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KEY PARAMETERS FOR ESTIMATING BURIED PIPE DAMAGE

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ABSTRACT

Current methods for estimating seismic damage to buried pipelins are reviewed and paramters which have the strongest influence on results are identified. Earthquake damage to buried pipelines can be characterized as being due to seismic wave propagation (WP) or permanent ground deformation (PGD). Current procedures for estimating seismic damage to these systems require information on both these seismic hazards (peak particle velocity for WP and the amount and spatial extent of ground movement for PGD) as well as fragility relations between hazard and damage, and between damage and system performance. The paper reviews the currently available empirical procedures for quantifying the seismic hazard. For WP, these take the form of attenuation relations for strong ground motion parameters. For PGD, there are relatively recent procedures for estimating the amount of permanent ground movement. The WP hazard typically can be estimated within a factor of two (that is, observed values greater than half the predicted value, and less than twice the predicted value). The scatter for the PGD hazard is somewhat greater.

Fragility relations for buried pipe subject separately to WP and PGD hazards are then investigated. For WP, existing empirical relations between normalized pipe damage (in repairs per unit length) and peak particle velocity are reviewed. It is shown that the relation yields predicted normalized damage within a factor of roughly three of observed values. For PGD similar scatter in fragility relations and in the expected spatial extent is noted. Similar information for serviceability estimates for lifeline systems are presented. Finally, recommendations for improvements in this methodology are suggested.

KEYWORDS

seismic hazard, wave propagation, permanent ground deformation, attenuation relations, fragility relations, buried pipelines, component vulnerability, system performance.

INTRODUCTION

Often the first step in the seismic upgrade of a pipeline system is an evaluation of the likely amounts of damage in the existing system due to postulated future earthquakes. This process typically begins with characterization and quantification of the seismic hazards of interest. Fragility relations are then used to estimate the amount of component damage, that is, the expected number of pipeline leaks and breaks.

Finally the direct repair costs, immediate post-earthquake system functionality (expected number of customers without service), and estimated system restoration time are calculated.

This paper reviews current methods for estimating each of these three elements, that is, seismic hazard, component vulnerability and system performance. Special attention is paid to the variability or scatter in these relations, and parameters which have the strongest influence on results are identified.

SEISMIC HAZARDS

For buried pipelines, the seismic hazards of interest are wave propagation (WP) and permanent ground deformation (PGD). Although there have been some events where pipe damage has been due only to wave propagation (e.g., Mexico City in the 1985 Michoacan earthquake), in many events pipe damage is due to a combination of hazards. Typically PGD damage occurs in isolated areas of ground failure (with high damage rates in terms of repairs per kilometer of pipe) while wave propagation damage occurs over much larger areas, but with lower damage rates.

Wave Propagation Hazard

Seismic wave propagation refers to the transient strains and curvatures induced in the ground due to the passage of traveling seismic waves. For most pipe diameters, ground strain ε_g is the more important effect. It is given by

$$\varepsilon_g = V_{max}/C \qquad (1)$$

where V_{max} = the peak horizontal particle velocity, and C = the apparent propagation velocity of the waves with respect to the ground surface.

Because of this, V_{max} is the ground motion parameter used to characterize the WP hazard in more recent studies. Empirical or semi-empirical attenuation relations are typically used to estimate the range of V_{max} values for the system in question (Kamiyama et al. 1992). Although one can argue the relative merit of any given relation, when one plots observed values from a given event against predicted values, there is always a fair amount of scatter. For example, Figure 1 compares V_{max} at rock sites in the 1989 Loma Prieta event against values predicted by the Kamiyama et al. relation. The scatter in this figure is fairly typical in that, even with the "best" attenuation relation, observed values are only within a factor of two of predicted values.

