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Seismic Fragility Formulations for Segmented Buried Pipeline Systems Including the Impact of Differential Ground Subsidence

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Abstract

Though Differential Ground Subsidence (DGS) impacts the seismic response of segmented buried pipelines augmenting their vulnerability, fragility formulations to estimate repair rates under such condition are not available in the literature. Physical models to estimate pipeline seismic damage considering other cases of permanent ground subsidence (e.g. faulting, tectonic uplift, liquefaction, and landslides) have been extensively reported, not being the case of DGS. The refinement of the study of two important phenomena in Mexico City –the 1985 Michoacan earthquake scenario and the sinking of the city due to ground subsidence– has contributed to the analysis of the interrelation of pipeline damage, ground motion intensity, and DGS; from the analysis of the 48" pipeline network of the Mexico City's Water System, fragility formulations for segmented buried pipeline systems for two DGS levels are proposed. The novel parameter PGV^2/PGA, being *PGV* peak ground velocity and *PGA* peak ground acceleration, has been used as seismic parameter in these formulations, since it has shown better correlation to pipeline damage than *PGV* alone according to previous studies. By comparing the proposed fragilities, it is concluded that a change in the DGS level (from Low-Medium to High) could increase the pipeline repair rates (number of repairs per kilometer) by factors ranging from 1.3 to 2.0; being the higher the seismic intensity the lower the factor.

Keywords: Ground Subsidence, Segmented Pipelines, Pipeline Fragilities, Mexico City.

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1. Introduction

Empirical correlation between buried pipeline damage and ground motion intensity parameters has been proposed since the mid 70's. Katayama *et al.* (1975) proposed a fragility function for segmented cast iron pipelines that relates pipeline repair rate (RR), measured as the number of pipe repairs per kilometer of tube (rep/km), and peak ground acceleration (PGA) as measure of seismic intensity. Thereafter, Eguchi (1983) proposed relationships between RR and Modified Mercally Intensity (MMI), for six pipe types; these formulations where refined later (Eguchi, 1991).

Instead of using MMI and PGA as pipeline damage indicators, subsequent formulations employed peak ground velocity (PGV) as seismic parameter due to its linear relationship with ground deformation, which is represented in Equation 1 (Newmark, 1967), where ε is maximum ground strain, and C is seismic wave propagation velocity. Equation 1 has been modified to differentiate the estimation of ε for surface and body waves (ASCE, 1984; O'Rourke and Liu, 1999).

$$\varepsilon = PGV/C \tag{1}$$

By assuming that ε, produced by transient seismic wave propagation, is directly related to RR, several fragility formulations have been developed. Barenberg (1988) collected pipeline damage information from three U.S. earthquakes and proposed a fragility relationship for cast iron pipes, in terms of PGV. Augmenting Barenberg's database with data from other 3 earthquake damage scenarios, O'Rourke and Ayala (1993) proposed a power function to relate RR and PGV. Later, with damage information from the 1994 Northridge event, O'Rourke and Jeon (1999) proposed a new PGV -based power damage function; though this function has the same functional form than the fragility formulation of O'Rourke and Ayala, the differences between both of them are considerable as it is further explained.

While MMI and PGA are ground motion parameters that could be used to measure seismic intensity, their use as pipeline damage indicators has relevant disadvantages. In the case of MMI, the subjective nature of its definition creates ambiguity in the damage assessment analysis. By other hand, while PGA can be accurately estimated from acceleration time histories, it is more related to inertia forces than to ground strain, suggesting that it is an appropriate damage indicator for above-ground structures, not for buried structures like pipelines. MMI and PGA can be used as damage indicators for pipelines due to their direct relationship with seismic intensity; however, since they are not theoretically related to ground strain, their use provide a coarse relationship with buried pipeline damage.

In a project of the American Lifeline Alliance (ALA, 2002), a linear fragility formulation for pipelines is developed using 81 RR - PGV data points from 12 earthquakes. The damage database used for the creation of this fragility function comprises, in part, the data used by O'Rourke and Ayala (1993) and O'Rourke and Jeon (1999). The fragility curve of O'Rourke and Ayala (1993) was created with information from six damage scenarios (four from U.S. and two from Mexico) for pipelines made of asbestos cement, cast iron, concrete, and prestressed concrete cylinder pipes. The fragility curve proposed by Jeon (1999) was created with damage information from the Northridge earthquake and includes only damage data of cast iron pipes. The large amount of scatter around the linear fragility function produces a wide confidence interval in the fragility equations.

The remarkable differences of the O'Rourke and Ayala (1993) and the O'Rourke and Jeon (1999) fragility formulations were analyzed by O'Rourke and Deyoe (2004). The authors state that the main reasons for the differences in both formulations are: the wave type that caused the pipeline damage, the presence of corrosion in some pipes, and low statistical reliability of the data points. By removing doubtful data points and classifying the remaining data points according to the presumably dominating wave type, the authors calculated the values of ε for surface and body waves associated to the already computed repair rates. Only the 1985 Michoacan earthquake damage scenario was considered to be caused by surface waves; therefore, ε for the three data points, related to the 1985 event, was computed with an assumed C value for Rayleigh waves equal to 500 m/sec. ε, for the rest of the data points, was computed assuming that body waves (S-waves) controlled the respective ground motion scenarios; then, the C value used for S-waves was assumed equal to 3,000 m/sec. As a result of the calculation of data points, depending on wave type, the new ε-based fragility function shows a reduced dispersion in comparison to the previously proposed fragility functions.

$$RR = 513\varepsilon^{0.89} \tag{2}$$

A further modification to Equation 2 considers the effect of permanent ground deformation on pipeline damage with the inclusion of the damage databases of Sano *et al.* (1999), from the Northridge earthquake, and Hamada and Akioka (1997), from Japan. Subsequently, Equation 3 combines the effects of seismic wave ground strain and permanent ground deformation. By assuming seismic wave velocity values, for body waves of 3 km/sec, and for surface waves of 0.5 km/sec, O'Rourke and Deyoe proposed a fragility formulation for both wave types in terms of PGV: Equation 4 for surface waves (e.g. Rayleigh waves); and Equation 5, for body waves (e.g. S waves). Both equations show the same power functional form.

$$RR = 724\varepsilon^{0.92} \tag{3}$$

$$RR_R = 0.034PGV^{0.92} \tag{4}$$

$$RR_S = 0.0035 PGV^{0.92} \tag{5}$$

The exceptional damage scenario left by the 1985 Michoacan Earthquake on the Mexico City's Water System (MCWS) has been used in several studies to compute buried pipeline fragility formulations; in some of them, already mentioned in this paper, the network was divided in three zones for its study (O'Rourke and Ayala, 1993; American Lifeline Alliance, 2002; and O'Rourke and Deyoe, 2004). Other studies, totally focused in the MCWS, have proposed fragility formulations for pipelines based on detailed analyses of the 1985 event scenario.

