Earthquake Damage Assessment of Lifelines and Utilities

라이프라인과 공공설비의 지진피해 평가

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국문요약

본 논문은 지진으로 인한 라이프라인과 공공설비에 대한 위험 지역 묘사 및 물리적 손실추정에 중점을 두었으며, 또한, 지리정보시스템(GIS)과 지진영향의 공간적 특성 평가에 사용된 송수관망을 통한 GIS 적용이 강조되었다. 1994년도의 Northridge 지진에서 얻어진 물 공급 능력이 기록된 GIS 자료를 통하여 매장된 라이프라인 피해와 다양한 지진 매개변수들의 상호 관계가 검증되었으며, 통계학적으로 가장 뚜렷한 상호 관계를 갖는 지진 매개변수들이 발견되었다. Northridge 지진으로부터 얻어진 GIS 자료를 이용하여 송수관의 손상률, 종류, 직경, 그리고 다양한 지진 매개변수들이 평가되었다.

주요어 : 지리정보시스템, 지진피해, 라이프라인과 공공설비

ABSTRACT

This paper focuses on the earthquake hazard delineation and physical loss estimation for lifelines and utilities. Emphasis is given to geographic information systems(GIS) and their application to pipeline networks in evaluating the spatial characteristics of earthquake effects. The paper examines the GIS databases for water supply performance obtained for the 1994 Northridge. Relationships among buried lifeline damage and various seismic parameters are examined, and the parameters that are statistically most significant are identified. Using GIS data from the Northridge earthquake, the relationships among pipeline repair rate, type of pipe, diameter, and various seismic parameters are assessed.

Key words : geographical information system, earthquake damage, lifelines and utilities

1. Introduction

Lifelines are often grouped into six principal types of systems(in alphabetical order) : electric power, gas and liquid fuels, telecommunications, transportation, wastewater facilities, and water supply. These systems share three common characteristics : geographical dispersion, interconnectivity, and diversity.[11] Lifelines are geographically dispersed over broad areas, and are exposed to a wide range of seismic and geotechnical hazards, community uses, and interactions with other sectors of the built environment. They are interconnected and interdependent. Each lifeline system is composed of many interconnected facilities and is influenced by the performance of other lifeline systems. Lifeline performance is related to the characteristics of many diverse components ; most lifeline networks have been built over many years and function with parts produced according to different construction and/or manufacturing techniques, standards, and design procedures.

Pipeline networks are an essential part of water, wastewater, gas, and liquid fuel conveyance systems, and are used extensively in telecommunication and electric power networks. The paper begins with an examination of GIS, followed by a discussion of buried pipeline response to earthquakes. The recent investigations are summarizing the important lessons learned for future applications.

The rapid development of computer mapping and visualization tools, embodied in GIS, provides a powerful basis for evaluating earthquakes effects on lifelines, as well as the consequences of these interactions on communities. It is not surprising, therefore, that GIS has become an engine for driving new methodologies and decision support systems focused on the spatial variation of potential earthquake effects. GIS, for example, is the backbone of the national loss estimation methodology sponsored by FEMA and implemented through HAZUS computer software.[10],[20] GIS also has been harnessed to explore the engineering and socioeconomic impacts of earthquakes through multidisciplinary studies of the losses incurred by disruptions of water supply and electric power systems.[4],[17]

Data from the Northridge earthquake has been compiled in GISs of unprecedented size and complexity that allow for a detailed examination of the spatial relationships among lifeline damage, permanent and transient ground deformation, and the surface, subsurface, and groundwater conditions.

Statistics were compiled for each of six types of pipe composition, summarizing the number of repairs, length of

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affected pipeline, repair rate(repairs divided by affected pipe length), and damage mode observed in either the pipe body or joints. The highest repair rates were incurred by steel pipelines with threaded couplings, asbestos cement(AC) pipelines, and cast iron(CI) pipelines. The overall repair rates for ductile iron(DI) and welded steel pipelines were approximately one third of that for CI mains, and the predominant mode of failure for DI pipelines was pullout at mechanical joints. DI pipelines equipped with earthquake-resistant restrained joints were not damaged, even in areas of liquefaction-induced PGD. Pipeline repair rates were inversely proportional to diameter and increased in direct proportion to peak ground acceleration. Repair rates in areas of liquefaction-induced PGD were 6 to 10 times higher than repair rates in areas of comparable peak ground acceleration with no PGD effects.

