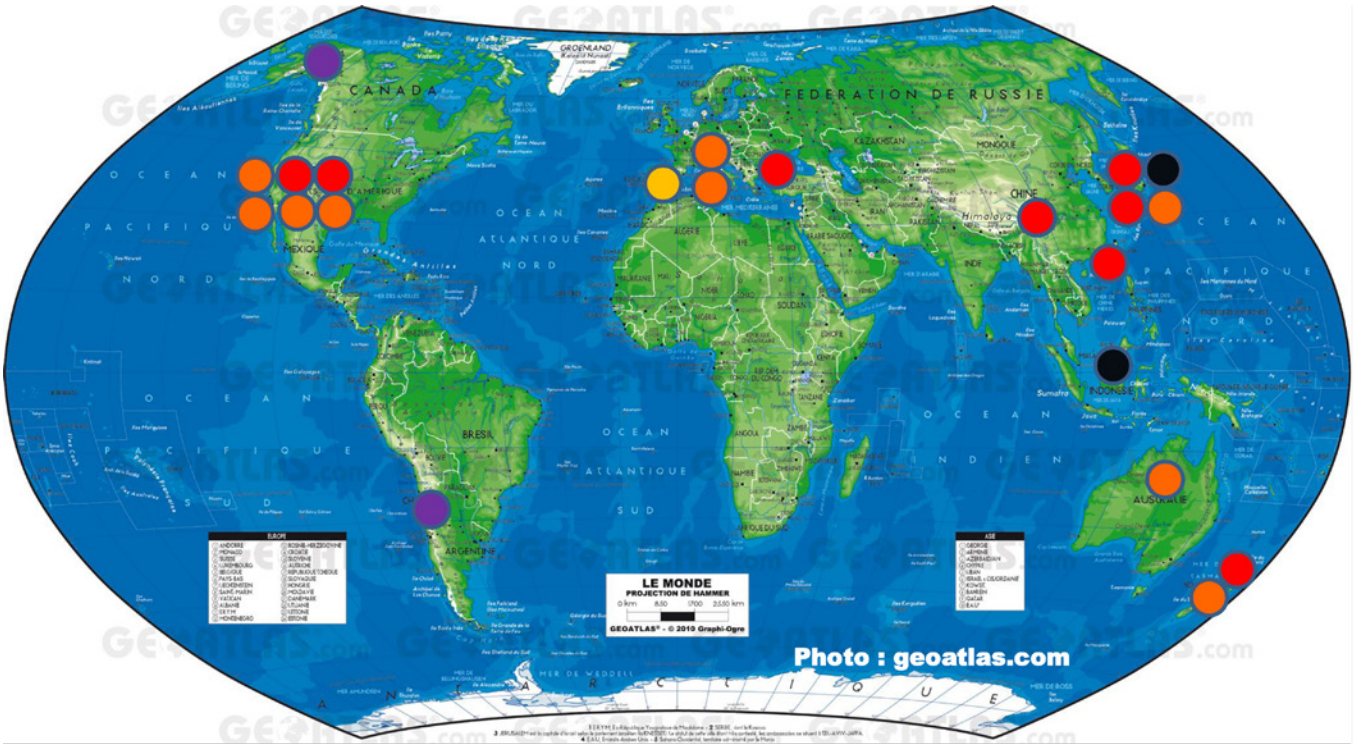

***Figure 1**: Reviewed earthquakes around the world for this article. (Picture from www.geoatlas.com)*

» Reports and publications from two RFCS (Research Fund for Coal and Steel of the European Commission) co-funded projects: GIPipe and INDUSE ([19] & [20]).

PRCI L-51927 Report guidelines provide a quite complete methodology for seismic design and assessment of pipelines, with extensive qualitative mitigation measures. Similar recommendations are also available in the AFPS CT15 guidelines, with the supporting extensive parametric studies for fault crossings, liquefaction-induced movements and vibration-induced strains.

A practical issue is that of performing a post-seismic check of the pipeline system, and this is partly addressed by complying with the recommendations, but in some cases more specific checks might be necessary. The discussion is also open about the need for more in-depth comparison of strain-based criteria used in the different documents, or even further work on these subjects.

1.2 Earthquake resistance assessment – specifics of buried steel transmission pipelines

Like any other infrastructure, buried transmission pipelines may be subjected to earthquakes during their lifespan, so their resistance to seismic loads needs to be assessed. Many design codes and guidelines address the design and behaviour of above-ground infrastructure under such loads. However, these standards cannot be directly applied to buried transmission pipelines because of their two specific features:

1. Being buried, transmission pipelines are not affected by inertia, which usually dominates the behaviour of above-ground infrastructure. Buried pipelines follow ground displacements, e. g. deformations are directly applied by the ground to the pipeline.
2. Being very long linear structures, a pipeline cannot be associated with a single uniform seismic load. The nature and amplitude of seismic loads vary greatly along the pipeline route. Consequently, it is not relevant to assess the behaviour of each pipeline section based on local conditions. Much more generic approaches must be used.

