PHYSICS-BASED REPAIR RATES FOR PIPELINES SUBJECT TO SEISMIC EXCITATIONS

Leandro IANNACONE¹, Paolo GARDONI²

ABSTRACT

Seismic motion can have devastating effects on buried pipelines, often overlooked in favor of aboveground structures. Differential ground movement at the ends of the different segments of a pipeline can give rise to stresses and deformations that can cause leaks and ruptures, ultimately impairing the serviceability of the entire water network and generating major, catastrophic disruption of essential services for human needs. For this reason, it is important to quantify the consequences of seismic motion due to earthquakes on the serviceability of the system. In particular, tools are needed to predict the level of intervention required on the network in the immediate aftermath of the seismic event, in order to properly allocate resources and optimizing the recovery of the system. Current approaches for the assessment of reliability and resilience of networks subject to a hazard event typically use repair rate curves for the elements in the network, with no clear distinction between the linear elements and their connections. These curves provide estimates for the number of repairs needed after the occurrence of an earthquake of given intensity. They are characterized by high levels of uncertainties being based primarily on expert judgement and on a limited amount of data points and, in general, they do not provide accurate estimates. This work develops physics-based repair rate curves for the quantification of the damage due to seismic events. In particular, the proposed probabilistic models estimate the capacity and the demand of pipelines taking into account the properties of the pipes as well as of the soil they are buried in. By linking capacity and demand to physical variables, it is possible to develop new repair rate curves that are specific for given physical variables of the pipe and soil. The proposed model allows to accurately assess the effects of an earthquake on networks pipelines, providing valuable information for the resilience and life-cycle analysis of these systems.

Keywords: Water Network; Repair Rate; Earthquake; Pipelines; Reliability

1. INTRODUCTION

Segmented buried pipelines undergo seismic damage as a consequence of wave propagation due to earthquakes, which causes strains on the segments and dislocation at the joints. It is of utmost importance to quantify the damage expected on a network as a consequence of a seismic event of given intensity, in order to properly identify the required deployment of resources in the aftermath of the event and predict the capability of the damaged system to withstand the new demands (Guidotti et al. 2017). By relating the intensity measure of the shock to the expected number of repairs per unit length of line, repair rate curves constitute the basis of the analysis for the entire network. Models are available in literature to quantify the reliability and resilience of water networks subject to wave propagation (such as Guidotti at al. 2017, Porter et al. 2017, Jeon and O’Rourke 2005); these models try to predict the performance of the network as a whole but the predictions are often based on repair rate curves for the pipelines that are generally empirical and roughly take into account the physics of the problem (American Lifeline Alliance 2002). In addition to providing poor estimates, these curves suffer from poor flexibility as they use a set of approximate coefficients to adjust for different scenarios such as different soils, different materials and different burial depths. Furthermore, the final output of number of repair per unit length

¹PhD Student, Dept. of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA, leandro@illinois.edu
²Professor, Dept. of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA, gardoni@illinois.edu
of pipeline does not distinguish between damage to pipeline joints and damage to pipeline segments, which might require different procedures for repair and ultimately affect the recovery of the system. This paper proposes a method to obtain physics-based repair rate curves by formulating models for the capacity and the demand for both the segments and the joints of the pipelines, with a particular focus on the demand model. By relating these quantities to the physical variables involved (such as material properties, soil properties and burial depth), we will obtain curves that are specialized for the pipeline under investigation and separate the damage at joints from the damage on the segments. In addition, given the availability of deterioration models for the physical properties of the system (Zhou et al. 2012, Leis and Stephens 1997 and Zhang et al. 2012), it would be possible to update the repair rate curves to incorporate the age of the pipelines. This is not possible in the current formulation as the physical variables do not enter the repair rate formulation directly but only through approximate coefficients. Repair rate curves for a particular set of pipelines are provided together with the curve provided by American Lifeline Alliance (2002).

2. REPAIR RATE CURVES FORMULATION

Segmented buried pipelines have been seen experiencing significant seismic damage in numerous events such as the Mexico City earthquake (Pineda-Porras and Ordaz 2012) and the Christchurch earthquake (O’Rourke et al. 2014). The damage has been observed to be mostly localized at joints, although it has been proven how pipeline segments, as well as continuous buried pipelines, can also experience damage (O’Rourke and Elhmadi 1988). In general, segmented pipelines can be modeled as a series of \( n_j \) joints connecting \( n_s \) pipeline segments. The joints are modeled as localized springs (both rotational and axial), while the segments can be modeled as beam elements made of isotropic materials.

