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SEISMIC RISK ASSESSMENT OF BURIED PIPELINES AT ACTIVE FAULT CROSSINGS

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ABSTRACT

A methodology is presented on assessing the seismic risk of buried steel pipelines crossing active tectonic faults through a comprehensive analysis by incorporating the uncertainty of the loading resulting from fault movement, soil response and the response of the pipeline itself. The proposed methodology is a two-step process. In the first step Probabilistic Fault Displacement Hazard analysis is implemented to quantify the probabilistic nature of the load, namely the imposed differential displacement on the pipeline due to large permanent fault displacements, incorporating all pertinent uncertainties regarding, for example, seismicity rate, maximum moment magnitude, etc. The second step is the “transition” from seismological data to pipeline structural response through a vector intensity measure represented by the fault displacement components in 3D. Advanced pipeline numerical simulations are then carried out in order to form pipeline strain hazard curves as a useful engineering tool for pipeline fault crossing seismic risk assessment.

INTRODUCTION

Worldwide rising energy demands lead to the construction of fuel pipelines that extend to thousands of kilometers. Several of these exist in seismic regions where they inevitably encounter active faults. So, pipeline-fault crossing is sometimes unavoidable, given that design of new pipelines is usually undertaken within a strict framework of constraints regarding environmental regulations, avoidance of populated areas and achievement of a high level of safety and efficiency. Thus, wherever a fault crossing is attempted, the potential for large differential fault displacements often becomes the premier cause of pipeline failure, as indicated by past events, and buried pipelines have to resist the strains and stresses developed when the surrounding soil undergoes large deformations. Acknowledging that pipelines are structures of high risk, whose potential failure or leakage may have irreversible consequences, it is deemed appropriate to perform a comprehensive risk analysis of pipeline fault crossing hazard by incorporating the uncertainty of the loading and the response of the soil and the pipeline itself. For this purpose in the present study a two-step methodology is presented comprising two independent and interrelated steps, i.e. quantification of the uncertain nature of the loading and pipeline structural analysis.

Considering that earthquakes and the associated fault displacements are naturally random events, the question arises as to what is the appropriate magnitude of imposed displacement that has to be taken into account during the structural design of a new pipeline. At this point two approaches are possible: the first is the deterministic one, where a particular seismic scenario upon fault activation is evaluated consisting of a postulated occurrence of an earthquake with a specified magnitude, or

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characteristic earthquake, at a specific location. However, using the Deterministic Seismic Hazard Analysis (DSHA) no further information is provided about the expected level of shaking or fault activation during pipeline life-cycle, the earthquake occurring probability and the effects of uncertainties in the various methodology steps. The second approach is the so called probabilistic one. The variable nature of earthquake loading and the commonly accepted incomplete knowledge related to the complex properties of the soil and the structures highlight the necessity of probabilistic concepts for earthquake assessment. Comparing the two available approaches, we prefer the latter to achieve more reliably the stringent safety requirements and simultaneously accomplish a compromise between safety and economy.

To achieve the above mentioned goal the proposed strategy consists of two tasks: (a) conduct the probabilistic analysis of fault displacement hazard, (b) perform pipeline structural analysis and then combine the results to carry out seismic risk analysis. Regarding the first task, the suitable tool for quantifying the probabilistic nature of the loads is the Probabilistic Fault Displacement Hazard Analysis (PFDHA) introduced by Youngs et al. (2003). PFDHA aims at quantifying the mean annual rate of exceeding various fault displacement levels at the site of pipeline fault crossing by taking into account the probability of fault existence and activation, fault location, fault slip rate and the strongest expected earthquake, as well as their epistemic uncertainties. Additionally, PFDHA provides the necessary information to assess potential effects to structural integrity of a buried pipeline and to make a risk-informed decision regarding site suitability for pipeline crossing when geological investigations are inconclusive. Proceeding to the second task, the numerical simulation fulfills the requirements for reliable and computationally efficient assessment of pipeline structural response. This latter dual objective can be succeeded using any available commercial structural analysis software capable of modeling pipeline through beam-type finite elements and pipeline-soil interaction through nonlinear translational springs. Then, combination of results leads through seismic risk analysis to the creation of hazard curves for selected pipeline intensity measure.

1. FAULT DISPLACEMENT HAZARD ANALYSIS

1.1 PIPELINE FAULT CROSSING

A continuous buried steel pipeline is investigated, considering for simplicity only a straight segment where it crosses a fault line. The fault itself is assumed to be planar with zero thickness and it appears on the ground surface as a straight line. The topology of the problem is illustrated in Fig.1. Therein, β is the pipeline-fault horizontal crossing angle, LF the fault length, L_p represents the distance of the crossing point on the surface from the closest fault end and ψ is the fault dip angle. The fault displacement can be represented in 3D by three spatial components: Δ_1 and Δ_2 are the fault-parallel and fault-perpendicular horizontal displacements, while Δ_3 represents the vertical component. When rotating the axes horizontally by the crossing angle β, Δ_1 and Δ_2 are transformed to Δx and Δy, i.e. the longitudinal and the transverse displacements with respect to the pipeline axis. The vertical displacements, Δ_3 and Δz coincide:

