

Influence of diameter on seismic response of buried segmented pipelines

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1. Introduction

Fragility relations for segmented buried pipelines has been a topic of interest in the lifeline earthquake engineering community for the past 35 years. Until recently, they have been based almost exclusively upon observed damage rates in past earthquakes. Recently O'Rourke and Vargas-Londono [15] have presented results from an analytical model which are remarkably consistent with observed seismic damage to small diameter cast iron pipe. Herein the analytical model will be used to determine the influence of diameter on seismic behavior of cast iron pipes, arguable the most common pipe material in the United States.

The influence of diameter is considered particularly important since in comparison to smaller diameter distribution network pipe, larger diameter transmission lines have a stronger impact on immediate post-event serviceability. They take longer to repair thereby lengthening outage durations, and are costlier to repair.

An analytical approach for determination of large diameter pipe behavior is particularly useful since statistically valid observation of transmission pipe damage is much more difficult to obtain than statistically valid observations of distribution network pipe damage. As noted by O'Rourke and Deyoe [11], for a given damage rate (repairs/km) there is a corresponding minimum sample size in terms of pipeline length. For example, a moderate wave propagation related repair rate of 0.10 repairs/km requires a sample size of 138 km of pipe to ensure that the sampled repair rate is within 50% of the true value with 95% confidence. The area of strong shaking would need, as a minimum, to be about 70 km in radius so that a single nominally straight transmission line could be exposed over 138 km of its length.

However, for a distribution network with pipe buried along each N-S street, N-S streets being separated by 0.1 km, the area of strong shaking would only need to be about 2.1 km in radius. That is, the difference between a line (large diameter transmission) and a grid (small diameter distribution) is about 1.5 orders of magnitude in radius (2.1 km vs 70 km) and about 3 orders of magnitude in area (13.8 km² vs 15,386 km²). Hence an analytical relation for seismic damage to larger diameter transmission pipe would be particularly useful due to the difficulty in obtaining statistically valid empirical observations.

2. Fragility relations

Over the years, fragility relations for buried segmented pipe have taken many forms. Katayama et al. (1975) developed one of the first, in which seismic damage (in repairs per kilometer) to primarily segmented cast iron pipe is plotted as a function of peak ground acceleration. Subsequently, Eguchi [4], 1991 separated "ground shaking" or wave propagation (WP) damage from Permanent Ground Deformation (PGD) damage. For WP, the author presents a bilinear relation between repairs per 1000 feet and Modified Mercalli Intensity (MMI). Following Eguchi's lead, most subsequent relations consider WP damage separately from PGD damage. For example, Barenberg [3,10,15], and the American Lifeline Alliance [1] all present relations between WP repair rates versus peak ground velocity V_{max} . This recognizes that V_{max} is arguably a better measure of the WP hazard than MMI.

In terms of PGD damage, Porter et al. [9] present bilinear relations between pipe breaks per 1000 ft. and ground displacement for five different pipe materials. Eguchi [4] and ALA [1] present somewhat similar PGD relations.

The most recent change in empirical observation based fragility relations occurred in 2004 when O'Rourke and Deyoe [12] established fragility curves wherein pipe damage is presented as a function of ground strain. The use of ground strain as the independent variable has two advantages. First, ground strain is arguably a more direct and better measure of the seismic hazard to buried pipelines. Secondly, with ground strains characterizing the hazard, both WP and most PGD damage can be plotted on the same graph. Note that fault rupture/abrupt ground offset is the only significant pipeline hazard that cannot be properly characterized by ground strain.