There are two observed tendencies for developing fragility formulations: the use of damage scenarios for several pipelines systems and earthquakes; and the use of damage scenarios for only a specific pipeline system and earthquake. While the first tendency provides general pipeline fragilities, characterized by its wide applicability due to the typical mixture of pipeline types and other factors (e.g.: ALA, 2001), they are also usually related to high uncertainty levels. By other hand, with the use of information of a specific pipeline system and well-studied damage scenarios, the uncertainty could be controlled since the number of unknown variables related to pipeline damage (e.g. variables related to earthquake environment, soil properties, and pipeline conditions), for that particular study case, is lesser than if several systems and events are included in the analysis. The authors' philosophy in this paper and its precedents (Pineda and Ordaz, 2003; and Pineda and Ordaz, 2007) is to analyze exclusively the MCWS in order to control the uncertainty of the proposed fragility formulations. The relationship between damage and seismic intensity is then studied through the division of the pipeline system in zones of similar seismic intensity levels and in several ways. In the 2003 and 2007 papers, the network was divided in nine different forms in order to have a more objective way to calculate the fragility functions since there is not a unique way to divide the network. The authors do not know about other studies where pipeline systems are divided in more than one way in order to compute fragility functions. The fragility functions previously proposed for the MCWS are further described below.

Pineda and Ordaz (2003) proposed a fragility formulation for buried pipelines employing the 1985 damage scenario published by Ayala and O'Rourke (1989), and the detailed PGV maps for Mexico City proposed by Pineda and Ordaz (2004). In order to analyze the variability of the RR - PGV data points for several ranges of seismic intensity, nine scenarios were used to generate the fragility function shown in Equation 6, where Φ is the cumulative normal function (CNF), shown in Equation 7. The authors chose the CNF functional form since it fitted better the cloud of RR - PGV data points, in comparison with other function types (linear, power, etc.). In Equations 6 and 7, and thereafter, RR and PGV units are rep/km (repairs per kilometer) and cm/sec, respectively.

$$RR = \begin{cases} 0 & if \quad 0 < PGV < 5.35 \text{ cm/sec} \\ 0.1172 + 0.7281 \cdot \Phi(PGV; 51.8964, 19.7811) & if \quad 5.35 \le PGV < 95 \text{ cm/sec} \\ 0.00137PGV + 0.70458 & if \quad PGV \ge 95 \text{ cm/sec} \end{cases} \tag{6}$$

$$\Phi(PGV; \mu, \sigma) = \int_{-\infty}^{PGV} \frac{1}{\sqrt{2\pi\sigma}} e^{-(1/2)[(v-\mu)/\sigma]^2} dv \tag{7}$$

In a subsequent study, Pineda and Ordaz (2007) proposed PGV^2 / PGA as a new seismic parameter for buried pipelines. From a theoretical development, the authors found that λ_{pr}, defined by Equation 8, interrelate the peak ground response parameters PGA, PGV, and PGD; being PGD peak ground displacement[†]. λ_{pr} has three important characteristics: it is non-dimensional; it is always higher or equal to 1.0; and it can be a measure of spectra bandwidth. Further details on λ_{pr} are already available in the 2007 paper; thus, they are out of the scope of this paper.

By isolating PGD in Equation 8, it is found that PGD and PGV^2 / PGA have a direct relationship through λ_{pr} (Equation 9). Based on the assumption that ground strain, main cause for the pipeline damage, is related to PGD; pipeline damage is then also related to PGV^2 / PGA and λ_{pr}. Since λ_{pr} varies in a delimited range for Mexico City, it was implicitly included in the fragility formulation. The comparison of the new fragility function in terms of PGV^2 / PGA (Equation 10), in cm, with the fragility function in terms of PGV (Equation 6), in cm/sec, revealed that the new parameter is a better damage predictor for pipelines than PGV alone.

$$\lambda_{pr} = \frac{PGA \cdot PGD}{PGV^2} \ge 1.0 \tag{8}$$

$$PGD = \lambda_{pr}\left(PGV^2 / PGA\right) \tag{9}$$

[†] Note that in literature PGD is also used as the acronym of Permanent Ground Deformation.

$$RR = \begin{cases} 0 & if \quad PGV^2/PGA < 1.8 \text{ cm} \\ 0.122 & if \quad 1.8 \le PGV^2/PGA < 8.72 \text{ cm} \\ 0.032\left(PGV^2/PGA\right) - 0.157 & if \quad PGV^2/PGA \ge 8.72 \text{ cm} \end{cases} \tag{10}$$

Though the described fragility formulations are useful for pipeline damage estimation, they do not consider the possible effects of differential ground subsidence (DGS), a phenomenon widely observed in Mexico City. The objective of this paper is to propose fragility formulations for segmented buried pipelines considering two DGS levels. The important advances on the study of the 1985 Michoacan earthquake scenario and the sinking of Mexico City have contributed to the analysis described in this paper, which comprises the study of the impact of DGS in the seismic response of the 48" pipeline network of the MCWS during the 1985 event. The proposed fragilities use PGV^2/PGA as seismic parameter since it has shown better relationship with pipeline damage than PGV alone (Pineda and Ordaz, 2007).

2. Impact of Ground Subsidence in the Mexico City's Water System

Ground subsidence, a very-well-known phenomenon in Mexico City, occurs when the ground level sinks due to a complex interaction between soil and groundwater flow variations. The intensive water pumping activity in the city has contributed to the consolidation of the typical soft clay stratigraphy of the Valley of Mexico causing exceptional ground subsidence levels that have not been observed in any other place worldwide.

Mexico City, the once biggest city in the world, with its more than 20 million people, demands an impressive water flow of 60 m^3/sec, of which 40 m^3/sec are obtained from the underground aquifers located beneath the city. The continuous water pumping over the last decades has caused a fall in the water level and, therefore, cumulative ground subsidence. According to Illades *et al.* (1998), the subsidence rate through the city ranges from 5 to more than 35 cm per year; and the greatest levels of cumulative ground subsidence, found in the downtown zone, range from 8 to 10 m due to the consolidation process in the period 1891-1995.

The non-uniformity of the sinking of Mexico City affects buried structures because the original restrain provided by the surrounding soil is altered causing stability problems. One case was observed in the Metropolitan Cathedral and the Sagrario Church, where underground excavation was employed to stabilize these historical buildings (Ovando and Santoyo, 2001).

There are several studies focused on the relationship between groundwater flow and ground subsidence in Mexico City. Rivera *et al.* (1991) created a non-linear model of the interaction between soil compaction and total subsidence on a multilayered system through a simultaneous numerical solution of the groundwater flow equation and a one-dimensional consolidation equation. In another study, Cisneros-Iturbe and Dominguez-Mora (2005) reported the impact of the overexploitation of the aquifers beneath the city on the DGS levels. The authors observed that the overexploitation could reach incredible levels close to the 100% of the recharge capacity of the aquifers.

Other studies are focused on the measure of ground subsidence through the city. The construction and hydraulic operations department of the Federal District (DGCOH) developed a master plan for drainage, which comprised the analysis of ground subsidence and simulation of its future behavior (DGCOH, 1997). A relevant product of this study is the computation of a mean yearly ground subsidence map for Mexico City, for the period 1983-1992 (Figure 1). Other studies, related to the estimation of DGS rates for the city, were published by Strozzi and Wegmuller (1999), and Strozzi *et al.* (2005).