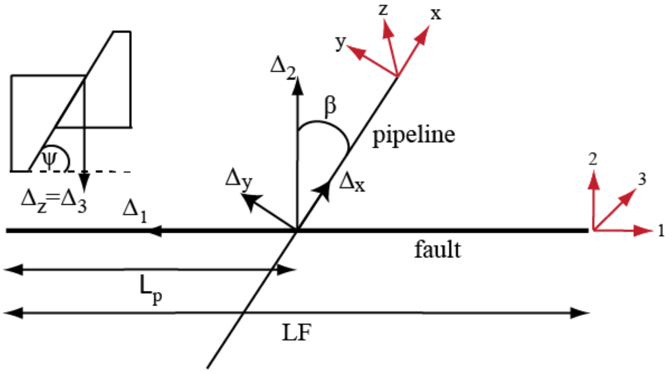

Figure 1. Pipeline fault crossing section (top left) and plan view (bottom right)

$$\Delta = \sqrt{\Delta_1^2 + \Delta_2^2 + \Delta_3^2} \text{ (fault displacement norm) with } \Delta_3 = \Delta_2 \tan(\psi) \quad (1)$$

$$\Delta x = \Delta_1 \sin(\beta) + \frac{\Delta_3}{\tan(\psi)}\cos(\beta),\ \Delta y = \Delta_1 \cos(\beta) - \frac{\Delta_3}{\tan(\psi)}\sin(\beta),\ \Delta z = \Delta_3 \quad (2)$$

1.2 PFDHA METHODOLOGY

Youngs et al. (2003) introduced the basis of PFDHA and proposed two discrete approaches within it, the "earthquake approach" and the "displacement approach". The "earthquake approach" is derived from Probabilistic Seismic Hazard Analysis (PSHA) introduced by Cornell (1968) and explicitly relates the occurrence of fault displacement on a fault at a site at or near the ground surface to the occurrence of earthquakes in the site region. The "displacement approach" needs extensive recorded or paleoseismic data. For the purposes of this study where few past measurements are available, only the first approach is viable. Then, adopting a Poisson assumption for earthquake occurrences, the Mean Annual Rate of Exceedance (MARE) of the fault displacement d can be expressed as:

$$v(d) = v_o(M_{\min}) \int_{M_{\min}}^{M_{\max}} f(m) \left[\int_0^{\infty} f(r \mid m) P^*(D > d \mid m, r)\, dr \right] dm \quad (3)$$

where $v_o(M_{\min})$ is the rate of all earthquakes above a minimum magnitude of engineering significance and is calculated based on the equation describing the seismicity of the investigated seismic source zone, $f(m)$ is the probability density function (PDF) of earthquake magnitude between a minimum value $M_{\min}$ and a maximum value M_{max} that the source can produce and $f(r|m)$ is the conditional PDF of the distance r of the crossing site to the rupture zone of magnitude m occurring on the fault. $P^*(D>d|m,r)$ is essentially a prediction equation for fault surface displacement that plays the role of the ground motion prediction equation (GMPE) used in classic PSHA. It consists of two terms:

$$P^*(D > d \mid m, r) = P(\text{Slip} \mid m, r) P(D > d \mid m, r, \text{Slip}) \quad (4)$$

The first term of Eq.4, $P(\text{Slip}|m,r)$, is the conditional probability of slip and expresses the probability that the rupture of the fault reaches the surface at the location of pipeline crossing. This probability can be calculated using either simulation or empirical models. The proposed methodology adopts the empirical model proposed by Wells and Coppersmith (1993) that depends only on earthquake magnitude. Regarding the second term of Eq.4 $P(D>d_o|m,r,\text{Slip})$, it is the conditional probability that the fault displacement will exceed a specific value d_o, given that slip occurs due to an earthquake of magnitude m at a distance r from the pipeline crossing. It is noted that only principal faulting will be considered without taking into account distributed faulting issues (Youngs et al., 2003).

In seismic risk analysis the roles and work of seismologist and structural engineer are typically separated by the use of an interface variable, known as the intensity measure (IM). Thus, seismological-level analysis (i.e. PFDHA) will produce hazard curves of the MARE given values of IM, typically PGA or $S_a(T_1)$, or even a vector of such quantities (Bazzuro and Cornell, 2002). The structural engineer then only needs to estimate the (distribution of) response of the structural system to given IM values. Similarly, for pipeline assessment this is achieved by adopting as IM the fault displacement spatial components Δ_1, Δ_2 and Δ_3. However, as the fault is assumed to be planar, fault displacement components Δ_1 and Δ_3 are structurally independent variables and they are adequate and efficient to fully describe the structural model. Vector IM $[\Delta_1, \Delta_3]$ is the adopted vector interface variable. The selection of fault displacement components as IM is assisted by the fact that their magnitude is crucial not only for characterizing fault type as "normal", "reverse" or "strike-slip", but mainly for assessing expected pipeline behavior. Past earthquake events have proven that normal and strike-slip fault movement result in pipeline bending and tension, while reverse fault movement in pipeline bending and compression.