![Figure 1. Simplified model for segmented pipelines](image)

The axial stiffness and resistance of the pipe usually governs the behavior of the system, with the pipes being vulnerable to longitudinal waves much more than they are to shear waves (Elhmadi and O’Rourke 1990). Transverse capacity of the system is still of interest in the case of permanent ground deformations, when fault ruptures crossing the pipe might cause bending moments in the segments and rotations at the joints, as shown in Vazouras et al. (2010) and Paolucci et al. (2010). Due to this event being situational, the following formulation will focus on the strains and displacements due to longitudinal wave propagation. The procedure can be easily extended to include rotations at the joints and bending of the segments.

In order to evaluate seismic wave propagation effects on pipeline, one may choose different seismic intensity measures. A comprehensive list of pipeline fragility functions studies is available in Pineda and Najafi (2010) and it shows how the parameter that is most commonly used to quantify seismic damage is the Peak Ground Velocity (PGV) at the site. PGV is also one of the parameters chosen by the American Lifeline Alliance (2002) which is the most common reference for practical applications. In the present work, we propose a framework that uses the ground strain \( \varepsilon_g \) as intensity measure; this is consistent with previous work by O’Rourke and Deyoe (2004), which showed how using the ground strain in the fragility formulations can help reduce the scatter of wave propagation repair rates. However, the formulation proposed by O’Rourke and Deyoe is empirical and calibrated on a set of field data from past earthquakes. Maps for ground strain due to wave propagation can be obtained using state-of-the-art tools such as software like SPEED (Mazzieri et al. 2013 and Guidotti 2012). Alternatively, one may obtain shake maps in terms of the ground strain from the shake maps in terms of the Peak Ground Velocity (which are in general more commonly available) using the Newmark approximation (1967),
which relates the peak ground velocity PGV and the ground strain \( \varepsilon_g \) using the apparent wave propagation velocity of the surface waves \( C_s \).

\[
\varepsilon_g = \frac{PGV}{C_s}
\]  

Note that, while estimates for \( C_s \) can be easily found in literature, these values are subject to high uncertainties so that the computation of \( \varepsilon_g \) via more elaborate methodologies is still preferable. In order to properly quantify the number of repairs needed after an earthquake that causes a given ground strain \( \varepsilon_g \) and correctly distinguish between repairs on the segments and repairs at the joint, we will provide each one of these \( (n_s + n_j) \) components with a capacity value \( C_i \) and a demand value \( D_i \). Both capacity and demand can be seen as functions of a set of random variables \( \mathbf{x} \) which represents important physical variables they depend on, such as material property constants, member dimensions and imposed boundary conditions (Gardoni et al. 2002). When experimental data are available, a set of parameters \( \Theta \) can be introduced to fit the model to the observed data so that, for the \( i^{th} \) component

\[
C_i = C_i(\mathbf{x}, \Theta) \\
D_i = D_i(\mathbf{x}, \Theta)
\]  

Usually \( \mathbf{x} \) can be partitioned in the form \( \mathbf{x} = (\mathbf{r}, \mathbf{s}) \) where \( \mathbf{r} \) is a vector of geometric and material properties and \( \mathbf{s} \) is a vector of demand variables. If we define the limit state function for the \( i^{th} \) component as

\[
g_i = C_i(\mathbf{r}, \mathbf{s}, \Theta) - D_i(\mathbf{r}, \mathbf{s}, \Theta)
\]  

and the fragility for the component as the probability that the demand exceeds the capacity for a given set of demand variables \( \mathbf{s} \) and parameters \( \Theta \), we obtain

\[
F_i(\mathbf{s}, \Theta) = P[g_i(\mathbf{r}, \mathbf{s}, \Theta) \leq 0|\mathbf{s}, \Theta]
\]  