3. Pipeline Fragility Formulations Including the Impact of Differential Ground Subsidence

Before the calculation of any fragility model, it is important to analyze how DGS could impact the seismic response of buried pipelines. Figure 2 illustrates how a pipeline system may become more vulnerable due to DGS. Two pipes, with lengths L_1 and L_2 (segments A-B and B-C, respectively), connected by a bell-spigot connection (see detail in point B) are horizontally buried at a constant depth H; after DGS alters their original location (points A', B', and C'), the pipes now have slopes γ_1 and γ_2, and variable depth $h(x)$. By comparing the original and the final state of the pipe connection (details of points B and B', respectively), it is observed that the bending of the two-pipe system reduces the contact area of the gasket; hence, the seismic response capacity of the connection is affected. Though Figure 2 shows an extreme case of the impact of DGS in the system, its purpose is only the illustration of the case.

Straightforwardly, the parameter related to the system vulnerability is γ, which is defined as the variation of the slope of the tubes (Equation 11). In Equations 12 and 13, the slopes of both tubes are defined in terms of the sinking level of the tube ends (H_A, H_B, and H_C) and lengths (L_1 and L_2). Assuming that both tubes have the same length L (Equation 14), γ is then defined in terms of H_A, H_B, H_C and L (Equation 15). There are two cases where γ is zero: if the sinking is uniform ($H_A = H_B = H_C$), and if after the sinking both pipes have the same slope ($\gamma_1 = \gamma_2$); in these cases the vulnerability of the two-pipe system is not affected by DGS. It is important to note that the vulnerability of a multi-segment system could be affected by DGS if γ is different to zero in at least one joint.

$$\gamma = \gamma_2 - \gamma_1 \tag{11}$$

$$\gamma_1 = \frac{H_B - H_A}{L_1} \tag{12}$$

$$\gamma_2 = \frac{H_C - H_B}{L_2} \tag{13}$$

$$L_1 = L_2 = L \tag{14}$$

$$\gamma = \frac{H_C - 2H_B + H_A}{L} \tag{15}$$

The described model assumes the following conditions: 1) the flexural rigidity of the pipes is so large that ground subsidence cannot bend their straight shape; 2) there is no relative displacement between soil and pipes, so the impact of ground subsidence is straightforwardly concentrated in the tube connection; and 3) considering the last point, γ_1 and γ_2 are small enough that the pipes are not lengthened by the effect of DGS.

Though γ can be used to quantify DGS, for practical purposes, it has an important disadvantage for the computation of pipeline fragilities: it must be calculated at each pipe joint. On the contrary, for the generation of fragility functions, seismic intensity parameters (e.g.: PGV^2 / PGA) are generally computed at the mid point of each individual pipe to define the mean seismic intensity level of the segment (Pineda and Ordaz, 2003; Pineda and Ordaz, 2007). In order to estimate DGS at the mid point of each segment, Equation 16 can be used to define a new subsidence-related parameter (γ_r), which is the slope of each pipe segment. Though γ_r is based on a simpler model than the former one, the results described in this section show that γ_r can be used to represent DGS in the pipeline fragility analysis.

$$\gamma_r = \frac{H_B - H_A}{L} \tag{16}$$

For the computation of the fragility formulations, shown in Equations 17 and 18, γ_r was calculated for each segment of the 48" pipeline system of the MCWS employing the mean yearly ground subsidence map proposed by the DGCOH (1997) (Figure 1). γ_r values depend not only of the subsidence rate map shown in Figure 1, but also of the orientation of each pipe segment; hence, the identification of the most exposed pipes to the DGS effects may not be clear in the map.

The 48" network, formed by 323 km of concrete segmented pipes, was severely affected by the 1985 earthquake, causing extensive damage and a total count of 95 repairs reported after the event by Ayala and O'Rourke (1989). In Figures 1 and 3, the damage zones are marked with dots. According to the authors, 2/3 of the observed damage was located at pipe joints; the observed damage types include lateral crushing of pipes, and crushing and unplugging of joints.

Estimations of γ_r and PGV^2/PGA (Figure 3) were related to RR following a similar procedure employed by Pineda and Ordaz (2007), which is described below. Six steps were followed to generate the proposed fragility functions (Equations 17 and 18); these are: 1) the MCWS 48" concrete pipeline system was divided in segments of 50 m or shorter; 2) the ground subsidence level was computed at the location of both segment ends on the map of Figure 1; 3) by applying Equation 16, the DGS yearly rate (γ_r) was computed for each pipe segment; 4) hence, the network was divided in two groups, one composed by all the pipeline segments with γ_r values lower or equal to 0.001 (Low-Medium DGS), and the other formed with the rest of the segments (High DGS); 5) for each group, RR - PGV^2/PGA data points were calculated for four ground motion intensity levels (Table 1 and Figure 4); and 6) for each DGS fragility (Low-Medium and High), a linear functional form was adopted to compute Equations 17 and 18.

The arbitrary maximum 50-m-pipe-length was assumed to pursuit accuracy and uniformity in the estimation of γ_r. In a previous study (Pineda and Ordaz , 2002), it was found that by splitting the network in 50-m segments, the damage estimation of the resulting *PGV*-based fragility function is consistent with the 1985 damage scenario; if the length is increased to 100 meters, the damage estimation is underestimated by 1%; and shorter lengths (e.g. 25 m) provide practically the same results than those obtained with 50-m length segments mainly because of the resolution of the maps employed in the analysis. Based on the results of Pineda and Ordaz (2002), Pineda and Ordaz (2007) divided the network in 50-m segments for the creation of fragility functions; in this paper, the same consideration has been adopted since it has shown consistency with the studied damage scenario.

The $\gamma_r = 0.001$ boundary between the two DGS levels –Low-Medium and High– was arbitrary selected within the range $\gamma_r = 0\text{-}0.006$ related to the 1985 pipeline damage scenario; 1/3rd of the pipe damage cases are related to Low-Medium DGS and 2/3rd to High DGS.

In Figure 4, the relationship between γ_r and PGV^2/PGA for the 7,444 pipe segments (of 50-m or shorter) of the 48" network is shown. The horizontal dashed line, at $\gamma_r = 0.001$, splits the pipe segments in the two DGS levels; the vertical dashed lines separates the pipe segments in four seismic intensity groups (in terms of PGV^2/PGA). The repair rates (RR) for each DGS and PGV^2/PGA levels are computed by dividing number of repairs and pipe lengths (within each dashed-line rectangle); these results are shown in Table 1. The PGV^2/PGA values were calculated as the average value for each respective seismic intensity level; for instance, for the first seismic intensity zone, the PGV^2/PGA value is 5 cm, the average between 0 cm and 10 cm, and so on.

The fragility functions shown in Figure 5 were computed with four points each one mainly because of the limitation of the available information. In order to compute repair rates, at least one repair is needed for each γ_r-PGV^2/PGA area in Figure 4. Attempts to use five or more points for the generation of the fragility functions would produce RR values equal to zero, which would not predict adequately the expected damage for a specific seismic intensity level. Equal-size PGV^2/PGA intervals (of 10 cm) for splitting the network have been adopted for consistency in the calculation of RR with the increase in seismic intensity; there is no justification for splitting the network in non-equal intervals.