Focusing on the fault displacement hazard estimation, it consists of three elements: (a) earthquake magnitude, (b) length of rupture and (c) rupture position along fault trace. The primary key element describing the seismic source is earthquake magnitude, ranging from a minimum value ($M_{\min}$) of engineering significance to a maximum magnitude ($M_{\max}$). This range of magnitude values is discretized into a number of bins provided by the engineer in order to account for all possible magnitude values that the seismic source can produce. Furthermore, the second element is the rupture length on fault trace, as it is common sense that rupture during an earthquake event does not extend to the entire fault length. Therefore it deems appropriate to discretize fault length into a number of surface rupture lengths (SRLs) shorter than the entire fault length. Also, SRLs are integer multiples of a minimum SRL that can be either provided by the engineer according to common practice, or empirical equations of Wells and Coppersmith (1994) can be used as an indication. Additionally, SRLs are equiprobable as it is in general hard to estimate the length of the rupture before an earthquake event has happened. Thus, since there is no indication regarding the position of the rupture on the fault, there is no indication on whether the rupture crosses the pipeline site. Accepting this leads to the introduction of the third element regarding the SRL position on the fault trace. Therefore, every SRL is accounted for all possible positions on the fault line with equal probability, even though only some of them cross the pipeline and contribute to fault displacement hazard on the pipeline crossing site.

1.3 PFDHA CONCEPTUAL ALGORITHM

PFDHA as outlined in section 1.2 is presented through a conceptual algorithm that comprises all the modifications and the assumptions introduced. The MARE of a defined fault displacement value d_o on pipeline crossing site, defined by $\lambda(D>d_o)$, is the application of the total probability theorem, using earthquake magnitude M as the conditioning variable:

$$\lambda(D>d_o)=v_o\sum_{i}P(D>d_o\,|\,M_i)P(M_i) \tag{5}$$

where v_o stands for the rate of all earthquakes above a minimum magnitude of engineering significance and is calculated based either on the equation describing the seismicity of the investigated seismic source zone or provided by the engineer as an input parameter, $P(M_i)$ is the magnitude occurrence probability calculated according to Gutenberg-Richter Bounded Recurrence Law (1944). Probability function $P(D>d_o|M_i)$ estimates the probability that fault displacement exceeds a defined value d_o given earthquake magnitude M_i and is summed over all magnitude values. Further breakdown of the conditional probability $P(D>d_o|M_i)$ of Eq.5 according to the total probability theorem yields the following equation:

$$\begin{aligned}P(D>d_o\,|\,M_i)&=\sum_{i}\sum_{j}\sum_{k}P(D>d_o\,|\,M_i,SRL_j,FD_k,Pos_m)\times P(SRL_j,FD_k,Pos_m\,|\,M_i)\\&=\sum_{i}\sum_{j}\sum_{k}P(D>d_o\,|\,M_i,SRL_j,FD_k,Pos_m)\times P(SRL_j,FD_k\,|\,M_i)\times P(Pos_m\,|\,M_i)\\&=\sum_{i}\sum_{j}\sum_{k}P(D>d_o\,|\,M_i,SRL_j,FD_k,Pos_m)\times P(SRL_j,FD_k\,|\,M_i)\times\frac{1}{N_m}\end{aligned} \tag{6}$$

Thus, in order to calculate the conditional probability $P(D>d_o|M_i)$ via Eq.6, apart from earthquake magnitude range discretization in i bins and rupture length discretization in j bins, a third discretization for the fault displacement (FD) option of PFDHA is necessary. It is noted that the proposed conceptual algorithm similarly applies when using either the average fault displacement (AD) or the maximum fault displacement (MD) option of PFDHA. Decomposing Eq.6 leads to two main parts. The first is the conditional probability of exceedance $P(D>d_o|M_i,SRL_j,FD_k,Pos_m)$ which stands at the core of the PDFHA calculation algorithm and necessitates detailed calculations that are carried out over each combination of bins of earthquake magnitude, rupture length, fault displacement and all possible positions of SRL_j along the fault trace. It is noted that calculations regarding conditional probability of exceedance adopt empirical equations among fault characteristics proposed by Wells and Coppersmith (1994) for all three fault types, i.e. normal, reverse and strike-slip.