Once the fragilities for the different components have been obtained from Equation 5, they can be used to simulate failures via Monte Carlo simulations, whose results can ultimately be used to obtain the repair rate curves for the system of interest. For the particular case of a pipeline composed by \( n_j \) joints with the same properties and \( n_s \) segments of length \( l_s \) with the same properties, and assuming that the demand variables vector \( \mathbf{s} \) is reduced to the ground strain value \( \varepsilon_g \), it can be shown that the expected number of repairs per unit length \( l_u \) can be obtained with the following formula

\[
RR(\varepsilon_g, \Theta) = \frac{l_u}{l_s} \left( F_j(\varepsilon_g, \Theta) + F_s(\varepsilon_g, \Theta) \right)
\]  

where \( F_j(\mathbf{s}, \Theta) \) is the fragility function for the generic joint and \( F_s(\mathbf{s}, \Theta) \) is the fragility function for the generic segment. Please note that Equation 6 assumes that the chosen unit length \( l_u \) is larger than the length of the segments \( l_s \). This is usually the case as repair rate curves are usually expressed as number of repairs needed per kilometer or 1,000 feet, both quantities being much larger than the typical length of the pipeline segments.

3. MODEL FOR THE DEMAND

This section focuses on developing a physics-based demand function for joints and segments to be plugged into Equation 5. This formulation for the demand improves over currently available simplified models by properly accounting for the effect of the properties of the soil and for the burial depth of the pipe. The simplified model is combined with finite element analysis using the software AXPIL for geotechnical application to obtain the influence of the soil properties and burial depth on the demand.
3.1 Deterministic model for the demand

Assume that a link of length $L$ is defined as the part of the network between 2 nodes (see Figure 2). Provided that shake maps with the value of $\varepsilon_g$ for the ground can be obtained with one of the methods described in Section 2, each link of the network will be subject to an elongation in the surrounding soil $\Delta L$ equal to

$$\Delta L = \int_0^L \varepsilon_g(x) \cos \theta(x) \, dx \quad (7)$$

where $x$ is the local coordinate along the link and $\theta$ is the angle between the link and direction of propagation of the wave, which can be obtained from the software being used for the computation of $\varepsilon_g$ or, when $\varepsilon_g$ is obtained with the Newmark approximation (Equation 1), it is given by the angle between the link and the line connecting the location at $x$ to the epicenter of the seismic motion (Figure 2). Note that with this formulation we have maximum elongation for $\theta = 0$ and minimum elongation for $\theta = \pi/2$.

![Figure 2. Nomenclature for water network and definition of $\theta$](image)

It is hereby assumed that the end connections at the nodes are able to release the elongation of the different links connecting to them. This has a minimal influence on the final result as the connections at the nodes constitute a small subset of the total amount of joints in a water network, but the proposed model could be properly modified to account for the fragility of these elements.

The different links are modeled as a sequence of beam elements with Young modulus $E_s$ for the segments and linear springs of stiffness $K_j$ for the joints. At the two ends of the link, two springs of stiffness $K_{soil}$ are inserted to account for the contribution of the soil properties and the burial depth (see Figure 3). This model differs from other simplified models such as the one proposed by Elhmadi and O’Rourke (1990) because of the presence of the contribution from the soil.

![Figure 3. Simplified model for the link](image)
This model is able to account for different deformations of the pipeline compared with the surrounding soil. The difference between these two elongations has been named $\Delta_{sl}$ (see Figure A1 for additional details). The values of $K_{soil}$ was obtained modeling the pipeline in the finite elements software AXPIIL for geotechnical analyses. Additional details about the finite element models and about the procedure to compute $K_{soil}$ can be found in the appendix. Figure 4 shows how $K_{soil}$ and $\Delta_{sl}$ vary with the burial depth of the pipe. It can be clearly seen how the response of the pipe to ground deformation is a function of the compaction of the surrounding soil.

![Figure 4. Effect of burial depth on $K_{soil}$ and $\Delta_{sl}$](image)

The model in Figure 4 can be intended as a series of springs of different stiffness. We can think of the different pipe segments as springs of stiffness $E_sA/l_s$, where $l_s$ is the length of the beam elements and $A$ is the cross-sectional area of the pipe. If we apply a displacement equal to $\Delta L/2$ (where $\Delta L$ can be obtained from Equation 7) to both ends of the simplified model, the total elongation of the link will be partitioned among the different joints and segments according to the following relationship

$$\Delta L = \sum_{j=1}^{n_j} \Delta u_j + \sum_{s=1}^{n_s} l_s \varepsilon_s + 2\Delta_{sl}$$

(8)

where $\Delta u_j$ is the displacement of the $j^{th}$ joint and $\varepsilon_s$ is the strain of the $s^{th}$ segment.