Originally, the linear fitting of the data points γ_r-PGV^2/PGA for 15, 25, and 35 cm (Table 1 and Figure 5), for Low-Medium and High DGS levels showed slopes equal to 0.0547 and 0.061, respectively. This means that both lines have very close slopes. In order to simplify the fragility functions, it was assumed the same slope in both lines. Thus, the combined fitting of both lines, for Low-Medium and High DGS, was recalculated with the condition of sharing the same slope parameter (0.058 in Equations 17 and 18) resulting in simpler fragility curves.

$$RR = \begin{cases} 0 & \text{if } PGV^2/PGA < 1.25\,\text{cm} \\ 0.134 & \text{if } 1.25 \le PGV^2/PGA < 14.4\,\text{cm} \\ 0.058\cdot(PGV^2/PGA)\text{-}0.7 & \text{if } PGV^2/PGA \ge 14.4\,\text{cm} \end{cases} \quad (17)$$

$$RR = \begin{cases} 0 & \text{if } PGV^2/PGA < 1.25\,\text{cm} \\ 0.2 & \text{if } 1.25 \le PGV^2/PGA < 10.7\,\text{cm} \\ 0.058\cdot(PGV^2/PGA)\text{-}0.42 & \text{if } PGV^2/PGA \ge 10.7\,\text{cm} \end{cases} \quad (18)$$

Table 1. Repair Rates for Low-Medium and High DGS Levels

PGV^2/PGA [cm]	RR [rep/km]	
	Low-Medium DGS	High DGS
5	0.134	0.199
15	0.222	0.450
25	0.698	0.945
35	1.310	1.664

The proposed fragility relationship has three parts where RR can be: zero, constant, or linearly dependent of PGV^2 / PGA. This three-zone functional form is also observed in the fragility function for the MCWS, shown in Equation 10 (Pineda and Ordaz, 2007), and the fragility function for 48" concrete pipes (Equation 19) proposed by Pineda and Ordaz (2006). The first two parts, the no-damage and constant-damage zones, are also observed in the cloud of RR-PGV data points employed in the calculation of the fragility formulation of Pineda and Ordaz (2003). The no-damage zone is defined for seismic intensity levels not associated to pipeline damage in the 1985 damage scenario. A likely explanation of the constant-damage zone, observed in several fragility models, is the presumably about-to-fail precondition of some pipe segments due to two combined effects: the effect of earthquakes occurred previously to the 1985 event, and the increase of damage vulnerability because of the DGS impact. Due to scarcity of information, a separately analysis of the participation of each phenomenon in the damage cannot be done.

The proposed fragility formulations for Low-Medium and High DGS (Figure 5) fall below and above the fragility calculated for the entire 48" pipeline system (Pineda and Ordaz, 2006), respectively. Consequently, this comparison suggests that the 2006 fragility (2006) implicitly considers the impact of an intermediate DGS level, between the Low-Medium and High DGS levels defined in this study.

From Equations 17 and 18, and Table 1, it is concluded that a change in the DGS level (from Low-Medium to High) could increase the pipeline repair rates (repairs per kilometer) by factors ranging from 1.3 to 2.0; being the higher the seismic intensity the lower the factor.

$$RR = \begin{cases} 0 & \text{if } PGV^2/PGA < 1.91\,\text{cm} \\ 0.162 & \text{if } 1.91 \leq PGV^2/PGA < 11.82\,\text{cm} \\ 0.058 \cdot (PGV^2/PGA) - 0.534 & \text{if } PGV^2/PGA \geq 11.82\,\text{cm} \end{cases} \qquad (19)$$

The use of the proposed fragilities (Equations 17 and 18) for large scale damage estimation can be done according to the following steps: 1) divide the pipeline network in short segments of 50-m or lesser, depending on the resolution of the maps employed in the analysis (PGV^2/PGA and ground subsidence); 2) compute PGV^2/PGA and γ_r for each pipe segment; 3) choose one fragility curve depending on the γ_r value for each segment; 4) compute RR for each segment; and 5) add up all the products between RR and lengths for the segments of the whole network, or for a specific set of pipeline segments, depending of the desired analysis. The objective of step 5 is to compute the total number of pipe repairs for the whole pipeline network or for a specific pipeline segment; these results are useful for simulations of damage scenarios and assessments of post-earthquake serviceability.

4. Analysis of uncertainties for the proposed fragility functions

In previous fragility functions created from the 1985 Michoacan earthquake damage scenario (Pineda and Ordaz, 2003; and Pineda and Ordaz, 2007), the analysis of uncertainty has been addressed by analyzing the relationship between RR and seismic intensity from nine sets of damage data points. The fragility functions, proposed in this paper, were computed with only one set of damage data points (Table 1), for each DGS, due to the lack of enough information for dividing the network in more ways, as it was explained in Section 3. A conservative way to address the uncertainty in the damage estimation for the proposed fragilities is to assume that these fragility curves predict repair rates with the same uncertainty level associated to the PGV^2/PGA-based fragility function proposed by Pineda and Ordaz (2007).

Though it is clear that Equations 17 and 18 are useful for predicting repair rates including the effect of DGS, a parameter not considered in the fragility proposed by Pineda and Ordaz (2007), there is no way to analyze the variability of the damage estimation. By other hand, the comparison shown in Figure 5 shows that the proposed fragility curve effectively are related to two levels of DGS since both curves fall above and below the 48" pipeline fragility curve proposed by Pineda and Ordaz (2006), a fragility curve that have implicitly included the effects of DGS in the formulation.

The uncertainty analysis for the PGV^2/PGA-based fragility function proposed by Pineda and Ordaz (2007) is shown in Figures 6 and 7. The error related to each of the 63 PGV^2/PGA - RR data points is measured through $\varepsilon_{\ln}$, which is defined by Equation 20. D_c is the RR value for each data point, and D_t is the RR value predicted by the fragility function for the same PGV^2/PGA level corresponding to D_c. The variability of $\varepsilon_{\ln}$ can be observed in Figure 7. The natural logarithm form in Equation 20 was assumed looking for a uniform variance in the analysis. The standard deviation of $\varepsilon_{\ln}$ is equal to 0.1463. The confidence intervals for 1, and 2 standard deviations ($\sigma_{\varepsilon_{\ln}}$) above and below the median of the fragility curve are shown in Figure 6.

$$\varepsilon_{\ln} = \ln\left(D_c \big/ D_i \right) \tag{20}$$

The uncertainty of the proposed fragilities for the 48" network (Equations 17 and 18) can be assessed by assuming that the confidence intervals related to those fragilities have the same statistical properties than the PGV^2 / PGA-based fragility function; that means that the standard deviation of $\varepsilon_{\ln}$ ($\sigma_{\varepsilon_{\ln}}$) is the same for the proposed fragilities. The confidence intervals for the proposed fragility functions for two DGS levels (Low-Medium and High) are shown in Figure 8; they were computed with Equation 21. k represents the number of standard deviations above or below the median repair rate ($\overline{RR}$) calculated with Equations 17 and 18; and, $\sigma_{\varepsilon_{\ln}}$ is assumed equal to 0.1463.

$$RR_{(k)} = \overline{RR} \cdot e^{\pm k\sigma_{\varepsilon_{\ln}}} \tag{21}$$

The lack of damage data (e.g. more pipeline length and number of repairs) is an impediment to compute $\sigma_{\varepsilon_{\ln}}$ using only damage information for the 48" pipeline network. The use of $\sigma_{\varepsilon_{\ln}}$, calculated for the whole MCWS pipeline network, as the uncertainty parameter to define the confidence intervals for the proposed fragility functions (Equations 17 and 18) is based on the assumption that the new fragilities predict repair rates with the same uncertainty levels than the MCWS fragility function proposed by Pineda and Ordaz (2007), and shown in Figure 6. It is important to mention that the 48" pipeline network correspond to 53.6% of the whole MCWS pipeline length; which is favorable for the assumption of equal $\sigma_{\varepsilon_{\ln}}$ since a great part of the MCWS is comprised by 48" pipes. It is also important to mention that, if the dispersion in the fragility of Pineda and Ordaz (2007) is in part due to the effect of DGS; then, the equal-$\sigma_{\varepsilon_{\ln}}$ assumption for both fragility curves mentioned above, would produce conservative estimates of the variability of the repair rate estimation of the proposed fragilities; unfortunately there is no way to verify this statement.

