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Seismic Damage Estimation for Buried Pipelines: Challenges after Three Decades of Progress

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ABSTRACT

This paper analyzes the evolution over the past three decades of seismic damage estimation for buried pipelines and identifies some challenges for future research studies on the subject. The first section of this paper presents a chronological description of the evolution since the mid-1970s of pipeline fragility relations—the most common tool for pipeline damage estimation—and follows with a careful analysis of the use of several ground motion parameters as pipeline damage indicators. In the second section of the paper, four gaps on the subject are identified and proposed as challenges for future research studies. The main conclusion of this work is that enhanced fragility relations must be developed for improving pipeline damage estimation, which must consider relevant parameters that could influence the seismic response of pipelines.

Keywords: pipeline earthquake effects; pipeline seismic damage; seismic fragility relations; seismic damage estimation; buried pipelines.

INTRODUCTION

This paper presents the evolution of pipeline fragility relations, analyzes ground motion parameters as pipeline damage indicators, and identifies gaps in pipeline damage estimation.[1] Pipeline fragility relations comprise the most common tool for pipeline damage estimation.

The first section of this paper presents a chronological description of the evolution since the mid-1970s of pipeline fragility relations. This section then carefully analyzes for the same time period the use of several ground motion parameters as pipeline damage indicators.

In the second section, four gaps in pipeline damage estimation are identified and proposed as challenges for future research studies. These gaps are as follows:

1) Reliable damage estimation for continuous pipelines;
2) Knowledge on the proportion of leaks and breaks with respect to the number of pipe repairs that most fragility relations provide;
3) Pipeline damage estimation considering pipeline orientation; and
4) Enhanced pipeline fragility relations considering special soil and wave propagation conditions.

SEISMIC FRAGILITY RELATIONS FOR BURIED PIPELINES

For buried pipelines, a seismic fragility relation is a function (or group of functions) that relates pipeline damage rates with different levels of seismic intensity. Damage rates are usually defined as the number of pipe repairs per unit length of pipeline (e.g., the number of repairs per kilometer [rep/km]). Damage rates can also be defined as the number of pipe repairs per unit area of land (e.g., Trifunac and Todorovska 1997). Seismic intensity can be quantified through a diverse group of ground motion parameters computed from seismic records.

In the literature, at least nine ground motion parameters have been used for relating damage rates with seismic intensity (Table 1). The nine ground motion parameters are Modified Mercalli Intensity (MMI), Peak Ground Acceleration (PGA), Peak Ground Velocity (PGV), Peak Ground Displacement (PGD), Arias Intensity (AI), Spectral Acceleration (SA), Spectral Intensity (SI), maximum ground strain (ε_g), and the composite parameter PGV^2/PGA.

Table 1 provides references to the most known empirical pipeline fragility relations. Though there are many studies focused on computing analytical pipeline fragilities (e.g., Hindy and Novak 1979; O'Rourke, M. J., and El Hmadi 1988; and Mavridis and Pitilakis 1996), this paper only addresses empirical pipeline fragility relations—those computed from pipeline damage documented after earthquakes. For the sake of brevity, equations on the fragility relations, referenced in Table 1, are not included in this document. Readers are encouraged to look for more information on those studies by consulting the referenced papers directly.

Table 1. References to Pipeline Fragility Functions Studies

Seismic Intensity Parameter	Reference
PGA	Katayama et al. (1975)
	Isoyama and Katayama (1982)
	ASCE-TLCEE (1991)
	O'Rourke, T.D. et al. (1991)
	Hamada (1991)
	Hwang and Lin (1997)
	O'Rourke, T. D., et al. (1998)
	Isoyama et al. (2000)
MMI	Eguchi (1983)
	Ballantyne et al. (1990)
	Eguchi (1991)
	O'Rourke, T. D., et al. (1998)
PGV	Barenberg (1988)
	O'Rourke, M. J., and Ayala (1993)
	Eidinger et al. (1995)
	Eidinger (1998)
	O'Rourke, T. D., et al. (1998)
	O'Rourke, T. D., and Jeon (1999)
	Isoyama et al. (2000)
	ALA (2001)
	Pineda and Ordaz (2003)
	O'Rourke M. J., and Deyoe (2004)
	Jeon and O'Rourke T. D. (2005)
PGD, AI, SA, SI	O'Rourke, T. D., et al. (1998)
ε_g	O'Rourke M. J., and Deyoe (2004)
PGV^2/PGA	Pineda and Ordaz (2007)
	Pineda and Ordaz (2009)