Imposing equilibrium to the model in Figure 3 (which is done by imposing that all the elements are subject to the same constant normal stress), we can obtain analytical formulations for both the displacement at the joints and the strains in the different segments.

$$\Delta u_j = \frac{K_{eq}}{K_j} \Delta L$$

(9)

$$\varepsilon_s = \frac{K_{eq}}{E_sA} \Delta L$$

(10)

where $K_{eq}$ is the equivalent stiffness of the system soil-joints-segments, which for a series of springs can be computed with the well-known formula

$$K_{eq} = \left(\frac{2}{K_{soil}} + \sum_{j=1}^{n_j} \frac{1}{K_j} + \sum_{s=1}^{n_s} \frac{l_s}{E_sA}\right)^{-1}$$

(11)

Figure 5 shows the comparison between the displacement at joints predicted with the approximate method (Equation 9) vs the finite element model. The different data points were obtained by changing the ratio between the stiffness of the joints and the stiffness of the segments. As it can be seen, data points lie almost perfectly on the 1:1 line, indicating a good agreement between the finite element
formulation and the adjusted simplified model for virtually every possible scenario of stiffness.

Figure 5. FEM results vs simplified model results for the displacement at joints

Equation 9-10 constitute the analytical formulations that can be used to compute the demand imposed on the joints and on the segments in terms of displacement and strains, respectively.

3.2 Probabilistic model for the demand

Due to internal variability in the stiffness of the components of the model, some of the joints and segments will experience higher demands than others, and failures will most likely occur at weaker locations. We want to express the demand on the joints \( \Delta u_j \) and segments \( \varepsilon_s \) as a random variable in order to apply the procedure described in Section 2 and predict the amount of repairs expected along the line. In particular, we can think of the stiffnesses of the joints \( K_j \) and the Young moduli of the segments \( E_s \) entering Equation 9-10 as random variables, from which we can obtain the corresponding distributions for \( \Delta u_j \) and \( \varepsilon_s \). Distribution for \( K_j \) and \( E_s \) are generally not available, but values for their mean and standard deviations can be found in literature. In particular, statistics for the stiffness of the joints can be found in Elhmadi and O’Rourke (1988) and Elhmadi (1989) for Lead Caulked Joints and Rubber Gasketed Joints, while statistics for the Young moduli are usually provided with the specifications for the material.

If we have a function \( Y = g(Z) \), where \( Z = (Z_1, Z_2, ..., Z_n) \) is a set of random variables with known mean and standard deviations, we can find the mean and the standard deviations of \( Y \) with the second-order approximation formulas available in BIPM I et al. (2008).

\[
\mu_Y = g(\mu_Z) + \frac{1}{2} \sum_{i=1}^{n} \sum_{j=1}^{n} \frac{\partial g}{\partial Z_i} \rho_{Z_i Z_j} \frac{\partial g}{\partial Z_j} \sigma_{Z_i} \sigma_{Z_j}
\]

(12)

\[
\sigma_{\text{eq}}^2 = \sum_{i=1}^{n} \sum_{j=1}^{n} \text{Cov}(Z_i, Z_j) \frac{\partial g}{\partial Z_i} \frac{\partial g}{\partial Z_j} + \sum_{i=1}^{n} \sum_{j=1}^{n} \left[ \frac{1}{2} \left( \frac{\partial^2 g}{\partial Z_i \partial Z_j} \right)^2 + \frac{\partial g}{\partial Z_i} \frac{\partial^3 g}{\partial Z_i \partial Z_j} \right] \sigma_{Z_i}^2 \sigma_{Z_j}^2
\]

(13)

In particular, we have

\[
\Delta u_j = g(K, E)
\]

(14)

\[
\varepsilon_s = g(K, E)
\]