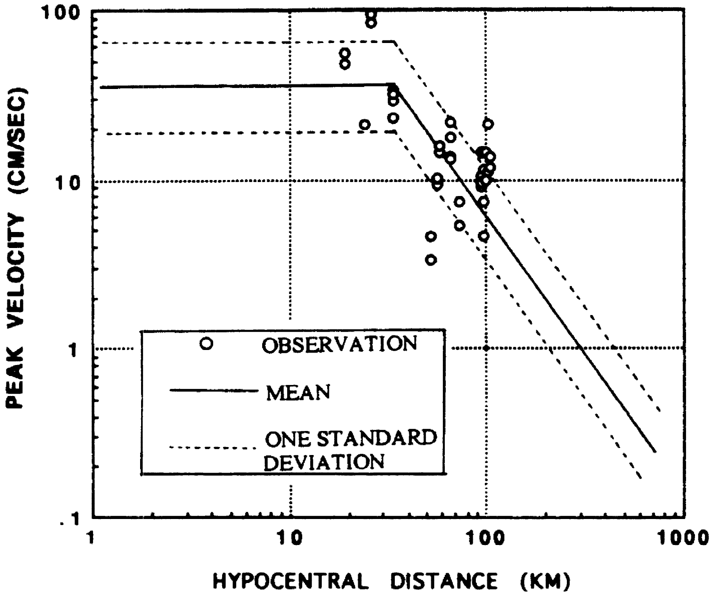

Fig. 1 Comparison of Peak Ground Velocity at Rock Sites in 1989 Loma Prieta Event with Kamiyama et al. Relation (after Kamiyama et al. 1992)

PGD Hazard

Permanent ground deformation refers to non-transient ground movements such as surface faulting, seismic settlements and liquefaction-induced lateral spreads. Due to space limitations, attention is restricted to lateral spreads. For this and some other forms of PGD, the hazard is characterized by the amount of ground movement and the spatial extent of the PGD zone.

Currently there are a number of relations for estimating the amount of PGD movement due to liquefaction-induced lateral spreading. Arguably one of the most accurate was developed by Bartlett and Youd (1995). The displacement is a function of earthquake magnitude, source to site distance, site geometry, as well as three geotechnical parameters. Figure 2 is a scattergram of measured versus predicted values from the Bartlett and Youd model. In terms of scatter, most observed values are within a factor of two of the predicted.

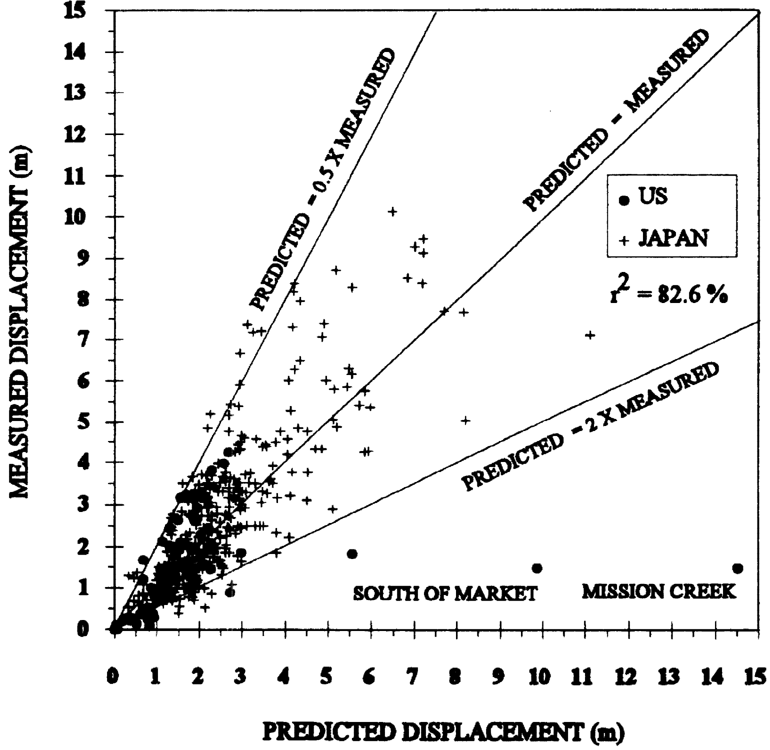

Fig. 2 Scattergram of Observed versus Predicted Values of PGD Movement (after Bartlett and Youd 1995)

Although the Bartlett and Youd relation is reasonably accurate, it requires geotechnical parameters, specifically, particle size, fines content and liquefiable layer thickness, which typically are not available in the form of maps. As a result, system evaluations often rely upon cruder PGD displacement relations such as the Liquefaction Severity Index (LSI) developed by Youd and Perkins (1987).

$$\mathrm{Log(LSI)} = -3.49 - 1.86\log \mathrm{R} + 0.98\mathrm{M_w} \tag{2}$$

Note that LSI (in inches) is a function only of the horizontal distance to the energy source, R, (in kilometers) and the moment magnitude M_w, and hence relatively easy to apply in system evaluation studies. On average, observed values of PGD displacement for events in Alaska and California are roughly half of LSI. That is, as noted by Youd and Perkins, LSI is an upper bound with observed values again for Alaska and California events rarely exceeding LSI given by Equation (2). As one might expect the scatter using the cruder LSI relation is larger than that in Figure 2.