Furthermore, as discussed in section 1.2, positions of SRL_j are assumed equiprobable, corresponding to a probability of $1/N_m$, with N_m being the total number of SRL_j positions. Thus, position is considered to be an independent variable. On the contrary, SRL_j and FD_k are well correlated given the earthquake magnitude. Therefore, for each combination (bin) (i,j,k) the value of $P(SRL_j,FD_k|M_i)$ needs to be estimated with the appropriate joint distribution $f(SRL_j,FD_k|M_i)$. The best known such distribution comes from Wells and Coppersmith (1994), that allows us to define $f(SRL_j,FD_k|M_i)$ as a joint normal PDF with non-zero correlation. For sufficiently small bins, the probability of SRL and FD falling in the bin given the magnitude can be approximated via a single PDF value at its center:

$$\begin{aligned} P_{i,j,k} &= \int_{FD_k-\frac{FD_{step}}{2}}^{FD_k+\frac{FD_{step}}{2}} \int_{SRL_j-\frac{SRL_{step}}{2}}^{SRL_j+\frac{SRL_{step}}{2}} f\left(SRL_j, FD_k \mid M_i\right) dFD\, dSRL \\ &\cong f\left(\log(SRL_j), \log(FD_k) \mid M_i\right) \Delta\log(FD) \Delta\log(SRL) \end{aligned} \tag{7}$$

To satisfy the requirement that the sum of $P_{i,j,k}$ over j and k (i.e. all values of SRL_j and FD_k) should be equal to one, we finally approximate the required probability function as:

$$P\left(SRL_j, FD_k \mid M_i\right) = \frac{P_{i,j,k}}{\sum_j \sum_k P_{i,j,k}} \tag{8}$$

1.4 UNCERTAINTY ANALYSIS

Uncertainties are incorporated in seismic hazard analysis due to the probabilistic nature of the problem. It is then a dire necessity to identify and quantify them since the use of mean hazard curve is highly sensitive to the most severe of the alternative scenarios considered and violates the distinction between uncertainties (Bommer and Scherbaum, 2008). From its origins, PFDHA can incorporate any quantifiable uncertainty. The present study incorporates epistemic uncertainties related to the inadequate understanding of the nature and can in time be reduced with better observations. Coming to practice, epistemic uncertainties lead to alternative hazard curves and are handled in seismic hazard analysis through logic trees. The construction of a logic tree includes the production of alternative models for various input variables and the assignment of weight factors to the different branches. After setting up a logic tree, hazard calculations are performed following each possible branch of the tree. Coming to weight factors, according to Abrahamson and Bommer (2005), they have to be selected in such a way that are not frequency-based probabilities, as tree branches represent the belief of the engineer in the alternative models.

In the proposed methodology the logic tree illustrated in Fig.2 is adopted, which accounts for three variables, i.e. seismic rate, earthquake magnitude and fault displacement option of PFDHA, either maximum or average. Regarding the first variable, seismic rate is a determinant feature of the seismic source with high uncertainty and usually the mean value of seismic rate is provided by seismologists. In this context, a weight of wv_2=0.40 is appointed to the mean value of seismicity and weights wv_1=wv_3=0.30 are appointed for seismicity values lower and higher that the mean value, respectively. Proceeding to the second variable, earthquake magnitude plays a crucial role among earthquake characteristics. While minimum magnitude M_{min} is chosen by assuming that lower values do not contribute to seismic hazard, mean maximum magnitude M_{max} provided by seismologists is under question. So, weight for mean value of M_{max} is chosen as wM_2=0.60 and lower and higher values are chosen as wM_1=wM_3=0.20. Finally, Youngs et al. (2003) suggest the use of either average or maximum fault displacement option for normalizing fault displacement data sets throughout calculation of ground motion prediction equation. Wells and Coppersmith (1994) suggest the use of average fault displacement value for underground facilities because it is generally unknown whether the maximum displacement will occur at the site of interest. Under this suggestion it is considered that the average displacement is a more reliable quantity compared to the maximum displacement. So, a weight of wD_1=0.70 is adopted for the average displacement approach, while a weight wD_2=0.30 for the maximum displacement approach. It is noteworthy that the weights for logic tree branches adopted here are within the scope of illustrating the proposed methodology. In practice, selection of weights is a more complicated procedure that often depends heavily upon expert opinion elicitation.