1.3 How specifics shape assessment of pipeline resistance to earthquake

Both practical experience and past studies showed that in the majority of cases, current design and construction practices for buried steel transmission pipelines are sufficient to grant their resistance to seismic loads (either dynamic or static loads). Therefore the goals of seismic design and assessment methods currently in use worldwide (USA, Europe, Japan) are twofold:

» Compliance with regulatory requirements and relevant design standards,
» Identification of the few cases for which mitigation measures are needed to ensure pipeline resistance to earthquakes.

Following recent major events, seismic regulation is evolving towards more stringent requirements, e. g. in Europe revision of seismic zoning and application of Eurocode 8-4 (EC 8-4). While Eurocode 8-4 describes methods to check pipeline resistance to vibrations which depend on peak ground acceleration

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(abbreviated PGA), which may become a design issue only in very rare cases, it states also the need to check for pipeline resistance to permanent ground displacements (commonly abbreviated PGD, which may stand for peak ground displacement, too). In this latter case, methods are not completely described, leaving room for wide interpretation. In addition, EN 1594 also requires resistance to seismic loads.
Therefore, pipeline operators are now facing the need for a common understanding and an acknowledged methodology to verify and justify the resistance of pipelines to earthquakes.

2. LESSONS LEARNT FROM PAST EARTHQUAKES: PIPELINES RESIST WELL TO SEISMIC LOADS

As pipelines are relatively widespread in some areas, analysing their behaviour during past earthquakes is very useful for establishing the seismic loads which they resist well or not.

2.1 Systematic review of 22 major earthquakes

A literature review (reflecting the review in AFPS – CT15 – 2013 [16]) was performed for the following 22 major earthquakes with a systematic focus on pipeline behaviour: KANTO (Japan, 1923), LONG BEACH (California, 1933), FUKUI (Japan, 1948), KERN COUNTY (California, 1952; 1954), ANCHORAGE (Alaska, 1964), SAN FERNANDO (California, 1971), FRIULI (Italy, 1976), IMPERIAL VALLEY (California, 1979), EDGECUMBE (New Zealand, 1987), TENNANT CREEK (Australia, 1988), LOMA PRIETA (California, 1989), NORTHRIDGE (California, 1994), KOBE (Japan, 1995), IZMIT (Turkey, 1999), CHI-CHI (Taiwan, 2002), SUMATRA (Indonesia, 2004), WENCHUAN (China, 2008), L'AQUILA (Italy, 2009), MAULE, (Chile/Argentina, 2010), CHRISTCHURCH (New Zealand, 2011), TOHOKU, (Japan, 2011), LORCA (Spain, 2011).
The magnitudes for these earthquakes are represented on the world map in ***Figure 1***.

2.2 Summary of lessons learnt on buried pipeline resistance to earthquakes

This literature review documents, if possible quantitatively, the effects of earthquakes on buried transmission pipelines and also in a few cases on water supply and gas distribution systems. Overall, we note that transmission systems exposed to earthquakes responded very well, while buildings were destroyed, as indicated by the MMI scale (see ***Table 1***). During an earthquake, underground transmission lines are mainly subject to two types of seismic loads:

- Seismic waves which can affect very extensive areas and thus a large number of lines;
- Permanent ground displacement such as faults or liquefaction, may affect pipeline systems in a limited number of sites.

The effect of seismic waves on transmission systems is limited to the rupture of welds on very old systems, which were performed using poor welding techniques (oxy-acetylene welding, unprotected arc welding, see Table 1) and on lines the corrosive condition of which is unacceptable in Europe. Seismic waves do not cause any damage to the transmission systems assembled since these techniques have been abandoned. Permanent ground deformations due to liquefied zones or fault movements may damage transmission systems. Yet again, poor quality welding caused weak points in the old systems. However, very few ruptures are seen in recently installed pipelines, even when ground movements are particularly severe for buried systems. The examples of earthquakes in Northridge (1989) and Tohoku (2011) demonstrate the excellent mechanical response of recent pipelines: while an old pipeline was broken by movement of a liquefied zone, a replacement pipeline which was subject to the same permanent ground deformations resisted in Northridge, and a transmission system which suffered vibrations caused by record accelerations of more than 2.0 g (up to 3.0 g in the zone) was not damaged during the Tohoku earthquake.
In Figure 1, Color of the point indicates the magnitude ($M_{richter}$, M_s, M_w, etc.) of the earthquake: yellow for $5 \leq M < 6$; orange for $6 \leq M < 7$; red for $7 \leq M < 8$; purple for $8 \leq M < 9$ and black for $M \geq 9$. In black and white printing, the lightest grey indicates the weakest earthquakes. Picture © 2010-GEOATLAS.com.