The other key parameter needed to characterize the PGD hazard is the spatial extent of the PGD zones. Based on data from the 1964 Niigata event, Suzuki et al. (1989) suggest that the width of PGD zone (spatial dimension perpendicular to the direction of PGD movement) is proportional to the amount of the ground movement and the scatter is roughly a factor of two.

While the use of ground movement/spatial extent interrelationships may be appropriate for an individual site, analyses of pipeline networks more frequently rely upon liquefaction susceptibility maps to identify PGD areas. Due to the conservation inherent in available maps, a reduction factor should be used to transform from areas susceptible to liquefaction to areas actually expected to liquefy. These reduction factors are typically based upon engineering judgment coupled with case history experience. Table 1 presents reduction factors suggested by two independent groups for use in an earthquake loss estimation project in the U.S.

Relative Susceptibility	Reduction Factor	
	Group 1	Group 2
Very High	0.90	0.25
High	0.75	0.20
Moderate	0.50	0.10
Low	0.15	0.05
Very Low	0.05	0.02

Table 1. Reduction factors for liquefaction susceptible area to area expected to liquefy

Note that these reduction factors which are intended to model average behavior differ by factors ranging from 2.5 up to 5.0. Hence there is a fairly large amount of uncertainty attached to estimates of the likely pipeline length in the network subject to PGD effects.

COMPONENT VULNERABILITY

For buried pipelines, empirical correlations between observed seismic damage typically in repairs per kilometer of pipe, and some measure of ground motion are often used to characterize component vulnerability. One of the first of these relations was developed by Katayama et al. (1975) in which damage rate is plotted as a function of peak ground acceleration. This relation includes both wave propagation and PGD damage. It appears that Eguchi et al. (1983) were the first to consider wave propagation and PGD damage separately in relation to fragility curves. Currently, that approach is typically used.

Wave Propagation Fragility

As noted previously component fragility relations for wave propagation effects often use peak ground velocity to characterize the hazard. Figure 3 shows one such fragility relation developed by O'Rourke and Ayala (1993) using information for relatively brittle water system materials (specifically asbestos cement, cast iron, and concrete pipe) from 4 U.S. events and 2 Mexican events. In terms of scatter, the observed values are typically within a factor of roughly 2.5 of predicted values. The unexpectedly large observed damage ratios were attributed to corrosion and variable subsurface ground conditions.

larger diameters, and deeper joints which would be better able to accommodate a given joint displacement demand for larger diameter segmented concrete pipe. Such modifications are probably appropriate for studies of larger diameter transmission lines. However, considering the other uncertainties identified herein, diameter modification may not be warranted for system studies in which large diameter lines composed a relatively small portion of the total network.

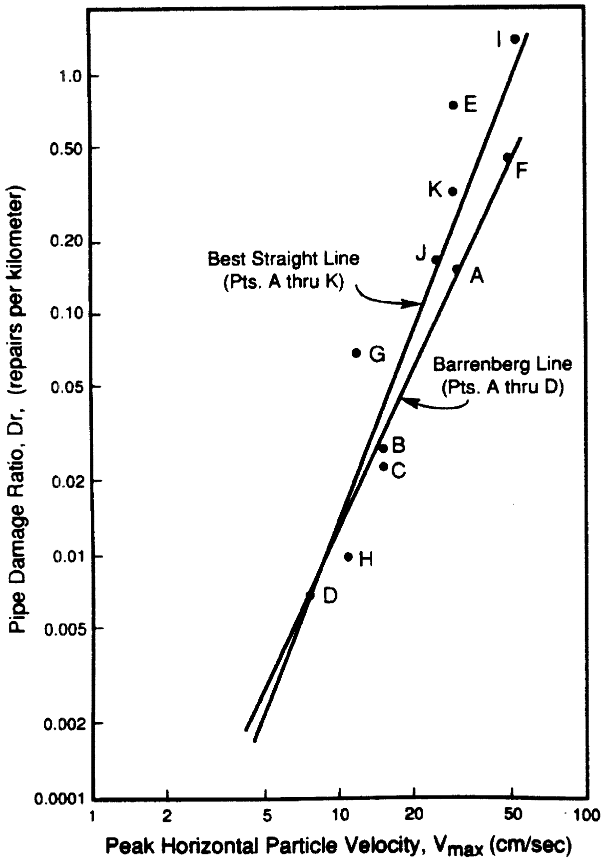

Fig. 3 Fragility Relation for Wave Propagation Damage (after O'Rourke and Ayala 1993)