(15)

where \( K = (K_1, K_2, ..., K_n) \) is the vector of stiffnesses of the joints and \( E = (E_1, E_2, ..., E_n) \) is the vector of Young moduli for the pipe segments. Table 1 shows the comparison in the estimate of the mean and the standard deviation of the displacement at joints for a link with 10 joints subjected to a ground strain of \( \varepsilon_g = 0.001 \) computed using the 1st and 2nd order approximation and obtained from a Monte Carlo simulation of \( 10^6 \) runs, where the stiffness of the joints was drawn from a log-normal distribution. The coefficient of variation for the stiffness of the joints was varied in order to highlight
how the procedure performs well for the different scenarios. As it can be seen, the estimate for the mean using the methodology proposed coincides with the mean obtained with the simulations, while the estimated standard deviations are characterized by errors lower than 5% for the 2nd order approximation.

### Table 1. Statistics for displacements at joints using 1st and 2nd order approximation vs Monte Carlo simulations

<table>
<thead>
<tr>
<th>C.o.V. (K)</th>
<th>Mean (1st order)</th>
<th>Mean (2nd order)</th>
<th>Mean (MCS)</th>
<th>Std deviation (1st order)</th>
<th>Std deviation (2nd order)</th>
<th>Std deviation (MCS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td>0.005</td>
<td>0.005</td>
<td>0.005</td>
<td>0.00025</td>
<td>0.00025</td>
<td>0.00024</td>
</tr>
<tr>
<td>0.10</td>
<td>0.005</td>
<td>0.005</td>
<td>0.005</td>
<td>0.00050</td>
<td>0.00049</td>
<td>0.00047</td>
</tr>
<tr>
<td>0.25</td>
<td>0.005</td>
<td>0.005</td>
<td>0.005</td>
<td>0.00130</td>
<td>0.00122</td>
<td>0.00117</td>
</tr>
<tr>
<td>0.40</td>
<td>0.005</td>
<td>0.005</td>
<td>0.005</td>
<td>0.00200</td>
<td>0.00186</td>
<td>0.00185</td>
</tr>
</tbody>
</table>

The proposed procedure can be successfully used to obtain the demand imposed on the pipelines to be plugged into Equation 4.

### 4. MODEL FOR THE CAPACITY

Once the demand for both the segments of the pipeline and the joints has been obtained using the procedure developed in Section 2, we need to compare it with the capacity for each one of the elements. The following sections are dedicated to an overview of the capacity models for both the segments and the joints that can be implemented in the proposed framework.

#### 4.1 Capacity for the pipe segments

The capacity for the segment elements usually depends on the failure mechanism of the material the pipeline is made of, and it is generally expressed in terms of the ultimate stress that the material can sustain. For example, for cast iron, which is one of the most common materials used in potable water networks, the ultimate tensile strength of the material is substantially lower than its ultimate compressive strength, so that the cast iron failure criterion is best represented by the distortion energy theory developed by Von Mises. The Von Mises stress $\sigma_{VM}$ can be obtained from a combination of the axial stress $\sigma_x$ and the hoop stress $\sigma_\theta$ on the pipe (see Figure 6), according to the following relationship (Mises 1913 and Mair 1968)

$$\sigma_{VM} = \sqrt{\sigma_x^2 - \sigma_x \sigma_\theta + \sigma_\theta^2}$$  \hspace{1cm} (16)

![Figure 6. Axial stress and hoop stress on a segment of pipeline](image)

Different formulations are available in literature to translate the demand in terms of strains (as it has
been shown in Section 3) into a demand in terms of stresses $\sigma_x$ and $\sigma_0$, so that the Von Mises stress computed from Equation 16 can be compared to the ultimate stress for the material $\sigma_u$. In particular, Rajani et al. (1996) and Rajani and Tesfamariam (2004) have proposed a detailed model for pipe-soil interaction in which they obtained analytical formulations for the axial and hoop stresses on the pipe by combining the effects of axial pipe movement, internal water pressure, temperature differential and longitudinal bending. Specifically, for the axial stress

$$\sigma_x = \chi_1 E_s \frac{\partial u}{\partial x} + \chi_2 P_i - \chi_3 E_s \alpha_s \Delta T$$

(17)

where $E_s$ is the Young modulus of the pipe material, $P_i$ is the internal pressure, $\Delta T$ is the temperature differential, $\alpha_s$ is the expansion coefficient of the pipe material, $\chi_1$, $\chi_2$ and $\chi_3$ are physics-based coefficients and $\partial u / \partial x = \epsilon_x$ is the axial strain on the pipe which can be obtained from Equation 10. For more information about this model and the physics-based coefficients $\chi_1$, $\chi_2$ and $\chi_3$, see Rajani et al. (1996) and Rajani and Tesfamariam (2004).