3. REVIEW OF GUIDELINES FOR SEISMIC DESIGN AND ASSESSMENT

The reviewed documents cover the intersection of two topics – pipelines and seismic design/assessment. Therefore three categories emerge: on one side, seismic design codes, that can address pipeline issues to some extent (least specific), on the other side, pipeline codes that reference seismic design issues (more specific), with the intersection of the two being the most specific category – specialized seismic design/assessment guidelines for buried transmission pipelines. While the latter most specialised documents address the issues in the most comprehensive and readily applicable way, their regulatory coverage is less broad/strong than that of other less explicit and less complete references. Their applicability is therefore also conditioned by their compatibility with the more general codes of the other two categories. While these different focuses can be confusing, we try to highlight the different features and provide guidance mainly by comparing them in ***Table 2***.

3.1 Seismic design / assessment guidelines

"Eurocode 8: Design of structures for earthquake resistance" is a European standard, and is mandatory in some EU countries. It provides the basis of seismic design / assessment methodologies for structures in Europe. It contains a specific part addressing buried pipelines (see below § 3.3).

3.2 Gas transmission pipeline design codes and standards

The following codes and standards were reviewed in this section, and highlights summarised in Table 2:

- EN 1594:2008 European Standard 1594, Pipelines for Gas Transmission (P > 16 bar)
- ISO 13623:2009 Petroleum and natural gas industries-pipeline transportation systems

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» BS-PD 8010-1:2004 – Part 1 – Annex G.
» IGEM/TD/1 Edition 5 Steel pipelines and associated installations for HP gas transmission. Section 6.
» ASME.B31.8 Gas Transmission and Distribution Piping Systems.

3.3 Guidelines for seismic design / assessment of buried steel transmission pipelines

The three following guidelines are considered, and are by far the most comprehensive and readily usable:

» Eurocode 8: Design of structures for earthquake resistance – part 4 Silos, tanks and pipelines. Regulatory – part of EC 8 considered in § 3.1.
» AFPS (French Association for Seismic Design) – CT15: Buried steel transmission pipelines – Assessment methods for resistance to seismic loads. Regulatory in France.
» PRCI report L51927 – 2004: D. Honegger, Guidelines for the seismic design and assessment of natural gas and liquid hydrocarbon pipelines.

3.4 Comparative summary

In this section, we compare the different codes, standards and guidelines summarised in Table 2. In all guidelines, reference is made to seismic loads (displacements, velocities, accelerations and magnitudes) that are derived from probabilistic or semi-probabilistic approaches, and that are formalised in a seismic zoning for each country. This zoning is generally imposed by law, as its consequences on building design are significant.

Buried steel pipeline standards and guidelines all address generically the need to check pipeline resistance to earthquakes, without providing any specific guidance, with one exception, the ALA guidelines. The latter together with the three specific guidelines for seismic design/assessment of pipelines propose formulas for wave propagation-induced soil strains that are applied to pipelines (see Table 2). These are then compared to tensile/compressive strain criteria that are also proposed only in the four above-mentioned guidelines, with some variations. Without an explicit guidance in this respect, lessons learnt have shown that wave-propagation-induced strains are not a major concern for pipelines. The same analysis of lessons learnt showed that permanent ground displacements are the main issue for pipelines and the same tensile and compressive strain criteria mentioned above can be used to assess pipeline condition.

These strain limits are typically used to prevent localised wrinkling or tensile failure at girth welds while allowing for some controlled level of pipe steel yielding. Appropriate deformation limits such as strain or curvature limits were established based on testing and detailed analysis (e. g. fitness for purpose evaluation).

Due to the inherently non-linear soil-pipe interaction, it is not possible to develop simple design formulas for differential soil movements based on elastic stress analysis procedures, so FE modelling has to be implemented. It is noteworthy that the AFPS-CT15 guidelines present systematic parametric studies for a practical range of pipelines that cover different fault displacement and liquefactions scenarios, and that justify mitigation measures to avoid exceeding the acceptance criteria.

More generally, as mentioned in Table 2, AFPS-CT15 and PRCI L51927 are the only guidelines that propose practical mitigation measures that make these guidelines applicable in practice, and reflect the industry's best practices.

As a conclusion from these two sections the following can be stated:

» Vibration-induced strains are not a concern for pipelines provided modern welding techniques and corresponding NDE controls are performed that guarantee weld quality; simple analytical methods allow an easy quantification, and parametric studies as in AFPS-CT15 can justify pipeline resistance for a wide range of conditions without need for further studies
» Very severe Permanent Ground Displacements are more susceptible to cause pipeline damage, the modelling of which cannot be dealt with by analytical approaches. More complex FE modelling is required, and some highlights are presented in the next section. Two options are available when using these FE models: either a case by case study, or for moderate seismicity contexts like in Europe, parametric studies like those in AFPS-CT15, that can justify mitigation measures for a wide range of pipelines.