History of Pipeline Seismic Fragility Relations

Empirical correlation between buried pipeline damage and ground motion intensity parameters has been studied since the mid-1970s (Table 1). To compute fragility relations for segmented cast iron (CI) and asbestos cement (AC) pipelines in terms of PGA, Katayama et al. (1975) employed pipeline damage scenarios from six earthquakes: four in Japan (Kanto, 9/1/1923; Fukui, 6/28/1948; Niigata, 6/16/1964; and, Tokachi-oki, 5/16/1968), one in Nicaragua (Managua, 12/23/1972), and one in the United States (San Fernando, Calif., 2/9/1971). Katayama et al. (1975) included fragility relations for poor, average, and good soil conditions.

Early in the 1980s, Isoyama and Katayama (1982) employed the 1971 San Fernando earthquake damage scenario for computing a PGA-based fragility relation. The same damage data and information on other three pipeline damage scenarios (Santa Rosa, Calif., 10/1/1969; Nicaragua, 12/23/1972; and Imperial Valley, Calif., 10/15/1979) was used by Eguchi (1983 and 1991) to compute a set of fragility relations in terms of MMI for the following pipeline types: welded steel gas welded joints, AC, concrete, PVC, CI, welded steel with caulked joints, welded steel with arc-welded joints—Grades A and B steel—polyethylene, ductile iron (DI), and welded steel with arc-welded joints –Grade X steel.

Eguchi (1983 and 1991) concluded that AC and concrete pipes are more vulnerable than PVC pipes; PVC pipes are more vulnerable than CI pipes and welded steel pipes with caulked joints; DI pipes experienced on average about 10 times fewer repairs per unit length than the worst performing pipes; and finally, the repair rate of X grade steel pipes with arc-welded joints was approximately 10 times smaller than that of DI pipes.

In the late 1980s, Barenberg (1988) proposed the first documented PGV-based fragility relation for buried CI pipelines employing damage data from three U.S. earthquakes (Puget Sound, Wash., 4/29/1965; Santa Rosa, Calif., 10/1/1969; and San Fernando, Calif., 2/9/1971). The fragility relation of Barenberg (1988) suggests that a doubling of PGV will lead to an increase in the pipeline damage rate by a factor of about 4.5.

Early in the 1990s, Ballantyne et al. (1990) expanded the pipeline damage data of Barenberg (1988) with damage information from three other U.S. earthquakes (Puget Sound, 4/29/1949; Coalinga, Calif., 5/2/1983; and Whittier Narrows, Calif., 10/1/1987) and proposed new fragility relations by using MMI as a measure of seismic intensity.

Three PGA-based fragility relations were also published in the early 1990s. The Technical Council on Lifeline Earthquake Engineering (TCLEE) of the American Society of Civil Engineers (ASCE) published a comprehensive study on seismic loss estimation for water systems (ASCE-TCLEE 1991) in which PGA-based fragility relations were computed from a reanalysis of the damage data of Katayama et al. (1975) and the 1983 Coalinga pipeline damage scenario. Hamada (1991) proposed another PGA-based fragility relation by analyzing the damage scenarios of earthquakes in the United States (San Fernando, 2/9/1971) and Japan (Miyagiken-oki, 6/12/1978, and Nihonkai-chubu, 5/26/1983). O'Rourke T. D., et al. (1991) related pipeline damage with PGA, employing damage scenarios from seven earthquakes: seven in the United States (San Francisco, 4/18/1906; Puget Sound, 4/29/1965; Santa Rosa, 10/1/1969; San Fernando, 2/9/1971; Imperial Valley, 10/15/1979; Coalinga, 5/2/1983; and Loma Prieta, Calif., 10/18/1989), and one in Japan (Miyagiken-oki, 6/12/1978).