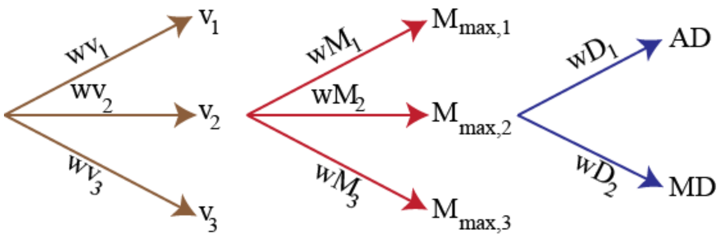

Figure 2. Uncertainty analysis logic tree

1.5 FAULT DISPLACEMENT COMPONENTS

In the proposed methodology fault displacement components are adopted as the IM between seismic hazard analysis and pipeline structural analysis. However, there are not sufficient data and information regarding their distribution with reference to fault displacement norm. Thus, in the present study a simple and approximate procedure for calculation of fault displacement components magnitude based on the fault type. Consequently, whether the fault type is normal/reverse (NR) or strike-slip (SS), the independent component of fault displacement is assessed assuming a uniform distribution. The latter is a reasonable assumption which may be replaced if more or adequate data are available in the future. The magnitude of the independent fault component is assumed to range from 2/3D up to 0.90D. The range limits adopted here are reasonable assumptions based on the fault characterization. Hence, the lower bound equals 2/3D, which is larger than 0.50D, in order to indicate the dominance of Δ_1 or Δ_3 component with respect to fault type being SS or NR, respectively. On the other hand, through the upper bound of 0.90D it is acknowledged that fault movement is usually three dimensional in nature. The aforementioned introduction of fault components distribution allows the evaluation of fault displacement hazard for a vector intensity measure. To do so, for each value of total fault displacement we sample corresponding equiprobable triplets of individual component values (Δ_1, Δ_2, Δ_3). Then, the respective value of MARE is equally distributed among the samples taken and the resulting cumulative function is numerically differentiated to estimate the Mean Annual Rate Density (MARD, Bazzurro and Cornell, 2000). MARD is not rate but rate density, in the same way that a PDF is related to a CDF. In other words an integration of MARD over a 2D interval of Δ_1 and Δ_3 (to which Δ_2 is functionally related) will result to the MARE of events occurring in this interval.

2 PIPELINE STRUCTURAL ANALYSIS

The physical problem of the pipeline-soil interaction is characterized by high complexity and uncertainty. However, the latter is not considered throughout the present study. Pipeline-soil interaction complexity is approached here using numerical modeling, which stands as the preferred way to handle it with sufficient accuracy, reliability and minimum computational effort.

2.1 PIPELINE NUMERICAL MODELING

Towards modeling pipeline-soil interaction, in the present study a reliable simulation technique is adopted by modeling the pipeline using beam-type finite elements, as their capability to calculate stresses and strains at selected locations along the pipeline length as well as over the cross-section allow engineers to quickly assess pipeline behavior. Moreover, pipeline-soil interaction effects are modeled using unidirectional nonlinear springs in three directions as illustrated in Fig.3. Particularly, pipeline-soil friction is modeled using springs in the pipeline longitudinal direction, which depend on backfill soil and pipeline coating characteristics; while pipeline transverse horizontal movement in the trench is modeled using horizontal springs. Finally, couples of springs in the vertical direction model pipeline's upward and downward vertical movement, with their characteristics being significantly different due to unlike characteristics of backfill soil over the pipeline and of the native soil underneath.

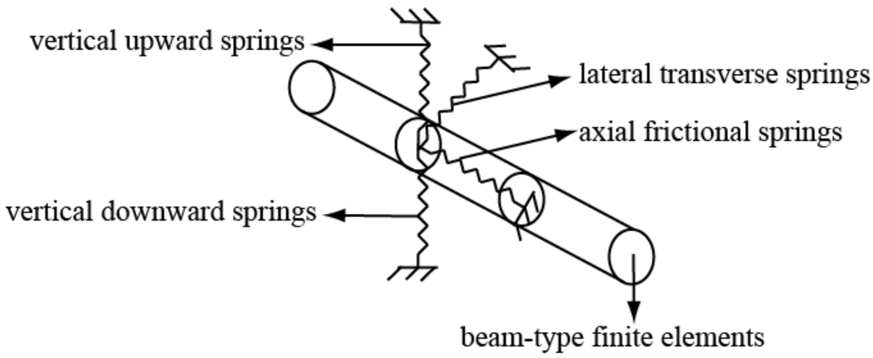

Figure 3. Soil-springs configuration

2.2 PIPELINE STRAIN HAZARD CURVES

Permanent ground displacements are imposed on the pipeline in a quasi-static manner due to the differential ground movement. Although pipeline steel is characterized by high ductility, high level strain concentration due to fault activation and the associated imposed displacements may be of great concern: high tensile strains endanger the integrity of girth welds between adjacent pipeline parts, while high compressive strains lead to wall local buckling. Both failure modes are associated with fractures, leakage and operability obstruction. So, since the primary consideration for buried pipeline design is the safety checking of strain demands against the respective capacities, strain hazard curves are a suitable tool to perform a probabilistic estimation of pipeline potential failures. Whilst numerical modeling presented in section 2.1 is the tool to define pipeline strain demands, Codes and Standards provide strain capacity terms of strain limitations in order to maintain longitudinal strains within operable limits. ASCE-ALA (2001) provisions suggest the tensile limit $\varepsilon_{t,c}$ of Eq.9 and the compressive limit $\varepsilon_{c,c}$ of Eq.10 for longitudinal strains resulting from ground movement due to earthquake.

$$\varepsilon_{\mathrm{t,c}} = 2\% \tag{9}$$

$$\varepsilon_{\mathrm{c,c}} = 0.50\left(\frac{t}{D'}\right) - 0.0025 + 3000\left(\frac{pD}{2Et}\right)^2$$
$$\text{where } D' = \frac{D}{1 - \frac{3}{D}\left(D - D_{\min}\right)} \tag{10}$$

where t is the pipeline wall thickness, D the pipeline external diameter, D_{min} the pipeline internal diameter, p the internal pressure and E the pipeline steel Young's modulus.