4. PIPELINE ASSESSMENT METHODOLOGY FOR PERMANENT GROUND DISPLACEMENTS

Modelling pipeline behaviour in permanent ground displacement cases means being able to track mutual deformations of the soil and of the pipeline, commonly called 'soil-pipe interaction'. This section highlights a few of the issues related with this highly non-linear mechanics problem, as it implies soil rupture in the most strained areas, as well as large strains for the pipeline material and large displacements for the pipeline structure.

4.1 Modelling pipe-soil interactions

It is important to recall that modelling of pipe-soil interaction has found in the bilinear spring concept a good balance between limiting necessary computing power and extending the length of the modelled pipeline segment to reach ideally the 'anchoring length' beyond which there is no pipe straining by the soil, and this type of model was already referenced in the 1984 ASCE Guidelines (see [2]). So the specialised guidelines AFPS-CT15 and PRCI Report L-51927 provide similar recommendations in this respect.

» PRCI Report L-51927 and AFPS CT15 based on ASCE 1984 recommendations

Assuming that an estimate of the ground movements that could occur along the pipeline route is known, pipeline strain has to be calculated. Representativeness of the chosen pipe/soil interaction model is a key issue. The recommended approach ([2]) for FE analysis is to model the pipeline with

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***Table 1**: Table summarizing the earthquakes and their consequences on transmission systems (Reminder: oxy-acetylene welding was practiced before the Second World War).*

Characteristics of the earthquake					Pipeline Charakteristics				Effects on the transmission system (gas, liquid hydrocarbons)		
Earthquake	Year	Magnitude (Mw)	Acceleration (m.s-2)	MMI	Diameter (mm)	Thickness (mm)	Rp (MPa)	Pressure (bar)	Permanent Ground Displacement (*)	Displacement/stress applied	Consequences
Long Beach	1933	6.4		VII/VIII					L		no consequences on transmission tubes
Fukui	1948	7.3	0.4 g	IX					L		no information on lines
Kern County	1952	7.7		VIII	864 150	11 -	330	55	F L	compression	deformation without buckling no damage despite oxy-acetylene weld. oxy-acetylene
Anchorage	1964	8.4		XI/XII					F		one line resisted one oil line ruptured
San Fernando	1971	6.4	1.25g	VII/XI	560 760 760		350 350 350		L L L	lateral displacement of 3m lateral displacement of 3m lateral displacement of 3m	no damage
Friuli	1976	6,4		IX/X	914	14.1	450	75	V		no damage
Imperial Valley	1979	6.6		VI/VII	100 200 250	4,8 7,1 4,8	170 240 290	28 28 50	F F F	axial displacement lateral and vertical displacement lateral and vertical displacement (compress.)	no significant stress no apparent damage no apparent damage
Edgecumbe	1987	6.3		IX/X	100	5	240	61	F	tension	no damage
Tennant Creek	1988	6.7			350	6		97	F	compression (0.8 to 1.8 m)	no leaks (shortened by 0.97m)
Loma Prieta	1989	6.9	0.64 g	VI/IX					L		no damage
Northridge	1994	6.9	1.0 g	VII/IX	300 550 600 750 400	5,6 7,2 6,4 - -	- - 415 360 360	17 12 - - -	L L L L L	- displac. 0.25 m (trac. + compr.) displac. 0.25 m (trac. + compr.) - -	rupture of oxy-acetylene weld joint/buckling rupture of welded joint (unprotected elec. arc) no damage no damage no damage
Kobe	1995	6.9		X/XI					L	displacement 0,7 m	no damage
Manzanillo	1995	7.9	0.4 g	VIII/IX					L		very little damage - flow re-established very quickly
Epagny (Fr)	1996	5.3		VII/VIII							no reported damage
Saint-Paul de Fenouillet (Fr)	1996	5.0	0.06g	VI							no reported damage

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Cariaco	1997	6.9	0.25g	IX					F/L	displacement 0.4 m	- compression buckling of a water pipeline - rupture in torsion within the fault zone of the same water line - no damage to gas and hydrocarbon transmission lines
Quindio	1999	6.1	0.57g	VIII							no damage
Martinique (Fr)	1999	5.4	0.13g								no damage
Izmit	1999	7.4	0.4 g		150 to 600			67	F/L	displacement. 4.3 m	a leak on the landing flange for the underwater pipeline repaired by tightening the nuts
Chi-Chi	1999	7.7	1.0 g						F/L	displacement 10 m; landslides	no quantified data on the gas system penstock water line from a hydroelectric station was not damaged
Salvador	2001	7.4		VI					L	Landslides	no reported damage
Bhuj	2001	7.5	0.48g	X							no damage differential displacement of an overhead line
Molise	2002	5.7									no reported damage
Bam	2003	6.5	0.98g								power cuts on the water system reported
Al Hoceima	2004	6.2	0.24 g						F		no reported damage
Les Saintes (Fr)	2004	6.3	0.16g	IX					L		no reported damage
Sumatra	2004	9			36"						no reported damage
Wenchuan	2008	7.9			159-377						leaks on corroded pipelines leaks on illegally tapped pipelines leaks on unchecked welds
L'Aquila	2009	6.3	0.65g		113	5		64	F	displac. 0.10 m	rupture in distribution pipelines around the fault line system damaged
Maule	2010	8.8	0.65g						F/L		rupture in pipeline as result of sand displacement no damage on the TransAndes gas pipeline
Christchurch	2010/11	7,1/6,3							L		no reported damage
Tohoku	2011	9	3.0 g						L		no reported damage
Lorca	2011	5.1	0.34 g								no reported damage