A notable change in the literature on seismic fragility relations for pipelines is observed from 1993: PGV began to be the preferred seismic parameter for pipeline fragility relations, and PGA and MMI were no longer used for new fragilities (with some exemptions described later in this section).

O'Rourke, M. J., and Ayala (1993) proposed a new pipeline fragility relation in terms of PGV by using the damage data points of Barenberg (1988) and damage information from three earthquakes: one in the United States (Coalinga, 5/2/1983) and two in Mexico (Michoacan, 9/19/1985, and Tlahuac, 4/25/1989). The damage data employed for computing the fragility relation are related to pipelines made of AC, CI, concrete, and pre-stressed concrete cylinder pipes. The fragility relation of O'Rourke, M. J., and Ayala (1993) was later incorporated into the loss assessment methodology HAZUS-MH of the Federal Emergency Management Agency (FEMA 1999). This fragility relation can be used for damage prediction of brittle pipelines. For ductile pipelines, the fragility relation must be multiplied by a suggested factor of 0.3 (FEMA 1999).

Eidinger (1995 and 1998) reanalyzed the pipeline damage data of O'Rourke, M. J., and Ayala (1993), along with information from the 1989 Loma Prieta pipeline damage scenario, in order to propose a set of fragility relations in terms of PGV that considered pipe material, joint type, and soil corrosiveness. Eidinger's fragility relations estimated damage for CI, welded steel (WS), AC, concrete, PVC, and DI pipes.

Hwang and Lin (1997) computed a pipeline fragility relation in terms of PGA by analyzing pipeline damage data obtained from six previous studies (Katayama et al. 1975; Eguchi 1991; ASCE-TCLEE 1991; O'Rourke, T. D., et al. 1991; Hamada 1991; and, Kitaura and Miyajima 1996).

O'Rourke, T. D., et al. (1998) employed a GIS-based methodology to investigate factors affecting the water supply service of the Los Angeles Department of Water and Power (LADWP) and the Metropolitan Water District (MWD) after the 1994 Northridge earthquake. Analyses of the relationship between damage rate and seismic intensity were conducted using seven seismic parameters: MMI, PGA, PGV, PGD, AI, SA, and SI. Pipeline fragility relations in terms of MMI, SI, PGA, and PGV are also included in the paper. O'Rourke, T. D., et al. (1998) concluded that PGV is best related to the pipeline damage than any other parameter and proposed PGV-based fragilities for steel, CI, DI, and AC pipelines. Later, O'Rourke, T. D., and Jeon (1999) developed a fragility relationship (for CI pipes) for scaled velocity, a parameter based on peak ground velocity but normalized for the effects of pipe diameter.

Isoyama et al. (2000) computed fragility relations in terms of PGA and PGV by analyzing the pipeline damage scenario left by the 1995 Hyogoken-nanbu earthquake. A multivariate analysis was carried out to compute empirical correction factors to account for pipe material, pipe diameter, ground topography, and liquefaction in the fragility relation.

The American Lifeline Alliance (ALA), a public-private partnership between FEMA and the ASCE, published a set of algorithms to compute the probability of damage from earthquake effects to several components of water supply systems (ALA 2001). For buried pipelines, the PGV-based fragility relation published by the ALA was computed from a set of 81 damage rate-PGV data points from 12 seismic damage scenarios. Similar to the fragility relations of Eidinger et al. (1995 and 1998), the ALA's fragility relation provides a factor to account for pipe material, joint type, and soil corrosiveness.

Pineda and Ordaz (2003) reanalyzed the pipeline damage scenario left by the 1985 Michoacan earthquake in the Mexico City's Water System (MCWS) (Ayala and O'Rourke 1989). They employed detailed PGV maps to study the relationship of damage rate to seismic intensity. As a result of the analysis, a PGV-based fragility relation was proposed for the MCWS.