The GIS database for the 1994 Northridge earthquake provides an exceptionally detailed and comprehensive assessment of earthquake performance in a large, geographically dispersed system and is discussed in detail in forthcoming sections of this paper.

2. Earthquake hazard delineation

This section is dealing with pipeline damage patterns. The pattern of post-earthquake damage allows for the identification of seismic hazards at the locations of concentrated pipeline repair. In this section, earthquake hazard delineation is examined through actual lifeline damage patterns as a means of identifying local PGD hazards, including liquefaction.

In this paper, the GIS database for water distribution system performance during the 1994 Northridge earthquake is used to delineate geotechnical hazards in the Los Angeles region. The earthquake-induced damage to water pipelines and the database developed to characterize this damage have been described elsewhere[(13),(14)], and only the salient features of this work are summarized herein. GIS databases for repair locations, characteristics of damaged pipe, and lengths of distribution(pipe diameter < 600mm) and trunk (pipe diameter ≥ 600mm) lines according to pipe composition and size were assembled with ARC/INFO software. Nearly 10,000km of distribution lines and over 1,000km of trunk lines were digitized.

Fig. 1 shows the portion of the Los Angeles water supply system most seriously affected by the Northridge earthquake superimposed on the topography of Los Angeles. The figure was developed from the GIS database, and shows all water supply pipelines plotted with a geospatial precision of ±10m throughout the San Fernando Valley, Santa Monica Mountains, and Los Angeles Basin. The rectilinear system of pipelines is equivalent to a giant strain gage. Seismic intensity in the form of pipeline damage can be measured and visualized by plotting pipeline repair rates and identifying the areas where the largest concentrations of damage rate occur. The resulting areas reflect the highest seismic intensities as expressed by the disruption to underground piping.

To develop a properly calibrated strain gage, it is necessary to select a measurement grid with material having reasonably consistent properties and a damage threshold sensitive to the externally imposed loads being measured. Fig. 2 presents charts showing the relative lengths of trunk and distribution lines according to pipe composition. As shown by the pie chart, the most pervasive material in the Los Angeles distribution system is CI. The 7,800km of CI pipelines have the broadest geographic coverage with sufficient density in all areas to qualify as an appropriate measurement grid. Moreover, CI is a brittle material subject to increased

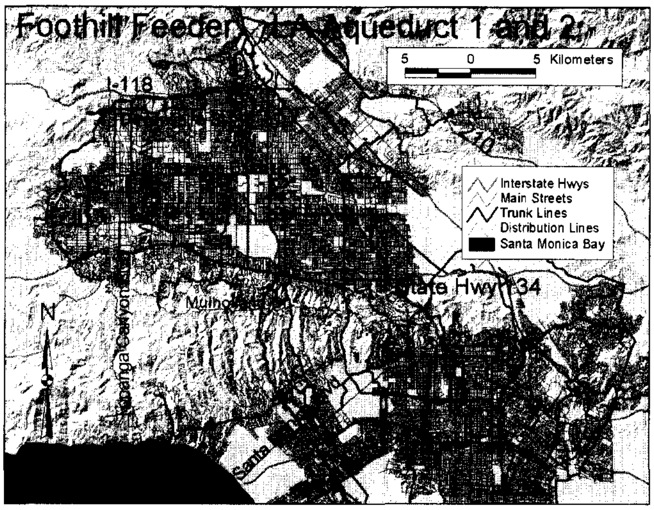


Fig. 1 Map of Los Angeles water supply system affected by Northridge earthquake[(13)]