3 ILLUSTRATIVE EXAMPLE

To illustrate the proposed methodology, a numerical example and its associated results are hereafter presented consisting of the proposed two-step methodology.

3.1 FAULT DISPLACEMENT HAZARD ANALYSIS

A normal fault is considered with length equal to 100km and fault dip angle equal to ψ=70°. Pipeline crossing is located at a distance of L_p=40km from the left fault edge, while pipeline-fault crossing angle equals to β=10°. The minimum earthquake magnitude under consideration is M_{min}=5.0 and the mean maximum earthquake magnitude is M_{max}=7.3. Fault displacement values under examination range from 0.01m up to 2m. Uncertainty parameters listed in Table.1 are in accordance to section 1.4.

Table 1. Uncertainty parameters considered in the analysis

v_1=0.18	wv_1=0.30	$M_{max,1}$=7.2	vM_1=0.2	AD	wD_1=0.70
v_2=0.20	wv_2=0.40	$M_{max,2}$=7.3	vM_2=0.6	MD	wD_2=0.30
v_3=0.22	wv_3=0.30	$M_{max,3}$=7.4	vM_3=0.2		

The implementation of PFHDA through the conceptual algorithm of section 1.3 results to Fig.4, illustrating the MARE of fault displacement values on pipeline crossing site ranging from 0.01m up to 2m. The descending curve shape is predictable, as the larger the fault displacement the smaller the MARE is. At the same time, the maximum MARE is lower than the value 1 even for a relatively small fault displacement, owing to the fact that on one hand a lower bound limit for earthquake magnitude is adopted in PFDHA and on the other hand that it has to be lower that the weighted average of seismic rate values. Furthermore, based on section 1.5, in Figs.5 and 6 the hazard surface for fault displacement components Δ_1-Δ_3 and the pipeline Δ_x-Δ_y displacement components on crossing site, respectively, are presented.