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'pipe'1 or 'beam' type elements and to represent the soil loading on the pipeline with discrete spring elements (in [5], refined laws are presented and updated in [11]). This can be modelled using any finite elements analysis package, as long as it is able to model:

» Internal pressure effects
» User-defined stress - strain curves for pipeline material
» Non linear soil springs
» Large changes in pipeline geometry: the software must manage soil springs in the local pipeline coordinate system
» And provide outputs on strains at multiple locations around the pipeline circumference

The length of the pipe-type elements must be adequately chosen. In areas where large strain gradients are expected, this element length should never exceed 1D. For field bends, the length should not exceed 15° of the bend angle.
Although for a locally detailed picture of the stress/strain field, full 3D finite elements modelling of the soil and pipe would provide the most detailed results, all the guidelines (EC 8, AFPS-CT15 in its first edition in 1998, PRCI, ALA) use the same approach of the 1984 ASCE guidelines, as mentioned above. The parametric studies in AFPS-CT15 were performed using four extreme soils to cover a wide range of cases: loose and dense sand, and stiff and weak clay.

4.2 Specific modelling recommendations

» PRCI Report L51927 Honegger

The PRCI L51927 guidelines provide expressions for calculating soil spring constants for different soils. The expressions for maximum soil spring force are based upon laboratory and field experimental investigations on pipeline response, as well as general geotechnical approaches for related structures such as piles, embedded anchor plates, and strip footings. Several of the equations have been derived to fit published soil properties to facilitate their use in spreadsheets or other computer-based applications.
An issue is also to determine an effective length of the area to be modelled: it should be short enough to minimise CPU time but long enough to provide a realistic model. It extends beyond the pipeline displacement area, and this „anchor length" is defined by the axial soil force that causes pipe yield:

$$L_{\text{anchor}} = \frac{\pi . D . t . \sigma_y}{T_u} \qquad (1)$$

where: D = pipeline outside diameter;
t = pipeline thickness;
σ_y = axial yield stress;
T_u = axial soil force.

Boundary conditions and applied loads must be carefully defined. In particular, defining ground displacement may be uneasy. Ground movements representative of the displacement patterns and amplitudes for fault displacements, liquefaction induced settlements / lateral spreads or landslides are applied to the base of the soil spring elements. These ground displacements should be specified based upon estimates of relative ground movement at the depth of the pipeline. In some specific cases, geotechnical field investigations may be useful.
It is always conservative to assume that ground displacements are steep (large gradient). Relatively steep ground displacements have been observed at surface faults, lateral spreads or at the top of landslides, maybe less for settlements. In some locations, it may be possible to infer future ground displacement patterns from past earthquake displacements. For locations with little earthquake experience to provide information to determine ground deformation patterns, a steep displacement cannot be ruled out without the assistance of a specialist in geology or geotechnical engineering.
The selection of material properties, soil strengths, and ground movement patterns is an inherently uncertain process. Generally, additional analyses should be performed to provide information on the sensitivity of the computed strain levels to changes in input parameters to account for uncertainties.

» Other standards and codes

In AFPS-CT15, FE analysis was conducted with an element length of at most one diameter. Realistic steel behaviour laws have to be used in computations (EC 8, EN 1594).

5. STRAIN CRITERIA FOR DEFECT FREE ONSHORE PIPELINES

For specifying structures' resistance in general, and in particular to earthquakes, two limit states are considered:

» Serviceability Limit State (SLS) - operations are still possible
» Ultimate Limit State (ULS) – integrity is ensured, operations are not guaranteed, but may resume after checks and repairs.

In the case of pipelines, there may be discussions about the relevance of this distinction as long as ancillary equipment like valves, or others, are not taken into account. Indeed, lessons learnt from past earthquakes shows that such ancillary equipments, that are generally operated at a lower design factor than the pipeline itself, are not prone to fail. So the criteria found in Table 2 reflects this perception, by having all four detailed guidelines providing what can be called ‚ULS' type of strain criteria (that vary between sources). In addition, the PRCI L-51927 Report distinguishes between displacement controlled and load-controlled loading cases. Depending on the type of permanent ground movement, it can actually be a mix of the displacement and load control cases, or a displacement-controlled load case. To interpret this, let's consider that the pipeline experiences no further soil load once both the soil and the pipeline have

