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Performance-based assessment of protection measures for buried pipes at strike-slip fault crossings

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ABSTRACT

Onshore buried steel pipelines are vulnerable to fault rupture, where large ground displacements are imposed on the crossing pipe and thus protection measures are often necessary to avoid failure. A three-step methodology based on the framework of performance-based earthquake engineering is presented on assessing the effectiveness of protection measures against the consequences of strike-slip faulting on pipes. Firstly, the randomness of the fault movement is quantified, next the pipeline mechanical behavior is numerically assessed and finally the results are combined to extract the strain hazard curves, which are easy-to-handle engineering decision making tools. The various protection measures used in engineering practice or proposed in the literature are evaluated through the mean annual rate of exceeding strain values, also including a simple safety checking format at the strain level. Conclusions are extracted from the proposed assessment methodology on the efficiency of measures with reference to engineering practice and safety requirements of the pipeline operator.

1. Introduction

Onshore buried steel pipelines are critical lifelines for both the society and the global economy, as they comprise the main means of fossil fuel transportation. However, pipelines located in seismic areas shall inevitably cross tectonic seismic faults, whose activation results to imposed large permanent ground displacements on the crossing pipeline. In major past earthquake events, fault movement has been found to be the dominant cause of pipeline failure compared to other seismic-induced actions, such as wave propagation [1]. The principal failure modes in such case are local buckling of the pipe wall due to developing compression and tensile fracture of girth welds between adjacent pipeline parts due to concentration of tensile strains. Taking into account that any potential pipeline failure may result to environmental pollution, economic losses and directly or indirectly to human injuries, it is deemed appropriate to establish a methodology for seismic risk assessment and to introduce protection measures to avoid the aforementioned repercussions.

Earthquakes are typical phenomena that are characterized by high randomness. This fact raises the question as to the appropriate magnitude of fault offset that has to be taken into account in the earthquake resistant design of buried pipes. In the commonly applied deterministic approach, a single fault displacement is considered as the worst case scenario, consisting of a postulated occurrence of an earthquake with a specific magnitude at a specific location. This approach provides only a point estimate of unknown likelihood, while the effects of uncertainties encountered in the various design stages are typically neglected, or at best handled with unknown conservatism. Instead, in the probabilistic approach it is attempted to quantify the randomness of the loading, given that the available knowledge and understanding of fault movement is inadequate. This approach allows the design of a new or the assessment of an existing pipeline at a pre-defined level of risk that is consistent with a desired allowable lifetime probability, as mandated by financial, regulatory and legal constraints. Therefore, a better balance between economy, safety and environmental responsibility can be accomplished. This probabilistic approach is thus adopted here.

The proposed methodology for seismic risk assessment of buried pipelines at fault crossings consists of three interrelated steps: (1) conduct seismic hazard analysis to quantify the fault displacement hazard, (2) perform pipeline structural analysis to obtain developing strains and then (3) combine the results to estimate the risk. The resulting risk is then used to directly compare the performance of a pipeline at a given site and thereby evaluate the effectiveness of alternative mitigating measures against the consequences of faulting. The theoretical background for the general case of unprotected buried pipelines is presented in [2]. The methodology is based on the framework for Performance-Based Earthquake Engineering of Cornell and Krawinkler [3], which has been adopted by the Pacific Earthquake Engineering Research (PEER) Center.

The appropriate tool for the seismic hazard analysis is the

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Probabilistic Fault Displacement Hazard Analysis (PFDHA), whose basis was introduced by Youngs et al. [4]. PFDHA aims at quantifying the mean annual rate (MAR) of exceeding (λ) various fault displacement levels at a given site. The MAR of exceedance is the primary means of representing time-related risk. Engineers are typically more familiar with the equivalent probability of exceedance over a given time period, such as the $p = 10\%$ probability of exceedance in $T = 50$ years being a design target for most buildings. This corresponds to a MAR of exceedance of $\lambda = -\ln(1 - p)/T = 0.0021$. In PFDHA the MAR of exceeding a fault displacement can be assessed by incorporating any available geological and seismological data, for example, fault slip rate, rupture location, fault activation probability and distribution of earthquake magnitudes along with the corresponding uncertainties. Within the present study, the aim is to extend this estimation to arrive at the MAR of exceeding given levels of pipeline strain due to faulting. The second step consists of the pipeline's structural analysis, where the maximum compressive and tensile strains are obtained, considering fault offset magnitudes obtained from the seismic hazard analysis. Finally, in the third step, results from the previous steps are combined to estimate strain hazard curves, i.e. curves of MAR of exceeding given strain levels. The evaluation of seismic risk for a selected limiting strain value, in terms of estimating its mean annual rate of exceedance [5], is adopted in this third step to assess the pipeline seismic risk.