O'Rourke, M. J., and Deyoe (2004) analyzed the differences of the fragility relations published by O'Rourke, M. J., and Ayala (1993) and O'Rourke, T. D., and Jeon (1999). Some reasons for the differences were identified from the analysis: the wave type that dominated each seismic scenario, the presence of corrosion in some pipes, and the low statistical reliability of some data points. By removing doubtful data points and classifying the remaining data points according to the presumably dominating wave type, O'Rourke, M. J., and Deyoe computed PGV-based pipeline fragility relations for surface waves (Rayleigh) by assuming phase velocity of 500 m/sec and for body waves (S-waves) by assuming apparent velocity of 3,000 m/sec; they also proposed a fragility relation in terms of ε_g. The new ε_g-based fragility relation also considers the effect of permanent ground deformation since O'Rourke, M. J., and Deyoe included repair rate-ε_g data points from the 1994 Northridge earthquake (Sano et al. 1999) and from Japan (Hamada and Akioka 1997). A recent modification to the ε_g-based fragility relation (O'Rourke, M. J., 2009) uses an apparent velocity of 1,000 m/sec for S-waves; that assumption is based on a study of Paolucci and Smerzini (2008).

Jeon and O'Rourke (2005) reanalyzed the pipeline damage data from a previous study (O'Rourke, T. D., et al. 1998) and compared the correlation between CI pipeline damage rates (from the 1994 Northridge earthquake) and PGV computed in different ways (geometric mean PGV, maximum PGV, and maximum vector magnitude of PGV). Their results showed that maximum PGV, computed as the peak recorded value, is better correlated with pipeline damage. Jeon and O'Rourke (2005) also provided fragility relations for WSJ Steel, CI, DI, and AC pipelines.

Pineda and Ordaz (2007) reanalyzed the effects of the 1985 Michoacan earthquake in the MCWS and found that for soft soils PGV^2/PGA is better related to pipeline damage than PGV alone. The 2007 study showed that the novel ground motion parameter PGV^2/PGA is directly related to PGD through a non-dimensional parameter $\lambda_{p_{r}}$; this fact implies that PGD could also be a damage indicator for pipelines located in soft soils, although this statement has not yet been proved.

Recently, Pineda and Ordaz (2009) computed fragility relations for 48-inch segmented pipelines, considering the effects of ground subsidence, a phenomenon largely observed in the Valley of Mexico. They analyzed the relationship between pipeline damage and seismic intensity (measured in terms of PGV^2/PGA) for two levels of differential ground subsidence (DGS). The proposed fragility relations fall above and below a previous fragility relation for 48-inch pipelines that does not explicitly consider the effects of DGS in the damage (Pineda 2006).

Seismic Damage Indicators for Pipelines

From an historical revision of empirical pipeline fragility relations (see Table 1), nine seismic ground parameters have been used as damage indicators for pipelines. This section provides further details about five of them—MMI, PGA, PGV, ε_g, and PGV^2/PGA. The other four parameters—PGD, AI, SA, and SI—are not discussed here because there is not enough evidence on their relationship with pipeline damage.

MMI was used as damage indicator for pipelines in the 1980s and 1990s (Eguchi 1983 and 1991; Ballantyne et al. 1990; and, O'Rourke, T. D., et al. 1998). However, the subjective nature of its definition made it difficult to accurately predict pipeline damage. A likely reason for the development of MMI-based fragility relations is the extended use of that parameter to describe damage to aboveground structures.

PGA was largely employed as a damage indicator for pipelines during the 25 years from 1975, with the study of Katayama et al., to 2000, with the last known PGA-based fragility relation of Isoyama (as shown in Table 1). Though it has been largely demonstrated that PGV is more related to pipeline damage than PGA—which is further explained in the following paragraphs—there are several reasons to explain why PGA, instead of PGV, was used to create some fragility relations before 2000. Two relevant reasons are the following:

1) Most seismic stations record time histories of acceleration instead of velocity. PGA can then be directly obtained from seismic records without involving the integration process needed for computing PGV.
2) Most attenuations laws provide estimates of PGA. (Before 2000, PGV attenuation laws were limited.) Then, for practical purposes, PGA was the ideal parameter for analyzing pipeline damage and, therefore, creating pipeline fragility relations.