PGD Fragility

Although PGD damage to buried pipe components is theoretically related to the amount as well as the spatial extent of the PGD zone, most fragility relations simply use the amount of PGD movement to characterize the hazard. An example of one such relation, developed by Porter et al. (1991), is shown in Figure 4. They plot damage rate (pipe breaks per 1000 ft) versus the amount of permanent ground displacement in inches. A bilinear relation was presented for bell and spigot cast iron pipe with lead and oakum joints. The initial (PGD $\leq$ 5 inches) portion of the curve is based on damage information for the Marina District in San Francisco during the 1989 Loma Prieta event (vertical settlements) while the later PGD $\geq$ 5 inches) portion is based upon the 1906 San Francisco event (later spreads). Engineering judgment is then used to develop similar relations for other pipe materials.

Note that subsequent research suggests that the Marina District pipe damage may have been due to wave propagation effects in the liquefied soil as opposed to simply the final vertical settlement. Nevertheless the scatter of observed data points about the predicted behavior line is comparable to those presented previously. That is, for PGD movement of 60 inches (~ 1.5 m) the observed damage ratio ranges from about 3 to 7 pipe breaks per 1000 feet.

More recent studies have suggested other empirically based relations between damage and the amount of ground movement. For example, Heubach (1995) suggests that expected damage to cast iron pipe with rigid joints is roughly a factor of four larger than that for modern welded steel pipe.

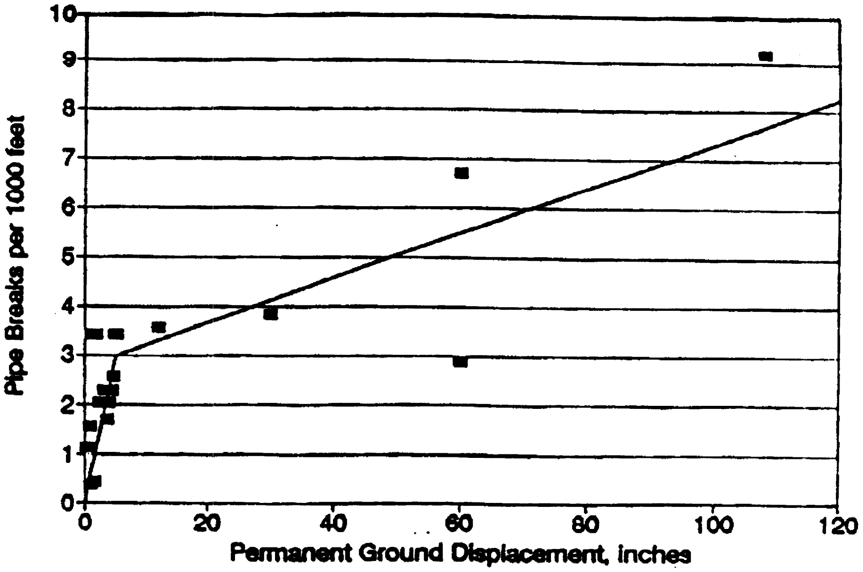

Fig. 4 PGD Fragility Relation (after Porter et al. 1991)

Along similar lines, Eidinger et al. (1995) proposed PGD damage relations which are functions of pipe material and joint type. For example asbestos cement and cast iron pipe with rubber gasket joints are expected to have about 25% less damage than the same materials with cement joints.

SYSTEM PERFORMANCE

Knowing the expected number of leaks and breaks in the pipeline network, the direct losses (i.e., expected repair costs) can be calculated. However, in terms of impact upon the population served by the system, an equally important measure of damage is expected system functionality. By this we mean the percentage of customers without service immediately after the event and the expected restoration time. Given sufficient resources and an estimate of damage, an estimate of system functionality can be determined from a hydraulic model of the damaged system. In such a model, one must distinguish between leaks and breaks. That is, a pipeline break has a much larger impact on functionality than a pipeline leak. Unfortunately, the information typically available after an event is the number and location of pipeline repairs (i.e., no discrimination between leaks and breaks). The authors are aware of only one detailed study of earthquake damage which clearly separates leaks from breaks. In their study of pipeline damage in the 1989 and 1965 events in the Puget Sound area, Ballantyne et al. (1990) indicate that 85% of the repairs were leaks while the remaining 15% were breaks.