5. Conclusions

From an interrelation analysis of pipeline damage, ground motion intensity, and DGS, for the scenario left by the 1985 Michoacan earthquake on the Mexico City's Water System, seismic fragility formulations for buried pipelines for two levels of DGS are proposed. These functions follow the same damage tendency observed in previous fragility models. From the comparison of the fragilities, it is concluded that the increase of the level of DGS, from Low-Medium to High level, may augment the pipeline repair rate by factors ranging from 1.3 to 2.0. Finally, the good fitting of the $RR - PGV^2 / PGA$ data points with the linear functions shows that PGV^2 / PGA can be used as damage predictor for buried pipeline fragilities including the effects of DGS. The use of the proposed fragility functions for damage estimation in other pipeline systems and its limitations are discussed in the following section.

6. Discussion

The generation of the proposed fragility functions was possible thanks to the refined PGA, PGV, and ground subsidence maps for the Valley of Mexico developed mainly over the past two decades by many researchers and engineers. The authors believe that the availability of information on the mentioned parameters for any place through Mexico City, and in particular, on the MCWS locations, produced a benefic impact in the generation of the fragility formulations.

The linear relationship between RR and PGV^2 / PGA suggests that RR and PGD could have also a linear relationship, due to the particular direct relationship between PGD and PGV^2 / PGA. PGD has not been used as seismic parameter in pipeline fragility formulations since the Newmark's equation establishes a direct relation between PGV and ground strain ε, the main cause of pipeline damage; so PGV has received more attention than any other seismic parameter, including PGD, and even parameters that have been used in fragility formulations in the past, like MMI and PGA.

There are serious implications in the use of PGV as damage indicator for buried pipelines in Mexico City. Straightforwardly, PGV could be used as damage indicator for pipelines, only if the seismic wave velocity values C are constant; in that case, the estimation of ε through the Newmark's equation would be accurate. In reality, C is far from being constant, especially for surface waves (e.g. Rayleigh waves) since it varies with wave frequencies. The relationship between C and frequency is usually given in a dispersion curve. For places like Mexico City, the use of the Newmark's equation for the estimation of ε could produce extremely conservative estimates. In the work of Bodin *et al.* (1997), the authors estimated ε by processing seismic records from an array of stations; they compare the results with those obtained through the Newmark's equation and found differences of more than one order of magnitude. The mentioned disadvantages of PGV encouraged the authors to look for a better damage indicator for pipelines. In a previous paper (Pineda and Ordaz, 2007), it was demonstrated that PGV^2 / PGA is a better pipeline damage predictor than PGV for Mexico City; the same conclusion has been made in this paper.

The computation of reliable pipeline fragility formulations including γ_r as variable is practically impossible, since the large amount of information required for the analysis. Even with the refined maps shown in Figures 1 and 3 for the estimation of ground subsidence and PGV^2/PGA, respectively, a pipeline fragility with γ_r as argument could not be computed since the damage scenario for the 48" pipeline system comprises only 95 repairs and a length of 323 kilometers. Instead of including γ_r as variable in the fragility model, the pipeline system was split considering two levels of DGS, Low-Medium and High; the results are satisfactory. Four levels of seismic intensity were chosen to compute mean repair rate values that were used to create the linear fragility functions.

The main objective of the fragility formulations is to illustrate the impact of DGS in the pipeline repair rate for several ground motion intensities. The use of these fragilities in other systems is complicated for two main reasons. First, the use of PGV^2/PGA as seismic damage parameter has been tested in the soft soils of Mexico City; for stiffer soils, the convenience of its use has not been verified yet. And second, since γ_r is a yearly mean value of DGS and not a measure of total DGS, γ_r values calculated for other cases may not be comparable with those computed for the MCWS case; to avoid such discrepancies, the following considerations must be taken into account. The proposed fragility formulations for two DGS levels can be cautiously used in other buried segmented pipeline systems. These fragilities should be used only for damage assessment in pipeline systems located in soft soils as those found in the Valley of Mexico. From the experience of the authors, a criterion to define "soft soils" could be those soils that have natural periods equal and higher than 1.0 sec. It is also suggested the analysis of the parameter λ_{pr}, defined by Equation 8, for the site where the studied pipeline system is located. It is suggested the use of the High DGS fragility for zones where ground subsidence might have a strong influence in the seismic response of the system and the Low-Medium DGS fragility for other zones. In any case, the suggested confidence intervals can be used as a way to address the uncertainty of the damage estimation by using the proposed fragility formulations.

There is no way to predict the damage of pipelines with larger or shorter diameter than 48" from the proposed fragility curves. The general trend observed for damage, caused only by seismic wave propagation, is that the larger the diameter, the lesser the damage (ALA, 2001); however, there is not a definitive relationship between the expected damage for pipeline systems with different diameters. By other hand, the influence of DGS in the damage for large diameter pipelines could be higher than the influence for shorter diameter pipelines; mainly because short-diameter pipelines can accommodate better underground settlement environments, over large distances, than high diameter pipelines; in other words, DGS could reduce more the seismic response capacity of high-diameter pipelines than the capacity of short-diameter pipelines.

It is important to mention that the proposed fragility formulations account for the influence of DGS in the seismic response of buried segmented pipeline systems. The impact of other types of permanent ground displacement phenomena in the seismic damage, like ground liquefaction, cannot be assessed with the proposed fragility functions.