Subsequently O'Rourke et al. [13] developed a revised ground strain relation based on the addition of four PGD data points from the 1999 Izmit Turkey event and the use of an incoherence consistent S wave propagation velocity. Fig. 1 shows the resulting plots of repair rate versus ground strain. In Fig. 1, both the linear in log-log space and the bilinear in log-log space relations are shown. Note that the bilinear relation shows the increase in repair rate with increase in ground strain (i.e., the slope of the line) is steeper for low values of the hazard and flatter for high values of the hazard. As such, the general shape of the bilinear relation in Fig. 1 is consistent with the 1991 Eguchi WP and the

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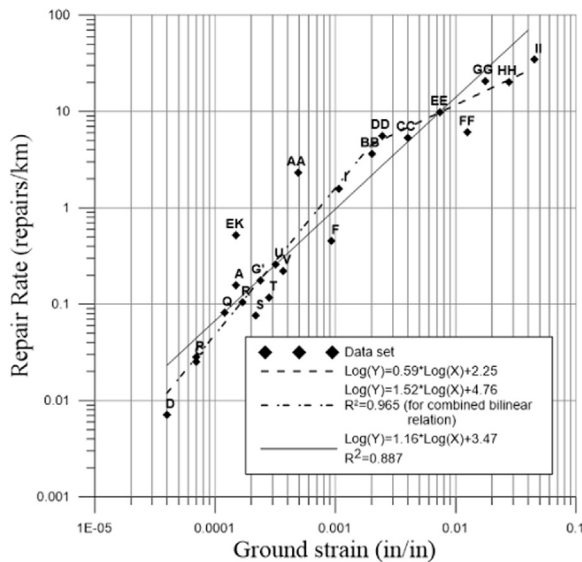


Fig. 1. Empirical Repair Rate (repairs/km) from O'Rourke, et al. (2015) – Linear and Bilinear Relations.

1991 Porter et al. PGD relationships.

In Fig. 1, the single letter data points (A, C, etc.) as well as EK are for WP damage, while the double letter data points (AA, BB, etc.) are for PGD damage. Hence the WP ground strains are generally less than 0.002 while the PGD ground strains are generally greater than 0.002. Note that there is a remarkable consistency over roughly four orders of magnitude of repair rate (three orders of magnitude of ground strain) when both WP and PGD damage is plotted versus ground strain. In Fig. 1 the R^2 value for the linear relation is 0.887 while the R^2 value for the bilinear relation is 0.965. Furthermore, the PGD damage rates for cast iron (C.I.) and asbestos cement pipe in the Christchurch N.Z. earthquake swarm as reported by T. O'Rourke et al. [16] are generally consistent with Fig. 1.

3. Influence of diameter

The fact that diameter has a significant influence upon segmented pipeline response has been known for quite a while. For example, using data from the 1923 Kanto earthquake, Kubo et al. [8], observe that “there is a consistent tendency for damage to decrease with an increase in pipe diameter”. Specifically, the diameter modification factors were 1.0, 0.94, 0.68, 0.71, and 0.68 for diameters of 6, 8, 10, 12, and 30 in. respectively. Other researchers have offered empirical evidence or opinions on the influence of diameter on the seismic behavior of buried pipelines in general or cast-iron pipe in particular. In their study of the Memphis Water System, Okumura and Shinozuka [9], postulate a diameter modification factor, apparently for all pipe materials, having a value of 1.0 for diameters less than 10 in., 0.5 for diameters between 10 and 20 in., 0.2 for diameters between 20 and 40 in., and 0.0 for diameters of 40 in. and above.

Similarly, Honegger [6] presents a “bounding trend” line which suggests diameter modification factors, again apparently for all materials, of 1.0 for diameters of 16 in. or less, and factors of 0.85, 0.31 and 0.063 for diameters of 24, 28, and 60 in. respectively.

ALA [1] shows that there was apparently little influence of diameter for C.I. pipe damage in the 1989 Loma Prieta event. Specifically, the diameter modification factor was 1.0, 0.92, 0.90 and 0.59 for pipe diameters of 6, 8, 10–12, and 16–20 in. respectively.