The results of a number of past earthquake functionality studies are shown in Figure 5 (Bendimerad and Bouabid, 1995). Note that the scatter in serviceability estimates is again roughly a factor of two with the average of about 50% and a range from 20 to 80% for a break rate of 0.1 breaks per kilometer.

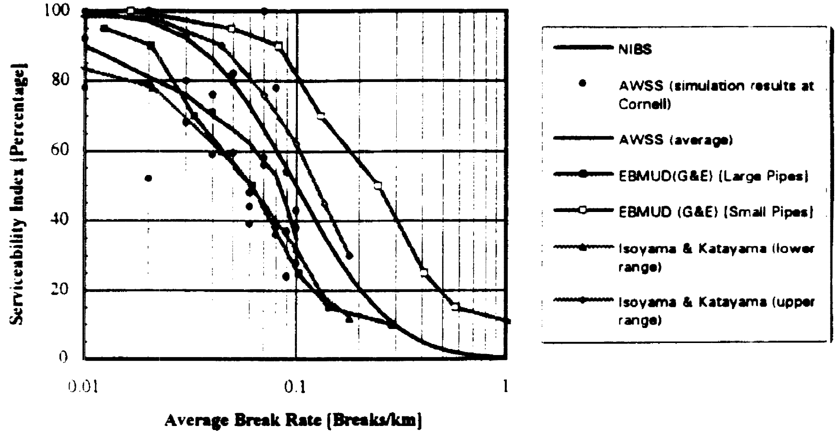

Fig. 5 System Performance Relationship (after Bendimerad and Bouabid, 1995)

CONCLUSIONS

A review of current methods for estimating seismic damage to, and the overall performance of buried pipeline systems is presented. Relations for characterizing the three elements of interest, namely, the seismic hazard, component vulnerability and system performance, are discussed. An attempt is made to quantify the variability or scatter in the available relations and identify key parameters and relations which have the strongest influence upon results.

Based upon this review, the following observations are made:

- The wave propagation hazard, at least in more recent studies, is quantified by the peak ground velocity, V_{max}. Observed values for V_{max} typically are within a factor of two of values predicted by available attenuation relations.
- The PGD hazard, at least in more recent studies, is often quantified by the expected amount of ground movement. The upper bound LSI relation is often used in this regard. The medium or average value of ground movement is typically one half LSI. Observed values of ground movement rarely exceed twice the average predicted values. However, observed values sometimes are as low as a tenth of the average predicted value.
- The expected spatial extent of PGD zones, which is needed to estimate the length of pipe exposed to these effects, is difficult to predict. Given a liquefaction susceptibility map, "best estimates" of the area actually expected to liquefy can vary by a factor of five. The scatter about a best estimate currently appears to be unknown.
- Available component fragility relations for wave propagation effects typically yield predicted damage ratio within a factor of two or three of observed values.
- Available component fragility relations for liquefaction-induced PGD effects relate damage to the amount of ground movement. Although the damage may well be positively correlated with the ground movement, the potential for damage is theoretically related to ground strain or curvature.
- With a few notable exceptions, there is relatively little empirical data for diameter, pipe material, and joint type modification factors to WP and PGD fragility relations. The authors believe that modification factor should be based, in some fashion, on measurable properties such as the pipe material tension failure strain.
- In evaluating system performance, one must distinguish between pipeline leaks and pipeline breaks. The authors are aware of only one study which provides point estimates for the percentage of these two types of damage. Apparently the expected scatter in these percentage estimates is currently unavailable.
- The expected scatter in system performance estimates, as a function of average break rate, is on the order of a factor of two.

Based on these observations, the authors believe that substantial improvement in our ability to evaluate seismic damage to pipeline networks will require; (1) improved estimates for the area actually expected to liquefy, (2) maps of geotechnical parameters directly related to the expected amount of ground movement and (3) procedures for converting repair rate to break rate, possibly as a function of the seismic hazard and/or pipe material. In addition, the authors believe that moderate improvement in seismic evaluation are possible, at least in the short term, if (1) fragility modification factors based upon measurable pipe properties are developed or (2) PGD fragility relations are based upon ground characteristics theoretically related to damage.

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