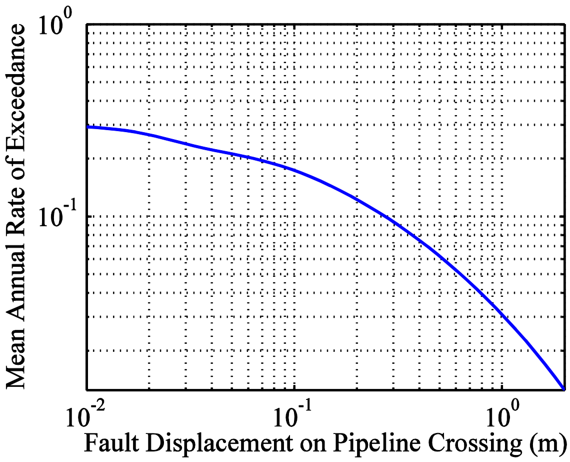

Figure 4. MARE for fault displacement on pipeline crossing site

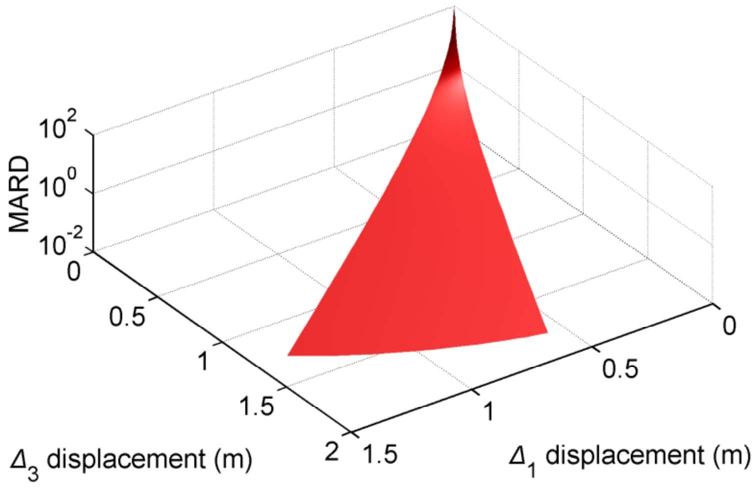

Figure 5. Δ_1-Δ_3 fault displacement components hazard curve

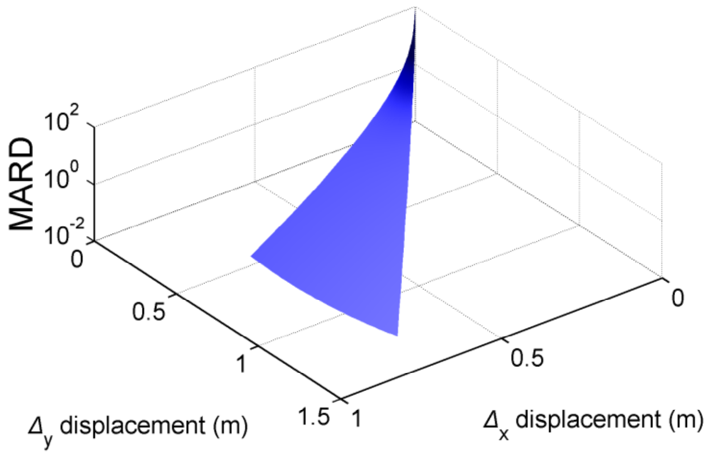

Figure 6. Δ_x-Δ_y pipeline displacement components hazard curve

3.2 PIPELINE NUMERICAL SIMULATION

Pipeline numerical modeling is performed with the commercial finite element software ADINA (2008). A typical buried high-pressure natural gas pipeline is considered, featuring an external diameter of 0.9144m (36in), a wall thickness of 0.0119m (0.469in), a total length of 1000m, while fault trace is located in the middle of the pipeline length and the pipeline is coated with coal-tar. The steel is of API5L-X65 type and is considered as bilinear with yield stress 448MPa, failure stress 531MPa, failure strain 23.50%, elastic Young's modulus 210GPa and plastic modulus 1.088GPa. Referring to burial conditions, it is assumed that the pipeline's top is buried under 1.30m of medium-density sand with friction angle equal to $\varphi=36^o$ and unit weight equal to $\gamma=18kN/m^3$.

Regarding the modeling technique introduced in section 2.1, the pipeline is modeled using beam-type finite elements with longitudinal mesh discretization equal to 0.50m, after a mesh density sensitivity analysis was carried out to investigate the optimum mesh density. Additionally, the soil is introduced through elastic-perfectly plastic unidirectional springs whose properties are estimated according to ASCE-ALA provisions and are listed in Table.2. Thus, the finite element model used herein consists of a total number of 10006 nodes and 2000 beam-type finite elements modeling the pipeline and 8004 spring elements modeling the soil, 2001 elements for every soil spring type presented in Fig.3. Finally, the differential ground movement is applied statically on the hanging wall of the fault, as permanent displacement in the corresponding ground "node" of soil springs, while a geometrically and materially nonlinear analysis is carried out proceeding incrementally to the final fault displacement derived from probabilistic hazard analysis.

Table 2. Soil spring properties considered in the numerical analyses

	Yield force (kN/m)	Ultimate displacement (mm)
axial (frictional) springs	40.72	5.00
transverse horizontal springs	320.22	88.58
vertical upward springs	45.47	18.00
vertical downward springs	1494.61	114.3

As an example, the numerical results from a single analysis of a pipeline subjected to 0.10m of fault displacement are presented in Fig.7 and Fig.8. The former illustrates the pipeline deformed shape at the end of the analysis in 3D, while the latter presents the distribution of maximum longitudinal strains and the distribution of soil friction force along pipeline axis. Evaluating the results it follows that the distribution of longitudinal strains demonstrates that about 150m of pipeline length on each side of the fault are under tension. However, the distinction between maximum and minimum longitudinal strains indicates that only for a distance of 50m away from fault the presence of compressive strains is notably. Additionally, soil friction force distribution in Fig.8 denotes that soil yielding extends along 50m on each side of the fault.

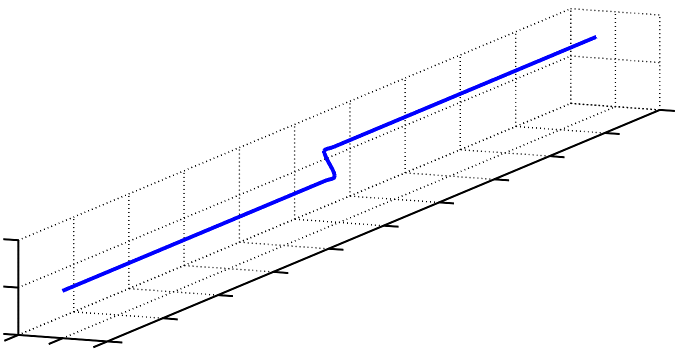

Figure 7. Pipeline deformed shape

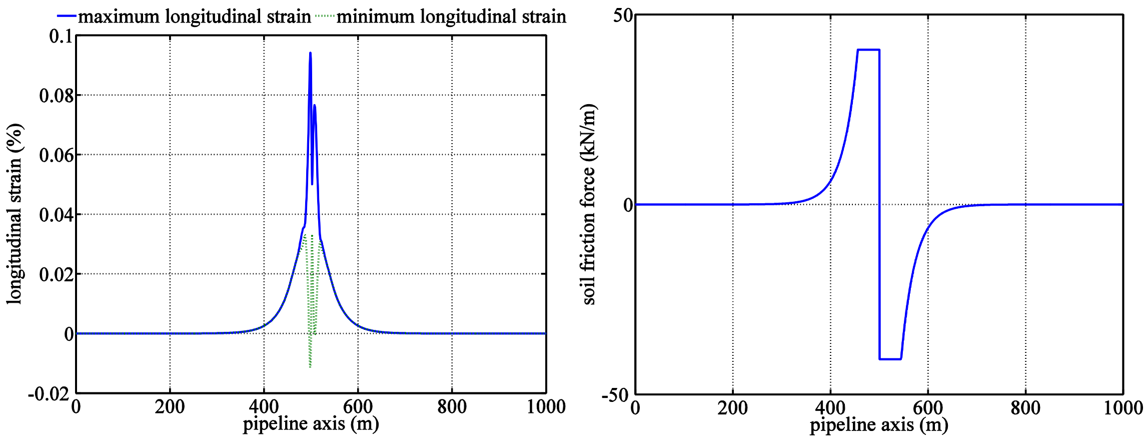

Figure 8. Distribution of longitudinal strains (left) and soil friction forces (right) along pipeline axis