1 These elements allow computation of the internal pressure.

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sufficiently deformed to match each other's movement. For these two load cases, the PRCI report provides values for strain criteria that are summarised in Table 2.
Pipeline resistance criteria are defined in terms of allowable longitudinal compression and tension strains for onshore pipelines. The strain criteria assume that an analysis of pipeline response is performed using finite element analysis and bilinear soil springs as described previously. The criteria defined in this section are not applicable to analyses based upon approximations of pipeline response carried out using hand calculations that cannot resolve pipeline strains within a length of approximately one diameter.
The strain limits provided in this section are applicable to pipelines that meet the following conditions:

1) Pipeline material and fabrication equivalent to that specified in API 5L.
2) Joint connections using full-penetration butt welds in portions of the pipeline expected to experience stresses near or above yield (e. g., no bell-end welded joints, slip joints, lap-welded joints, sleeves).
3) Weld quality consistent with current welding procedures (e. g., API 1104).
4) Weld strength matching or exceeding the expected actual pipeline strength.
5) Pipeline, weld, and heat-affected zone toughness:
   a) Average Charpy energy greater than 40 J (30 ft-lb), or
   b) Average CTOD toughness greater than 0.20 mm.
6) Ratio of yield strength to tensile strength (Y/T) less than 0.92

Only if these conditions are met, strain criteria reported in Table 2 can be used.

MITIGATION TECHNIQUES

If the pipeline response is found to exceed the acceptance criteria, then a series of mitigation measures are available to limit strain:

6.1 Modifying backfill characteristics

» PRCI Report L51927 & AFPS-CT15

In order to reduce the load imposed by the soil, its global strength can be significantly reduced by:
Using a loose granular backfill (sand or gravel, at least with an internal friction angle of 35° maximum), associated with a trench angle of 60° in order to guarantee a rupture interface located in the backfill and not in natural soil.
Using a low friction coating or protective wrapping.
Geosynthetic lining of sloped trench wall, in order to significantly reduce the lateral ultimate strength of the soil.
Replacing soil with geofoam or crushable material to limit maximum loads on the pipeline, and which mechanical characteristics are much better controlled than soil ones.

6.2 Optimizing pipeline configuration

» PRCI Report L51927 & AFPS-CT15

The capacity of a buried pipeline to withstand ground displacement components can be improved by maximizing the distance from the deformation zone (fault rupture, settlement, lateral spread, landslide, etc.) to points of anchoring, typically side bends, overbends, and sagbends. Sharp bends, tees, branch fittings, valves, etc. also anchor the pipeline to some degree against axial movement and should be avoided within or near a zone of potential ground displacement. Good design practice is to provide a straight segment of pipeline as long as practical through and beyond the potential ground displacement zone to maximize the length of pipeline available to distribute strain.
In some cases, minor modifications to proposed or existing pipeline configurations can greatly improve performance. Such modifications include increasing the pipeline wall thickness, increasing the strength and toughness of the pipeline material, and replacing sharp bends and elbows with induction bends or gradual pipeline field bends.
AFPS-CT15 provides a parametric study for fault displacements that outlines the importance of the fault crossing angle and provides recommendations on the crossing angles.

6.3 Isolating the pipeline from the soil

» PRCI Report L51927

Lateral soil loads can be greatly reduced by placing the pipeline on the ground surface or on aboveground supports. Typically this is done by attaching sliding shoes to the pipeline that bear on structural steel members tied to the ground or mounted in an aboveground configuration.
More generally, the relative movement between soil and pipeline can be minimized or eliminated by providing space around the pipeline that is larger than the relative movement associated with poor pipeline response. Isolating the pipeline from ground displacement is generally practical only when the ground displacements are relatively small, the length of pipeline requiring isolation is relatively short, or the pipeline diameter is relatively small.
Mitigation concepts using culverts allow the pipeline to respond in a manner similar to an on-grade condition. The term culvert refers to any buried structure built partially or completely around the pipeline to provide an unobstructed space for the pipeline to deform in a direction transverse to its axial alignment.

7. DISCUSSION, GAP ANALYSIS AND PROSPECTS

7.1 Pipeline specifics

Like any other infrastructure, buried transmission pipelines may be subjected to earthquakes during their lifespan, so their resistance to seismic loads needs to be assessed. Many design codes and guidelines address the design and behaviour of above-ground infrastructure under such loads. However, these standards cannot be directly applied to buried transmission pipelines because of their two specific features:

1. Being buried, transmission pipelines are not affected by inertia, which usually dominates the behaviour of above-ground infrastructure. Buried pipelines follow ground displacements, e. g. deformations are directly applied by the ground to the pipeline.
2. Being very long linear structures, a pipeline cannot