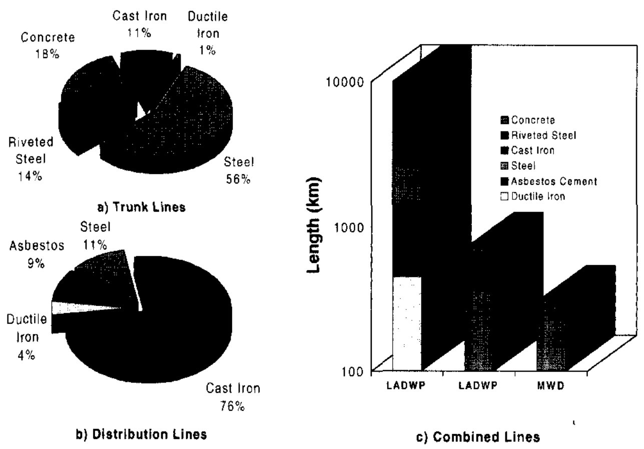


Fig. 2 Composition statistics of water trunk and distribution lines in the city of Los Angeles[(13)]

rates of damage at tensile strains on the order 250 to 500 $\mu\varepsilon$. It is therefore sufficiently sensitive for monitoring variations in seismic disturbance.

Fig. 3 presents a map of distribution pipeline repair locations and repair rate contours for CI pipeline damage. The repair rate contours were developed by dividing the map into 2km×2km areas, determining the number of CI pipeline repairs in each area, and dividing the repairs by the distance of CI mains in that area. Contours then were drawn from the spatial distribution of repair rates, each of which was centered on its tributary area. A variety of grids were evaluated, and the 2km×2km grid was found to provide a good representation of damage patterns for the map scale of the figure.(19)

The zones of highest seismic intensity are shown by areas of concentrated contours. In each instance, areas of concentrated contours correspond to zones where the geotechnical conditions are prone either to ground failure or amplification of strong motion. Each zone of concentrated damage is labeled in Fig. 4 according to its principal geotechnical characteristics. In effect, therefore, Fig. 3 is a seismic hazard map for the Los Angeles region, calibrated according to pipeline damage during the Northridge earthquake.

Of special interest is the location of concentrated repair rate contours in the west central part of San Fernando Valley (designated in Fig. 4 as the area of soft clay deposits). This area was investigated by USGS researchers, who found it to be underlain by local deposits of soft, normally consolidated clay.(7) Field vane shear tests disclosed clay with uncorrected, vane shear undrained strength, Suvst= 20-25kPa, at a depth of 5m, just below the water table. USGS investigators concluded that the saturated sands underlying this site were not subjected to liquefaction during the Northridge earthquake. Newmark sliding block analyses reported by O'Rourke(1998) provide strong evidence that near source pulses of high acceleration were responsible for sliding and lurching on the soft, normally consolidated clay deposit. The results of GIS analysis and site investigations have important ramifications because they show a clear relationship between PGD, concentrated pipeline damage, and the presence of previously unknown deposits of normally consolidated clay.

3. Physical loss estimation

In this section, physical loss estimation will be examined with emphasis on the Northridge earthquake database. Loss estimation is addressed with respect to TGD effects.

The records from 241 Northridge earthquake strong motion instruments were examined, and the data from 164 corrected records were selected for regression analyses.(13) In this paper, additional studies were performed with data from 142 selected Northridge earthquake records processed and catalogued by Silva(2000), and made available online by the Pacific Engineering Earthquake Center. All records were chosen to represent free field motion.

Fig. 5 shows the CI pipeline repair rate contours(see Fig. 3) superimposed on peak ground velocity(PGV) zones. The PGV zones were developed by interpolating the larger of the two horizontal components associated with each of 164 corrected motion sites. Using the GIS database, a pipeline repair rate was calculated for each PGV zone, and correlations were made between the repair rate and average PGV for each zone. As explained by O'Rourke(11), similar correlations were investigated for pipeline damage relative to spatially