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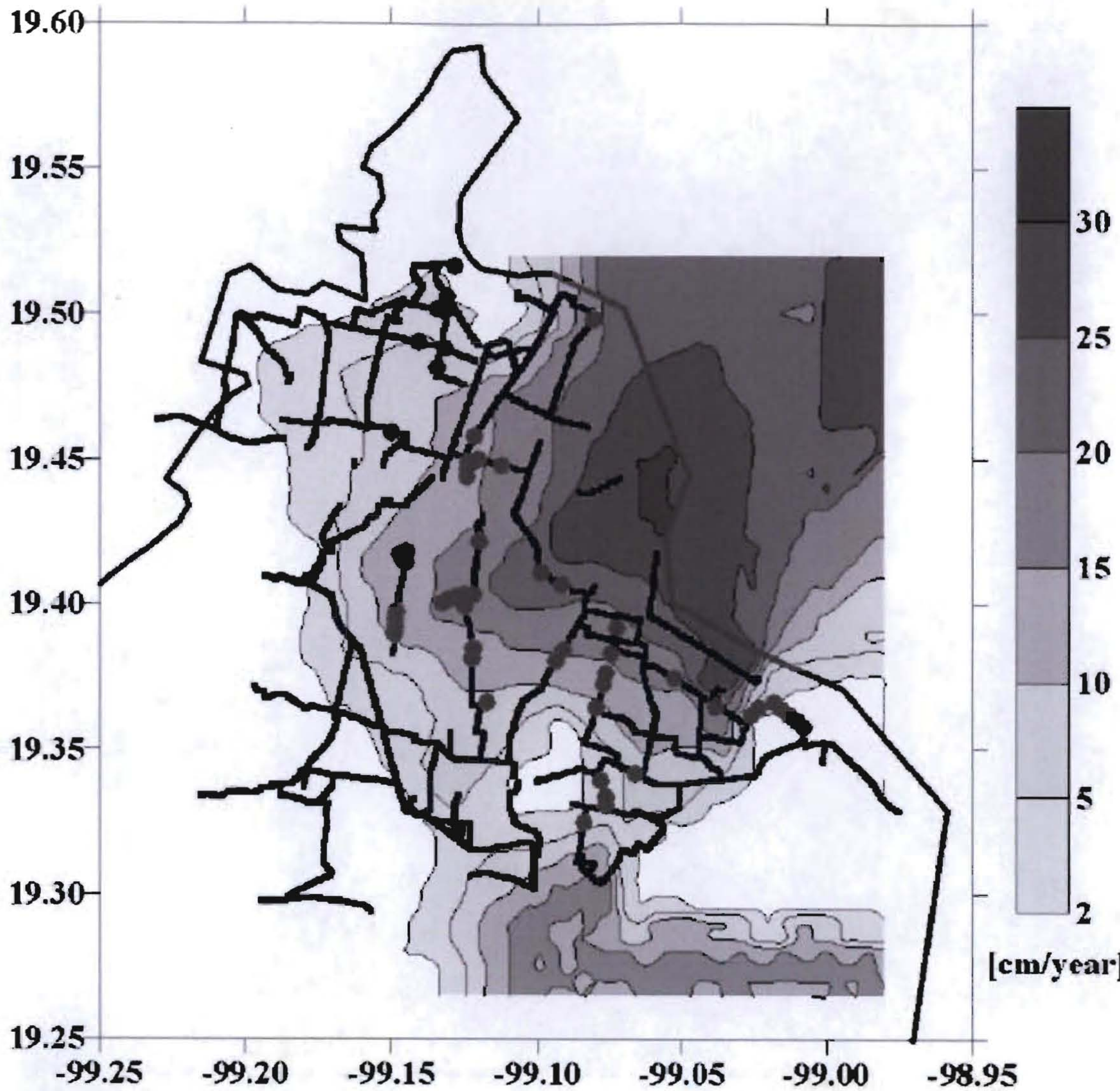

Figure 1. Mean Yearly Ground Subsidence Map (1983-1992) and Damage Zones (marked with dots) after the 1985 Michoacan Earthquake

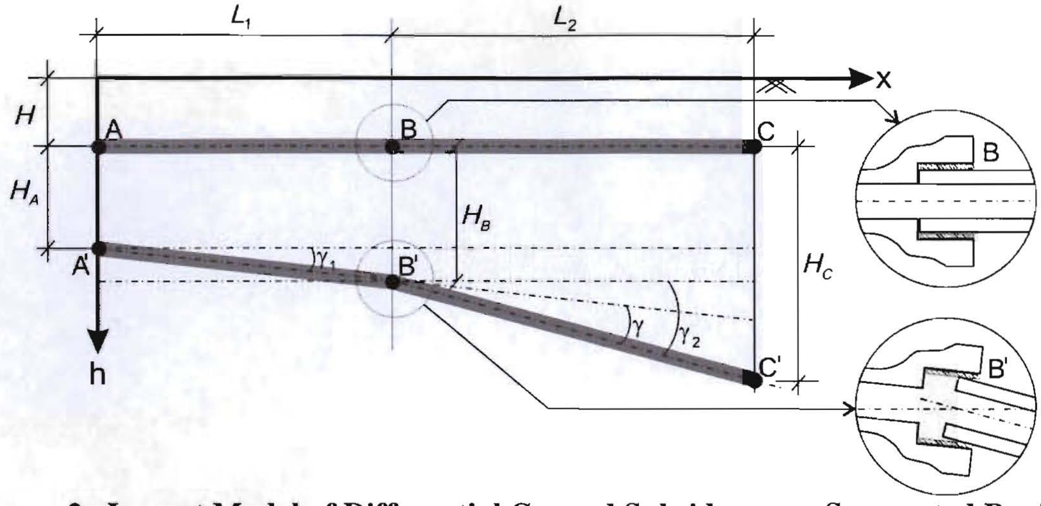

Figure 2. Impact Model of Differential Ground Subsidence on Segmented Buried Pipelines