In their detailed study of the 1994 Northridge event, O'Rourke and Jeon [15] present a best fit line to a plot of repair rate versus diameter for C.I. pipe. The resulting diameter modification factors are 1.0, 0.81, 0.60, and 0.36 for 6, 8, 12 and 20-in. diameters respectively.

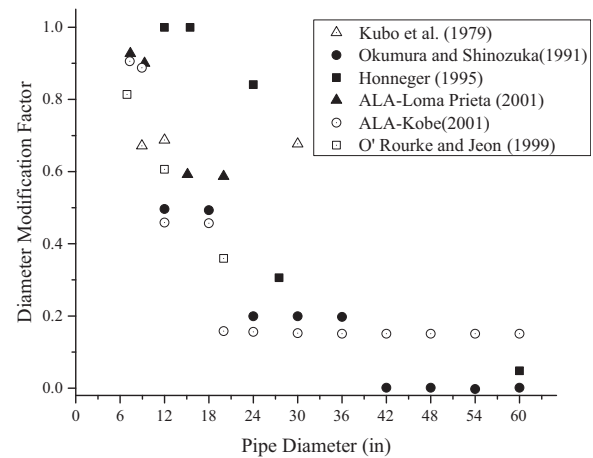


Fig. 2. Diameter Modification Factors Suggested by Others.

Finally, ALA [1] presents repair rates for C.I. pipe in the 1995 Kobe event. The resulting diameter modification factors are 1.0, 0.91, 0.46 and 0.16 for diameters in the 4–6-inch, 8–10-in., 12–18-in. and 20-in. or greater ranges.

The diameter modification factors for all segmented pipe materials (Okumura and Shinozuka, and Honegger) as well as the C.I. specific relations (Kanto, Loma Prieta, Northridge and Kobe) are presented in Fig. 2. Note that except for the Honegger “bounding” relation, the behavior is similar up to about 20 in. That is, the diameter modification factor is 1.0 for 6-in. diameter pipe, about 0.6 for 12-in. diameter and about 0.5 for 18-in. diameter pipe. Unfortunately, the variation in the modification factors increases as the diameter increases. For example, for a 60-in. diameter pipe, the modification factors range from zero (Okumura and Shinozuka) to 0.16 (Kobe) with Honegger in the middle with a modification factor of 0.063.

4. Mechanics based analytical model

An analytical model is used herein to establish the interrelationship between seismic damage to cast iron pipe and pipe diameter. It is based upon mechanics principles of equilibrium and compatibility and accounts for the probabilistic variability associated with leakage at the cast iron pipeline joints. The seismic hazard is uniform tensile ground strain along the pipes longitudinal axis (linear variation of ground displacement parallel to the pipeline) due to either seismic wave propagation (WP) or permanent ground deformation (PGD).

This characterization of the seismic hazard is generally consistent with both U.S. American Lifeline Alliance [2] and Japanese [7] design approaches in which the seismic hazard for buried pipeline is taken as ground strain nominally parallel to the pipeline longitudinal axis.

The key elements of the model are sketched in Fig. 3. The pipe segments are assumed to be rigid in the axial direction (i.e. $EA = \infty$). They are connected to the soil by non-linear soil springs. The individual pipe segments are connected to adjacent pipe segments with non-linear joint springs. Longitudinal soil spring are considered to be rigid – perfectly plastic, that is the onset of the plastic region occurs at very small relative movements between pipe segments and the surrounding soil. Furthermore, the backfill material is taken to be sand. For that case, the longitudinal resistance or drag force per unit length of pipe, τ_μ , is given by

$$\tau_\mu = \frac{\pi}{2} \cdot D \cdot H \cdot \gamma (1 + K_0) \cdot \tan \phi \quad (1)$$

where D is the pipe diameter, H is the burial depth to the pipe centerline, γ is the effective unit weight of soil, K_0 is the coefficient of lateral soil pressure at rest, k is a friction reduction factor and ϕ is the angle of shearing resistance for the sand. Herein cast-iron pipe is

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