PGV is better related to pipeline damage than PGA mainly due to two reasons:

1) PGV is related to ground strain, the main cause of pipeline damage due to seismic wave propagation; and
2) PGA is more related to inertia forces—forces that do not affect buried structures like pipelines.

Many studies have empirically demonstrated that PGV is a better pipeline damage predictor than PGA (e.g., O'Rourke, T. D., et al. 1998; Isoyama et al. 2000; and Pineda 2002).

PGV has been extensively used as damage indicator for pipelines, given two assumptions:1) PGV is directly related to maximum ground strain (ε_g); and 2) transient ground strain is the main cause of pipeline damage due to seismic wave propagation. The relationship between PGV and ε_g can be analyzed in Equation 1 (Newmark 1967), where C is seismic wave velocity. From Equation 1, PGV is directly related to ε_g only if C is constant. Since ε_g is non-dimensional, PGV and C must be expressed with the same velocity units.

$$\varepsilon_g = \frac{PGV}{C} \qquad [1]$$

Though PGV has shown a better correlation with pipeline damage than any other parameter, like MMI, PGA, PGD, AI, SA, and SI (e.g., O'Rourke, T. D. et al. 1998), Pineda and Ordaz (2007) found that PGV^2/PGA is better parameter than PGV for soft soils. The same observation was made in a further study that includes the effects of ground subsidence in pipeline damage (Pineda and Ordaz 2009).

Since transient ground strain is assumed to be the main cause of pipeline damage due to seismic wave propagation, ε_g is obviously the optimum parameter for analyzing the relationship between pipeline damage and seismic intensity. Rigorously, maximum transient ground strain (ε_g) can be estimated from displacement time histories $D(t)$ (Equation 2). In Equation 2, x is a space variable, $\varepsilon(t)$ is ground strain time history, and $\boldsymbol{max}$ represents the maximum of the expression between absolute value brackets | |.

$$\varepsilon_g = \boldsymbol{max}|\varepsilon(t)| = \boldsymbol{max}\left|\frac{\partial D(t)}{\partial x}\right| \qquad [2]$$

There are three major problems for estimating ε_g through Equation 2, as described here:

1) $D(t)$ is generally obtained through the double integration of acceleration time histories; this process causes loss of information due to the involved mathematical operations. Procedures like tapering, filtering, and correction of the base line could generate ambiguous results if the parameters used in those operations are modified.
2) The derivation process of $D(t)$ with respect to a space variable (x) implies that the seismic records, to be used in the analysis, need to be referenced to an absolute time scale. This is a very significant limitation since only ground motion information from seismic arrays that use the same time reference, and preferably located in the place of interest (e.g., the zone covered by a pipeline system), would be useful.

3) Finally, probably the most important problem are the high costs involved in the installation and operation of seismic arrays covering large extensions (e.g., area covered by a pipeline network).

To avoid the above-mentioned problems of Equation 2, Equation 1 has been used to obtain conservative estimates of ε_g. PGV can be easily obtained from seismic records or other sources (e.g., attenuation laws). By comparison, C is far from easy to obtain, which complicates the estimation of ε_g.

For the purpose of estimating ε_g with Equation 1, here are two examples to show how complex the estimation of C is:

1) The ε_g-based fragility relation proposed by O'Rourke, M. J., and Deyoe (2004) was computed by assuming C values of 500 m/sec for Rayleigh waves (surface waves), and 3,000 m/sec for S-waves (body waves). Later, the study of Paolucci and Smerzini (2008) suggested that the apparent propagation velocity of S-waves is closer to 1,000 m/sec. O'Rourke, M. J. (2009) then employed the new suggested C value for S-waves and proposed a new version of the 2004 fragility relation. Changing C from 3,000 m/sec to 1,000 m/sec in Equation 1 implies that ε_g increases with a factor of three. The objective here is to illustrate with a documented example how complex the estimation of ε_g is by assuming C values.
2) This example deals with the estimation of ε_g in soft soil zones. Singh et al. (1997) analyzed ground strains at the Roma micro-array in Mexico City for four earthquakes. They concluded that Equation 1 could be used to estimate ε_g by using a phase velocity (Rayleigh waves) of 600 m/sec instead of the value of C at the natural period of lake bed sites (estimated as 1,500 m/sec). Singh et al. (1997) indicated that the discrepancy in the value of C could be due to local heterogeneities within the array. This example illustrates how complex the estimation of C is for soft soils with presence of local heterogeneities.