Once the demand on the segments has been properly translated from strain into the equivalent Von Mises stress using Equation 16-17, it can be compared with the corresponding capacity in terms of the ultimate stress for the material. This capacity can also be properly modified to properly account for the effects of corrosion. This would lead to a repair rate formulation that is also time-dependent, furtherly enhancing the application of the proposed network. An example of formulation for residual stress in pipes containing different defects and corrosion pits has been proposed for cast iron pipes by Rajani and Tesfamariam (2007).

### 4.2 Capacity for the jointed connections

While different formulations for the capacity of segments have been extensively developed using simplified models from solid mechanics (as shown in the previous section), capacities for the connecting joints are usually not easily available as they are extremely specific to the stiffness of the materials being used and to the geometry of the connection. An example of a fragility formulation for lead caulked joints is available in Prior (1935). In this work, a total of 14 monotonically increasing axial extension tests were performed and the results were recorded to obtain the fragility curve for the joint in terms of the normalized relative joint displacement of the connection.

Curves like the one shown in Elhmadi and O’Rourke (1990) can provide the probability of failure in terms of the relative displacement of the joint $\Delta U/d$, where $d$ is the characteristic dimension of the joint. Alternatively, a physics-based model for the capacity of the joint can be obtained using a Bayesian approach such as the one developed in Gardoni et al. (2002), where the capacity of the element is expressed as

$$C(x, \Theta) = \hat{c}(x) + \gamma(x, \Theta) + \sigma \epsilon$$

(18)

where $\hat{c}(x)$ is a deterministic model for the capacity, $\gamma(x, \Theta)$ is a correction term to be calibrated based on experimental results (see Gardoni et al. 2002 for additional details), $\epsilon$ is a random variable with zero mean and unit variance and $\sigma$ represents the standard deviation of the model error. In the case where no deterministic model is available from the literature, the first term on the right hand side of Equation 18 can be dropped. A similar procedure can be applied to the capacity model for the segments to correct the deterministic models based on solid mechanics that have been introduced the previous section. The following section showcases how the procedure developed so far can be used to obtain physics-based repair rates for different pipelines. A comparison with the repair rate curves provided by the American Lifeline Alliance (2002) is also provided.

### 5. APPLICATION

The procedure developed has been used to obtain repair rate curves for pipelines with different properties buried in different types of soil. The properties for the pipeline object of study are available in Table 2. Figure 7 shows how the following methodology can be used to obtain repair rate curves for
several properties of the system without relying on empirical coefficients as proposed in the current regulations. The model for the capacity of the pipe segments being used is the one developed in Section 4, while the fragilities from Elhmadi and O’Rourke (1990) have been used for the capacity of the joints, with the horizontal dimension of the joint \( d \) taken as 5 cm. The obtained repair rate curves are compared with the repair rate curve that would be used when referring to the specifications from the American Lifeline Alliance (2002)

\[
RR = K_1(0.00187)PGV
\]  

where \( K_1 \) is an adjusting coefficient that depends on the materials and the geometry of the pipeline. For a cast iron pipe with mechanically restrained joints, \( K_1 = 0.7 \).