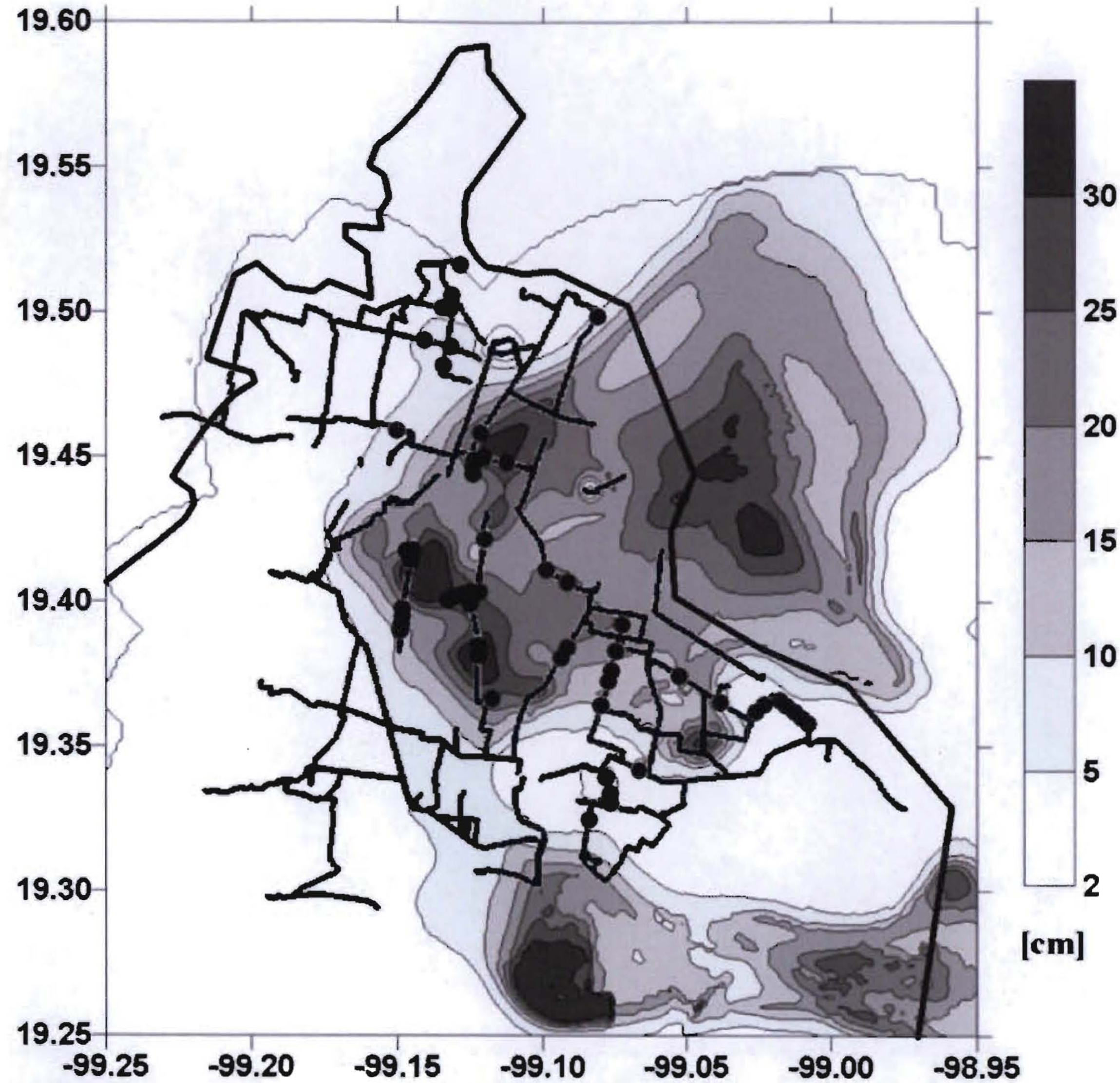

Figure 3. PGV^2 / PGA Map and Damage Zones (marked with dots) after the 1985 Michoacan Earthquake

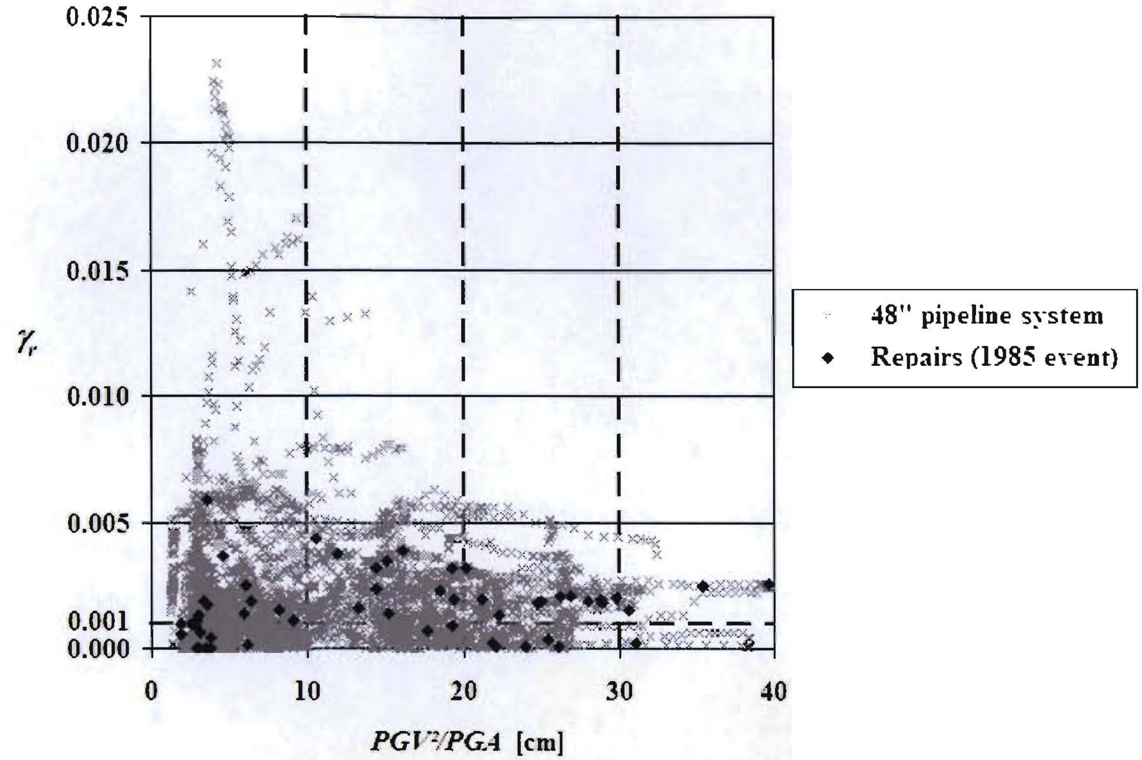

Figure 4. Relationship between γ_r and PGV^2 / PGA for the 48" pipeline system and the 1985 damage scenario (repair sites)

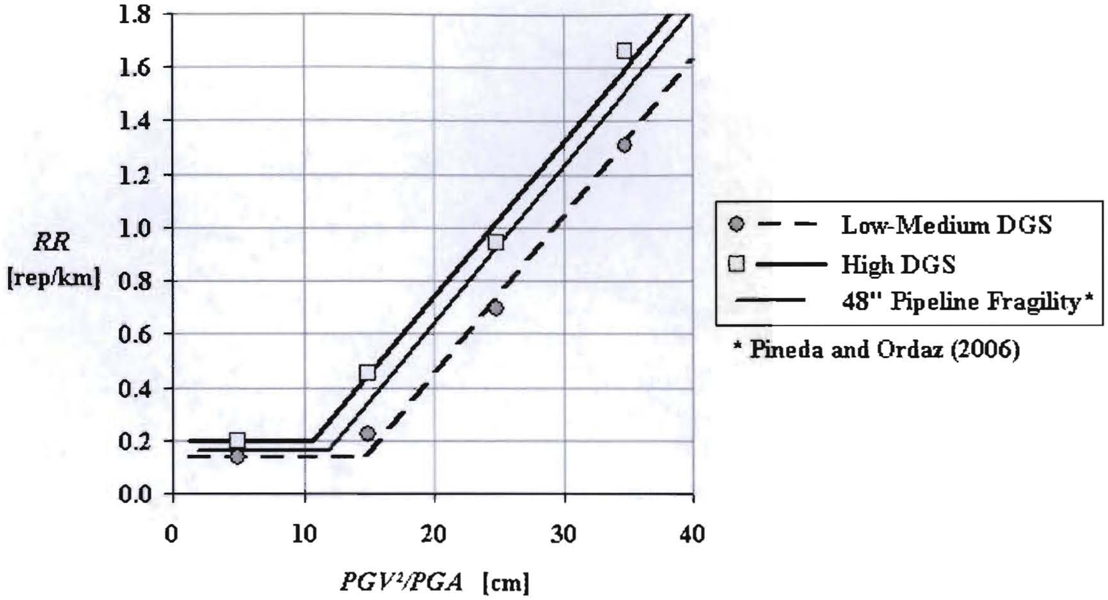

Figure 5. Seismic Damage Functions for Segmented Buried Pipelines Including Differential Ground Subsidence