Instead of ε_g, PGV is a more convenient parameter for analyzing pipeline damage due to seismic wave propagation; three reasons are as follows: 1) PGV is a parameter easier to estimate than ε_g; 2) Many studies have proved that PGV is well correlated with pipeline damage; and 3) Theoretically, there is a direct relationship between PGV and pipeline damage, taking into account the two assumptions already mentioned in this section. Notwithstanding these three points, there is evidence of a case in which PGV is not the best parameter for relating pipeline damage with seismic intensity—the particular case of Mexico City.

As described in the section on the history of pipeline seismic fragility relations, the studies of Pineda and Ordaz (2007 and 2009) demonstrate that PGV^2/PGA is better correlated to pipeline damage than PGV alone for soft soils. A plausible explanation is the fact that PGV^2/PGA is strongly related to PGD, a ground motion parameter related to very-low frequency contents. Though in the past it has been demonstrated that PGV is better pipeline damage predictor than PGD (O'Rourke, T. D., et al.

1998), studies exclusively focused on the relationship between pipeline damage and PGD (or PGV^2/PGA) for soft soil sites have not yet been done. Finally, two things must be noted. First, Pineda and Ordaz (2007 and 2009) employed PGV^2/PGA instead of PGD due to the rigorous theoretical relationship between both parameters (explained in the paper of Pineda and Ordaz 2007), the availability of detailed PGA and PGV maps for the 1985 Michoacan event (see Pineda 2006 for details about those maps), and the lack of enough information on ground motion to produce reliable PGD maps for the 1985 earthquake (Pineda 2006). And second, Pineda and Ordaz (2007 and 2009) define soft soils as those soils with natural periods equal to or higher than 1.0 sec.

FUTURE CHALLENGES IN THE SEISMIC DAMAGE ESTIMATION FOR PIPELINES

Though seismic damage estimation for pipelines has advanced considerably since the mid 1970s, a large list of subjects still needs to be further studied to better understand the impact of earthquakes on those structures. The following four relevant, unsolved issues constitute a challenge for future investigations. Unfortunately, actual pipeline seismic damage scenarios, practically speaking, are the only reliable source of information to definitively validate any analytical model or assumptions with respect to these four topics.

1) Damage Estimation for Continuous Pipelines

Pipelines are classified as segmented or continuous depending on the effects that earthquakes have on them. Segmented pipelines are commonly made of concrete, CI, and AC (e.g., cast iron pipe with lead caulked joints). Continuous pipelines are usually characterized by welded joints (e.g., steel pipe with welded joints).

The current fragility relations, available in the literature (Table 1), are based on damage scenarios for segmented pipelines. There are no fragility relations for continuous pipelines mainly because of the lack of evidence of damage due to seismic wave propagation. Some researchers believe that continuous pipelines are not affected by seismic wave propagation at all (e.g., O'Rourke, T. D., 2009). However, others have documented a few damage cases characterized by special circumstances (e.g., O'Rourke, M. J., 2009).

The HAZUS-MH methodology (FEMA 1999) suggests that damage to continuous pipelines (made of ductile materials) can be estimated with the fragility formulation for segmented pipelines (made of brittle materials) multiplied by a factor of 0.3. There is no solid evidence to validate the above-mentioned assumption. However, the HAZUS-MH's approach likely provides overestimated damage estimations.

The challenge on damage estimation for continuous pipelines is to answer two questions:

1) Can our colleagues assume that there will be no damage in continuous pipelines due to seismic wave propagation caused by future earthquakes?