3.3 PIPELINE STRAIN HAZARD CURVES

For the purposes of the presented illustrative example, we shall derive the pipeline strain hazard curves using the results from numerical analyses and adopting a basic deterministic approach by assuming that the fault displacement hazard is represented by the mean, considering epistemic uncertainties. In other words, only one worst-case combination of fault displacement components will be considered (essentially maximizing the transverse displacement). Thus, considering that fault is of normal type, it is assumed that distribution of fault displacement components in not uncertain and the Δ_3 vertical fault displacement component equals 90% of fault displacement D. The latter is in agreement with the uniform distribution of fault displacement components adopted in section 1.5. Thereby, Δ_3 fault displacement components are calculated for the range of fault displacement values under consideration. The rest of fault displacement components, namely Δ_1 and Δ_2, are estimated via Eq.1.

With regard to strain capacities, they shall also be considered to be deterministic rather than uncertain quantities. Longitudinal strain limits introduced in section 2.2, and especially compressive strain limit of Eq.10, includes a term for internal pressure, which in reality acts as a relief against external soil pressure. In the present case study it is assumed as a less favorable situation that internal pressure equals zero and the corresponding final term of Eq.10 is neglected. So, applying Eq.10 for our case study yields a compressive strain limit equal to 0.35%.

Combining results of numerical analyses with results of PFDHA leads to the creation of pipeline strain hazard curves that are illustrated in Fig.9 for longitudinal tensile and compressive strains, respectively. Assessment of stain hazard curves in Fig. 9 indicates that tensile strains exceed the strain limit of 2%, presented with dashed line, with mean annual rate of exceedance equal to 0.0095. Thus, given the adopted memoryless Poisson model in the probabilistic seismic hazard analysis, the longitudinal tensile strain will exceed the code-based limit on average once in 62 years or with P=1-exp(-0.0162×50)=55.51% probability in 50 years. On the other hand, compressive strains are sufficiently below the strain limit of 0.35% that is presented with dashed line. It is also useful to mention that the significant difference between compressive and tensile strain level is attributed to high level of tension compared to compression that results from normal faulting to buried pipelines. Thus, given the assumptions of the present analysis there is no risk of failure due to buckling phenomena, but there is considerable risk concerning tensile strains that mainly endanger girth welds.

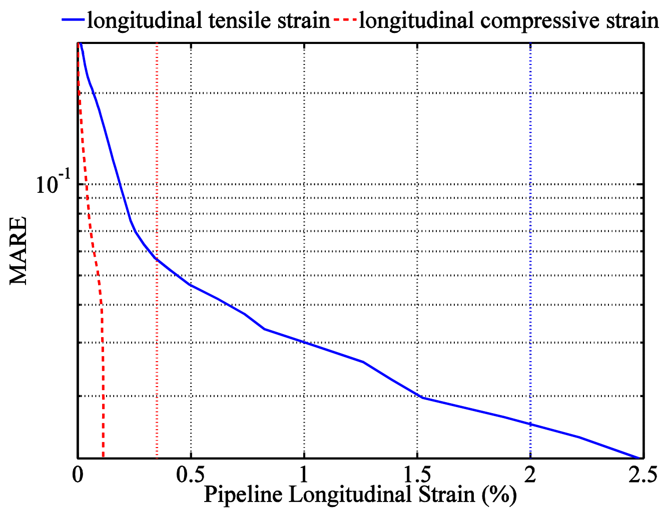

Figure.9 Longitudinal strains hazard curves

CONCLUSIONS

A methodology for seismic risk assessment of buried steel pipelines crossing active faults is presented. The first step includes the Probabilistic Fault Displacement Hazard Analysis methodology as adjusted for pipeline fault crossing. The conceptual algorithm of the proposed methodology is also presented, by also taking into account epistemic uncertainties. The second step is the "transition" from seismological data to structural analysis through the vector intensity measure of fault displacement components. Strain hazard curves are created by associating numerical results to hazard analysis in order to compute the mean annual rate of exceedance of longitudinal strains, which are compared to code-based strain failure criteria. The proposed approach offers a path for comprehensive performance-based assessment (and potentially design) of buried pipelines crossing active faults. Using a simple PFDHA implementation together with a nonlinear structural analysis software the hazard of pipeline crossing in terms of strains can be estimated. The proposed methodology provides engineers with a reliable estimation tool, admittedly requiring programing of the conceptual algorithm, but offering both seismic risk and pipeline numerical analyses at low computational effort.

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