In case of an earthquake event, the response of buried pipes differs from other structures, such as buildings and bridges, where the foundation is forced to follow the ground movement and the superstructure is excited due to its inertia. Contrary, buried pipes are embedded in soil and in case of fault movement, the structure is forced to follow the ground movement by developing excessive deformation and consequently significantly high strains. Therefore, the design against faulting is carried out in strain terms (Strain Based Design), rather than stress terms, as recommended by pertinent codes, for example, in ALA guidelines [6], given that the problem is displacement-controlled. The safety checking is thus expressed as:

$$\varepsilon_{dem} \leq \varepsilon_{cap} \tag{1}$$

where the strain demand ε_{dem} is obtained from the structural analysis and the strain capacity ε_{cap} is provided by structural codes and standards, where strains are limited to avoid local bucking and/or tensile fracture.

Pipe protection through minimizing the developing strains remains a top research objective both for the academia and the industry. An extensive overview, followed by a comprehensive evaluation of various seismic protection measures for buried pipes under faulting has been presented in [7]. Protection measures can be divided into three main categories:

- Friction reduction measures, which aim at reducing the pipe – soil friction that is developed on the pipe – soil interface due to the pipe movement in the trench.
- Pipe strengthening measures, which aim at increasing the pipe strength and stiffness.
- Other measures, which cannot be classified in the two previous categories.

A performance-based assessment of various mitigating measures is offered here. Initially, the seismic risk assessment theoretical background is outlined. Then, the effectiveness of measures is assessed through a case study. Special attention is paid (1) to the demonstration of the difference between the deterministic and the probabilistic approach on assessing the efficiency of protection measures and (2) in providing a framework for pipeline operators to decide whether any proposed measure can satisfy their requirements.

2. Methodology for performance-based assessment

2.1. Seismic hazard analysis

2.1.1. Fault displacement hazard

The "earthquake approach" of PFDHA that is directly derived from Probabilistic Seismic Hazard Analysis [8] is adopted, relating the occurrence of fault displacement (Δ) at a site to the occurrence of earthquakes at the fault. Only principal faulting is evaluated, without considering the contribution of distributing faulting on seismic hazard [4]. Moreover, only on-fault displacements are examined, as the problem under investigation is a main transmission pipeline crossing a primary fault and off-fault displacements [9] are not considered.

In the application of PFDHA four factors are considered: (1) earthquake magnitude (M), (2) surface rupture length (SRL), (3) rupture position along the fault trace and (4) position of the crossing site. The earthquake magnitude stands as the key factor for describing a seismic source and ranges from a minimum value ($M_{\min}$) of engineering significance, assuming that lower magnitudes do not contribute to the seismic hazard, to a maximum value ($M_{\max}$), which is constrained by the fault characteristics. The range of magnitude values is discretized into a number of bins to account for all possible values. Thereafter, accepting that different earthquakes may rupture fault lengths of different size, the surface rupture length (SRL) along the fault trace is introduced as the second factor. The position of SRL on the fault trace (third element) and whether it will intercept the pipe (fourth element) are considered, admitting that earthquakes of the same magnitude may rupture fault segments of different length. Thus, it is necessary to deal with a variety of potential SRLs, each at a different position. However, due to the lack of detailed fault-specific data, it is assumed that SRLs of the same size are equiprobable. For simplicity of bookkeeping, a minimum SRL size is determined, for example, as corresponding to the minimum earthquake magnitude of interest via empirical equations [10], while all subsequent larger SRLs are regarded as integer multiples. In practice, every SRL size is accounted for at all possible positions, keeping track of those that intercept the pipeline and thus contribute to fault displacement hazard at the pipeline crossing site.

PFDHA is implemented herein using the total probability theorem in order to estimate the MAR of exceeding fault displacement at the pipeline crossing site, denoted by $\lambda_\Delta(\delta)$. It is noted that, in general, the parameters are denoted by capital letters, for example, fault displacement parameter Δ, and their discrete values by lowercase letters, for example, corresponding fault displacement value δ. The MAR of exceedance is a summation over all possible distinct scenarios that could produce an exceedance of fault displacement δ:

$$\lambda_\Delta(\delta) = \nu \sum_i P(\Delta > \delta \mid m_i) P_M(m_i) \tag{2}$$

where ν is the rate of all earthquakes with magnitude $M > M_{\min}$ and $P_M(m_i)$ is the probability of earthquake magnitude M, for example, according to the Gutenberg-Richter Bounded Recurrence Law [11]. Kramer [12] provides also an interesting overview on the estimation of earthquake occurrence probability. The function $P(\Delta > \delta| \ m_i)$ estimates the probability that fault displacement exceeds a defined value δ, given an earthquake of magnitude m_i has occurred:

$$P(\Delta > \delta \mid m_i) = \sum_j \sum_t \sum_k P(\Delta > \delta \mid SRL_j, FD_t, Pos_{k,j}) \times P(SRL_j, FD_t \mid m_i) \times 1/N_j \tag{3}$$

Discretization of parameters is introduced in Eq. (3) to account for all possible cases: (1) earthquake magnitude (m_i) discretization in i bins, (2) rupture length (SRL_j) discretization in j bins, (3) $k = 1,2,\ldots,N_j$ number of positions of the rupture length and (4) keeping track and discretization of the average or the maximum displacement of the entire fault FD_t. It is noted that FD_t characterizes the entire fault rupture