<table>
<thead>
<tr>
<th>Pipeline</th>
<th>Soil/Miscellaneous</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter [mm]</td>
<td>200</td>
</tr>
<tr>
<td>Wall thickness [mm]</td>
<td>4</td>
</tr>
<tr>
<td>Young modulus of segments [MPa]</td>
<td>Stiff soil</td>
</tr>
<tr>
<td>Mean [GPa]</td>
<td>200</td>
</tr>
<tr>
<td>Coefficient of Variation</td>
<td>Stiff soil</td>
</tr>
<tr>
<td>Poisson ratio</td>
<td>0.25</td>
</tr>
<tr>
<td>Length of segments [m]</td>
<td>6.1</td>
</tr>
<tr>
<td>Stiffness of lead caulked joints [kN/m]</td>
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</tr>
<tr>
<td>Coefficient of Variation</td>
<td>0.25</td>
</tr>
<tr>
<td>Characteristic dimension of joint [cm]</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Soft soil</td>
</tr>
<tr>
<td></td>
<td>1,000</td>
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<tr>
<td></td>
<td>Poisson ratio</td>
</tr>
<tr>
<td></td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>Shear wave velocity [m/s]</td>
</tr>
<tr>
<td></td>
<td>600</td>
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<tr>
<td></td>
<td>Soft soil</td>
</tr>
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</tr>
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<td></td>
<td>Internal pressure [MPa]</td>
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<tr>
<td></td>
<td>Specific weight [N/m³]</td>
</tr>
<tr>
<td></td>
<td>20,000</td>
</tr>
</tbody>
</table>

Table 2. Properties for the pipeline and the soil object of study

![Figure 7](image-url)

Figure 7. Physics-based RR curves compared with the RR curve from American Lifeline Alliance (2002)

Imperial units have been used in Figure 7 for a direct comparison with the currently available repair rate curve. It can be appreciated how the developed methodology allows for a distinction between different cases whereas the current practice would use the same repair rate curve regardless of the variables entering the system as an input. It can also be seen how the obtained repair rate curves do not follow the linear trend proposed in literature.
6. CONCLUSIONS

A procedure has been developed to formulate physics-based repair rate curves for the estimate of the amount of repairs needed on a water network after the occurrence of an earthquake of given intensity. The framework hereby proposed improves over formulations currently available by looking at the capacity and the demand of the single components of the network, namely the jointed connections and the segments of the pipelines. By doing so, it is possible to adapt the formulation for the particular case under investigation and to distinguish the damage at joints from the damage on the segments, which might be required for recovery analyses where different types of damage are associated to different repair times. In addition, a new simplified model for the demand on pipelines subject to the propagation of longitudinal waves has also been proposed. This model improves over the formulations currently available by taking the effect of the soil properties into account. Physics-based repair rate curves for a particular set of input variables have been provided, together with the repair rate curve that would be used when following the current specifications. The framework can be furtherly extended to include the effect of deterioration of the pipelines over time. The procedure hereby developed is a comprehensive approach to the reliability of potable water networks characterized by physics-based results and high adaptability to different scenarios.

7. ACKNOWLEDGMENTS

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8. REFERENCES


**APPENDIX**

**Finite element model and estimation of $K_{soil}$**

A simplified model of total length $L$ with three segments and two joints has been modeled in the geotechnical software AXPIL. The purpose of this finite element model is to quantify the effect of the surrounding soil onto the final elongation of the pipe, as the ends of the pipe experience a smaller displacement when compared to the surrounding soil. The difference between the two displacements has been named $\Delta_{sl}$. The use of a geotechnical software was required to impose a displacement field onto the surrounding soil. To reflect a uniform ground deformation $\varepsilon_g$, the displacement field imposed to the pipeline is a linear field going from $-\varepsilon_g L/2$ to $\varepsilon_g L/2$. Once this displacement field has been imposed, the software is able to output the differential displacement $\Delta_d$ between the pipe and the surrounding soil and the total elongation $\Delta_p$ of the pipe alone, which can then be used to obtain the equivalent stiffness of the soil $K_{soil}$. Figure 1A shows this procedure.
The length of the deformed configuration can be expressed as $L + \Delta_p + 2\Delta_{sl}$, where the different components can be expressed in an analogous way to Equations 9-10

\[
\Delta_{sl} = \frac{K_{eq}}{K_{soil}} \Delta L \\
\Delta_p = \frac{K_{eq}}{K_p} \Delta L
\]

(1A)

(2A)

where $K_p$ is the equivalent stiffness of the pipe computed from Equation 11 omitting the terms relative to the soil. By imposing that the total elongation of the system is equal to $\varepsilon_gL$ and considering the equilibrium of the system, we can obtain the expression for $K_{soil}$ based on the results from the finite element model

\[
K_{soil} = \frac{\Delta_p}{\varepsilon_gL - \Delta_p/2} K_p
\]

(3A)