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Seismic loads considered for pipeline design / assessment					Pipeline assessment issues
Permanent Ground Displacements				Soil compressive/tensile strains induced by seismic waves	Modelling pipe-soil interactions
	Surface faulting	Liquefaction	Landslides		
Specialised guidelines for seismic design and assessment of pipelines					
AFPS-CT15 § 3.3	$\Delta_m = 10^{-4,8+0,69\,M_w}$	Parabolic deformation applied $y-1=\frac{-x^2}{2500}$	Qualitative counter-measures proposed	$\varepsilon = \frac{V_{\max}}{c}$ $\varepsilon_{\max} = \varepsilon\left(\lambda/4\right) \le \frac{\tau_u \lambda}{4eE}$ $\tau_u = \alpha c_u + \frac{1}{2} H\gamma\left(1+K_0\right)\tan\eta$	Winkler / FE models proposed
PRCI – Honegger § 3.3	$\log(MD) = -1.38 + 1.02\,\log(SRL)$ $\log(AD) = -1.43 + 0.88\,\log(AD)$ $R_{fp} = \frac{P_{fr}}{2.P_g}$	$\boldsymbol{CRR}_{(\text{SPT or CPT data})} > \boldsymbol{CSR}$ $= 0{,}65\,.\,\boldsymbol{PGA}.\left(\frac{\sigma_{vo}}{\sigma'_{vo}}\right).r_d(z)$	$L_D = B.PGA.\left(1-\frac{A_c}{PGA}\right)\left(\frac{PGA}{A_c}\right)^2$	$\varepsilon = \frac{V_{\max}}{\alpha_c.c}$	Winkler / FE models proposed
Plastification allowed European seismic design standards					
EN 1998-4 § 3.3	Has to be accounted for, but no specific guidelines are provided			Introduces an importance factor that amplifies PGA $\varepsilon = \frac{V_{\max}}{c}$	Non linear FEM
Pipeline design standards / guidelines					
EN 1594 § 3.2	Has to be taken into account				Proposes the FE approach and to use simplified models without details
B31.8 § 3.1	Has to be taken into account (in a very general way)				n/a
ALA-Section 11 § 3.1	Has to be taken into account			$\varepsilon = \frac{V_{\max}}{\alpha_c.c}$ $\varepsilon_{\max} = \frac{\tau_{u\,\lambda}}{4\,A\,E}$	same as PRCI
ISO 13623 § 3.1	No reference to seismic design / assessment				
BS PD8010 § 3.1	Seismic loading is to be considered				
IGEM/TD1 § 3.1	Refers mainly to EC8-4 and EN 1594				

***Table 2**: Comparison summary for three categories of guidelines addressing pipeline resistance to earthquakes – mainly critical strains.*

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General Modelling recommendations	Integrity criteria for defect free onshore pipelines			Comments
	Pressure integrity	Ensure normal operability for load-and/or displacement-controlled conditions		
		Displacement-controlled interaction	Load-controlled interaction	
Analytical models for deformation in bends	$\varepsilon_{g.\text{shaking}} = 40\frac{t}{D}$ $\varepsilon_{tp-\text{fault}} = 0.02\ to\ 0.05$ $\varepsilon_{cp-\text{fault}} = 35\frac{t}{D}$ Mitigation measures	–	see EN1594	similar to PRCI with extensive parametric studies available for French transmission pipelines
$L_{\text{anchor}} = \frac{\pi . D . t . \sigma_y}{T_u}$	$\varepsilon_{cp} = 1.76\frac{t}{D}$ $\varepsilon_{tp} = 0.02\ to\ 0.04$ Mitigation measures	$\varepsilon_{co} = 0.437\left(\frac{t}{D}\right)^{1.72}\left[1 - 0.892\left(\frac{p}{p_y}\right)\right]^{-1}$ $\left(\frac{E}{\sigma_y}\right)^{0.70}\left(1.09 - \left(\frac{\Delta}{t}\right)^{0.086}\right)$ $\varepsilon_{\text{to}} = 0.01$ to 0.02 Plastification allowed	$\varepsilon_{cl} = 0.75\,\varepsilon_{co} \geq 2.42\left(\frac{t}{D}\right)^{1.59}$ $\varepsilon_{tl} = 0.005$	
–	$\varepsilon_{cp} = 40\frac{t}{D}$ $\varepsilon_{tp} = 0.03$	–	see EN1594	Provides general recommendations
Three types of acceptable modelling: ring, beam and shell, no details provided	General outline	Outlines strain-controlled displacements without details	Stress-based design, in general 0,72Rt0,5 is the highest operating value, 0,9Rt0,5 can be used in temporary loading	Addressed in informative annexes, more general than EC8 - qualitative
n/a	Only warnings			Consider earthquakes in the design of piping systems
	$\varepsilon_{cp} = 1.76\frac{t}{D}$ $\varepsilon_{tp} = 0.04$ $\varepsilon_{cp}\text{wave} = 0.75\left[0.5\frac{t}{D'} - 0.0025 + 3000\left(\frac{pD}{2Et}\right)^2\right]$ $D = \frac{D}{1 - \frac{3}{D}(D - D_{min})}$ $\varepsilon_{tp\text{wave}} = 0.5\ \%$	$\varepsilon_{to} = 0.02$ $\varepsilon_{co} = 0.5\frac{t}{D'} - 0.0025 + 3000\left(\frac{pD}{2Et}\right)^2$	$\sigma\text{bending} < \sigma\text{yield}$	Outlines that differential soil movements can't be taken into account with an elastic stress analysis

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be associated with a single uniform seismic load. The nature and amplitude of seismic loads vary greatly along the pipeline route. Consequently, it is not relevant to assess the behaviour of each pipeline section based on local conditions. Much more generic approaches must be used.