2) If answer to question 1 is "no" and considering the HAZUS-MH approach, is 0.3 a reliable factor for estimating damage to a continuous pipeline without resulting in an unnecessary overestimation of pipe repairs?

2) Proportion of Leaks and Breaks with Respect to Number of Repairs

Most of the available fragility relations (Table 1) do not clarify the proportion of leaks and breaks with respect to the expected number of pipe repairs. There are two known references to the proportion of leaks and breaks. First, the HAZUS-MH methodology (FEMA 1999) suggests a proportion of 80% leaks and 20% breaks. Second, observations made after the 1994 Northridge earthquake revealed that the damage to the LADWP pipeline system was characterized by a proportion of 95% leaks and 5% breaks (O'Rourke. T. D., et al. 1998). More studies on this subject are needed to complement the current fragility relations in order to provide better models to describe earthquake effects on pipeline networks. These enhanced models could support logistic repair operations to reestablish pipeline distributions services (e.g., water supply) as soon as possible after a seismic event.

3) Damage Estimation Considering Pipeline Orientation

Theoretically, pipe orientation plays a very important role in pipeline damage caused by seismic wave propagation. For instance, if a straight pipeline is oriented in the same direction as the propagation direction of a group of Rayleigh waves, the damage is maximum. But if the same straight pipeline is perpendicular to the propagation direction of the same group of Rayleigh waves, the damage is zero.

Most (if not all) fragility relations provide "average" damage estimations with respect to pipeline orientation. This is because, in general, fragility relations are computed from damage scenarios of pipeline networks with complex geometry. In this context, a network with complex geometry means a network with pipeline segments oriented in all directions (e.g., the LADWP and the MCWS). Theoretically, a fragility relation, computed from a damage scenario for a pipeline network with complex geometry, must provide the same total damage estimates independently of the direction of seismic wave propagation.

The challenge with damage estimation that takes into account pipe orientation is to answer the following question: what is the expected damage for a straight pipeline system (or a system with a noticeable pipe orientation tendency) employing current fragility relations? Independent of the ground motion model used in the analysis, current fragility relations would provide an intermediate estimation of pipeline damage, between zero and the maximum damage, from the theoretical framework. That could result in making an underestimation or overestimation of the likely damage depending on the pipe orientation distribution of the network in study.

4) Pipeline Fragility Relations Considering Special Soil and Wave Propagation Conditions

The case of Mexico City raises a lot of questions about computing pipeline fragility relations for sites characterized by soft soils and surface wave propagation. Previous studies, already described in this paper, have shown that for the case of Mexico City there are discrepancies in the estimation of ε_g by using Equation 1 (Singh et al. 1997), and PGV^2/PGA is a better damage indicator than PGV alone (Pineda and Ordaz 2007). The first point likely explains the second one. For Mexico City, it seems that PGV is not directly related to ε_g (by assuming a constant C in Equation 1). Therefore, PGV apparently is not directly related to pipeline damage (caused by transient ground strain). Some unanswered questions remain:

- Is PGV^2/PGA related to ε_g? If so, is PGD related to ε_g?
- Can PGV^2/PGA (and PGD) be used as damage predictor for pipeline in soft soils (other than those of Mexico City) instead of PGV?
- Is pipeline damage in soft soils related to ground motion characterized by very low frequency contents (which would explain why PGV^2/PGA, and possibly PGD, is a better damage predictor than PGV)?
- How accurate are the current pipeline fragility relations for estimating pipeline damage in soft soils?

CONCLUSIONS

Seismic damage estimation for pipelines has advanced considerably since the mid-1970s. The relationship between pipeline damage and seismic intensity has been studied using diverse ground motion parameters and taking into account several aspects related to pipelines (e.g., diameter, material) and soils (e.g., softness, corrosiveness). Notwithstanding these advances, some gaps still exist on this subject, which must be studied if the current damage assessment methods are going to improve. As examples of the existing gaps, four unsolved issues on damage estimation for pipelines are raised. Enhanced fragility relations must be developed for improving pipeline damage estimation and must consider relevant parameters that could influence the seismic response of pipelines.

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