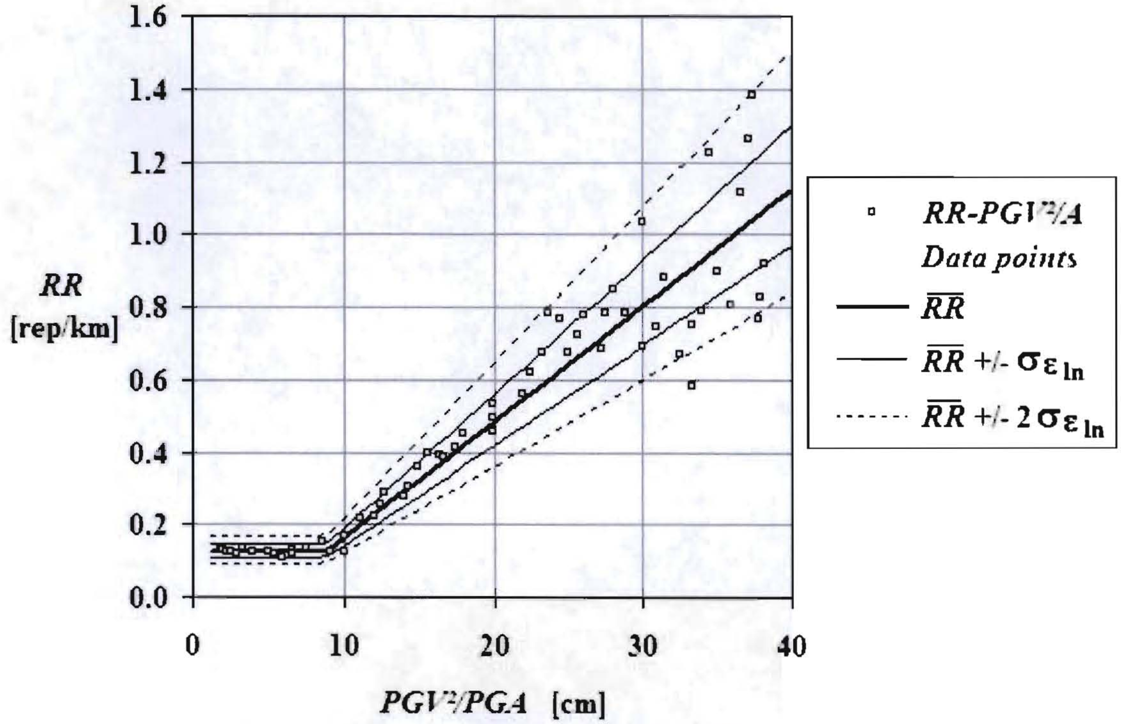

Figure 6. Variability analysis for the fragility function proposed by Pineda and Ordaz (2007)

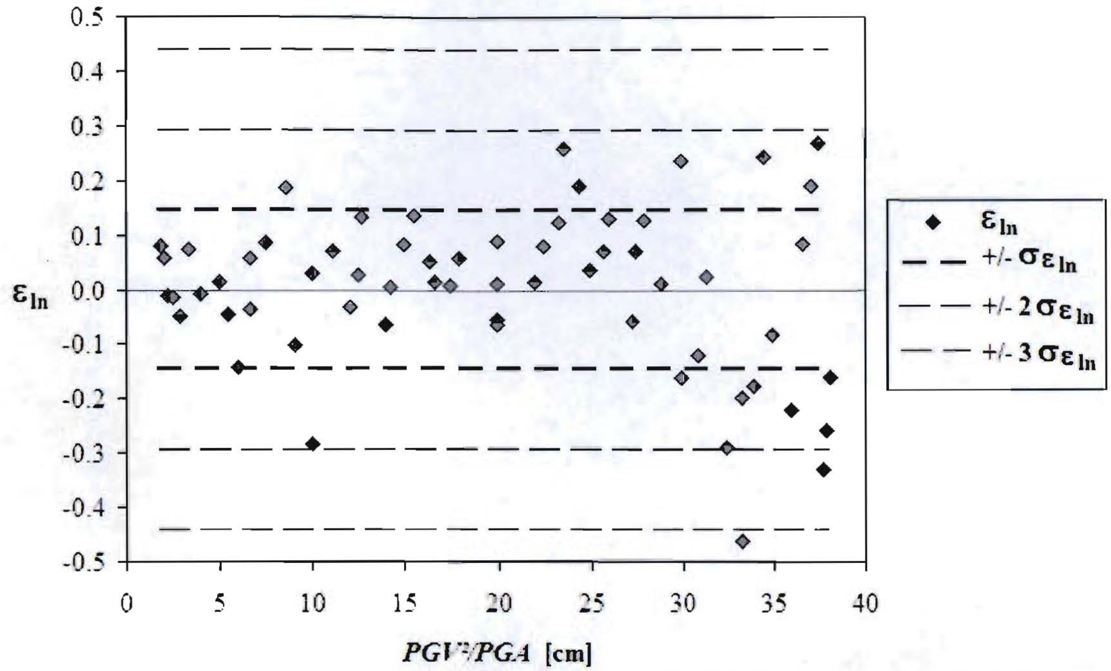

Figure 7. Analysis of Confidence Intervals for the MCWS Fragility proposed by Pineda and Ordaz (2007)

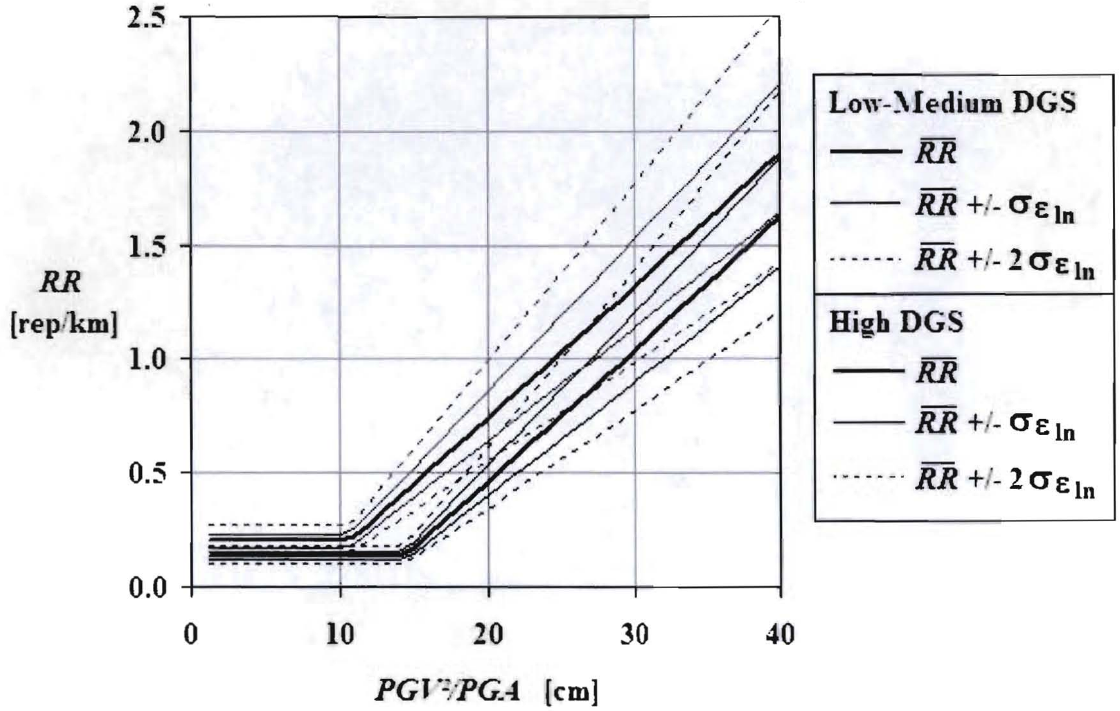

Figure 8. Confidence Intervals for the Proposed Fragility Functions