The need for generic approaches resulting from the last item can only be satisfied since buried pipelines resist very well to earthquakes. Lessons learnt from past earthquakes prove that pipelines compliant to modern standards have been able to withstand extremely large seismic loads without damage.

7.2 Guidelines based on an excellent feedback exist

Based on this very positive feedback, several standards and guidelines have been developed around the world, adopting generic approaches as mentioned above. A literature review performed here shows a very good agreement among these standards and guidelines regarding the overall methodology to be used to assess the resistance of pipeline to earthquakes. Some specific equations or criteria may differ from one document to another, leading to various degrees of conservatism. However the conditions in which special care is needed and mitigation techniques may be required are also similar. Only the two specialised guidelines for seismic design and assessment of pipelines AFPS-CT15 and PRCI L-51927 Report cover all issues in a systematic way, the less specialised documents leaving a lot of room for interpretations.

Based on these considerations, the following conclusions can be drawn to provide a consistent European approach to seismic design and assessment of pipelines. It is important to recall that application of EC 8 is compulsory in EC member states, which provides a common basis.

» Assess vibrations-induced strains in a wide-range parametric study

Deformations induced on pipelines by seismic waves are commonly regarded as an acceptable load for welded steel pipelines, as proven by the feedback from recent earthquakes. However, the amplitude of these deformations varies greatly depending upon the type of soil, the magnitude of the earthquake and the distance to the seismic source. Moreover, the consequences of these deformations for the pipeline depend on its geometry (OD and thickness). Therefore, a parametrical study should be performed to prove that seismic waves induce acceptable deformations on any type of soil and for any pipeline geometry, in an European context. This is feasible using a spreadsheet since simplified analytical equations exist and are commonly accepted. Special care is needed in this case for specific national interpretations (e. g. coefficient values) of EC 8-4 or lack thereof.

» Main issue: strains due to permanent ground movements

The main seismic loads to be considered are „permanent ground displacements“, i. e. surface faulting, soil liquefaction and landslides (possibility to be confirmed for an European context). For these loads, the approach is two-fold: (1) first apply a methodology to identify the zones where such events may occur, and quantify corresponding maximum soil displacements, (2) second assess pipeline resistance to such events.

The first step is usually addressed either through the use of local hazard maps or via calculations based on simplified equations. It is then relatively easy for an operator to map the zones concerned by the two/three phenomena mentioned above along a pipeline route. The second step can be more challenging and the use of numerical modelling is most of the time necessary. Although research is continuously being performed on numerical models for pipe-soil interaction, a current state of the art shows that the use of beams for the pipeline attached to special non-linear springs representing the soil is usually considered as the most robust compromise. The application of these models to the two/three scenarios can lead to various degrees of difficulty.

» For surface faulting and liquefaction, a generic and conservative geometry can usually be defined, depending only on quite few parameters. It is therefore possible to run a parametric study based on a numerical model that would provide the pipeline response in all representative configurations. Such an approach requires an initial investment in term of computation and modelling time, but avoids having to systematically perform specific studies for each identified hazard zone.
» For landslides, defining a conservative configuration is much more complicated and usually even impossible. Generic models can be applied but may often lead to extreme conservatism. The use of a specific model based on input parameters obtained locally in the field is then normally preferred. Treatment of the landslide hazard is indeed an area where improvements can be achieved in current standards and guidelines. Recent developments in monitoring techniques for both soil displacement and pipeline deformation should, among others, be regarded as a potential for significant improvement.

7.3 Way forward

Although the literature review has proven a good agreement on the methodologies to identify the seismic loads, define their nature, calculate their amplitude and model pipeline resistance when subjected to them, or suggest mitigation measures, some aspects of the current seismic standards and guidelines are open to discussion:

» The issue of pipeline check after an earthquake has not been explicitly formalised in the reviewed documents. While for modern pipelines, compliance with seismic design guidelines can be traced, and therefore the post-seismic pipeline check can be readily made, some aspects of the check may remain open, as illustrated by the case of very severe in-service defects.
» The state of the art review showed that while strain criteria are more relevant to displacement-controlled loads faced during ground movements,

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there is a gap documenting and formalising existing information on materials behaviour, and strain limits as a function of relevant material parameters.

» The issue of estimating permanent ground movements, already mentioned above, is an area where some research activities, especially on satellite use, are underway at PRCI. There are opportunities to assess whether these approaches may be relevant in Europe.

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