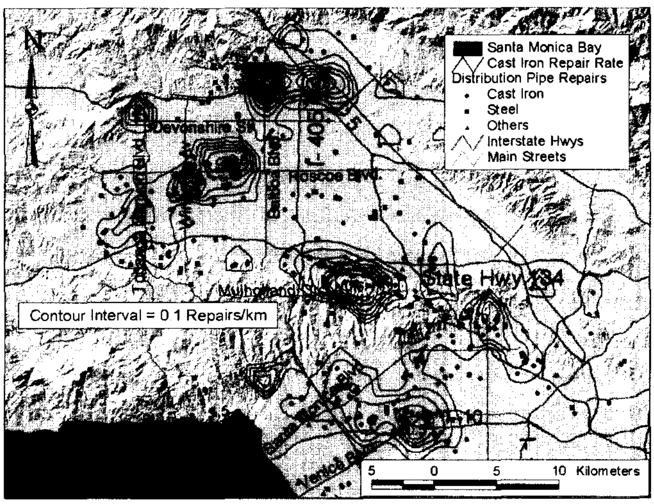


Fig. 3 Cast iron pipeline repair rate contours for the Northridge earthquake(13)

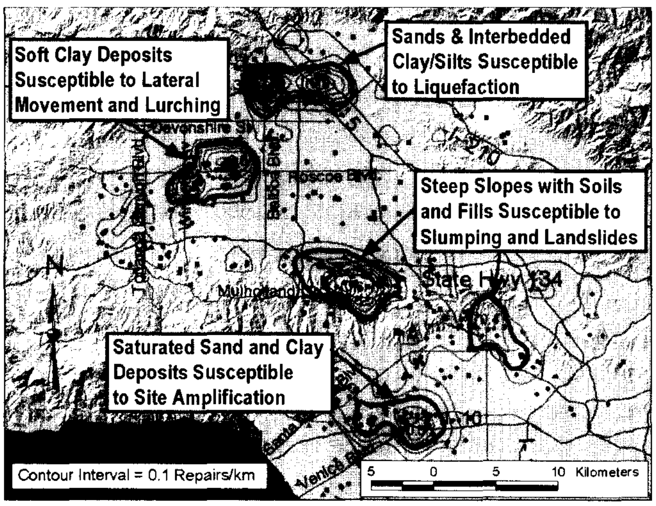


Fig. 4 Geotechnical characteristics of the areas of concentrated pipeline damage after the Northridge earthquake

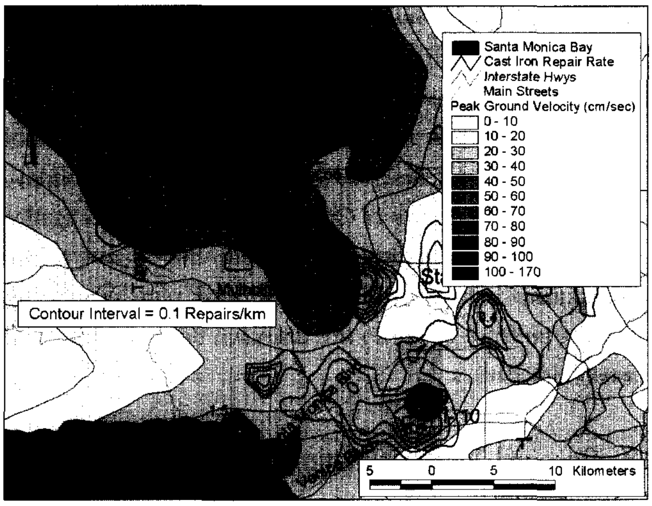


Fig. 5 Pipeline repair rate contours relative to Northridge earthquake peak ground velocity

distributed peak ground acceleration, spectral acceleration and velocity, Arias Intensity, Modified Mercalli Intensity (MMI), and other indices of seismic response. By correlating damage with various seismic parameters, regressions were developed between repair rate and measures of seismic intensity.

The most statistically significant correlations for both distribution and trunk line repair rates were found for PGV. The parameter, however, can be defined in several different ways. In attenuation relationships, PGV is commonly defined as the geometric mean of the two largest horizontal components.[3] PGV is also defined as the larger of the two horizontal components,[2] which is the value used in Fig. 5. PGV may also be defined as the maximum vector magnitude of the two horizontal components.

Figs. 6(a), (b), and (c) show the CI repair rates for the Northridge earthquake regressed against the geometric mean PGV, maximum PGV, and maximum vector magnitude of PGV. The data from the 142 records processed and catalogued by Silva were used to develop these regressions. The plots indicate that the choice of PGV makes little difference in the statistical significance of the regressions. All are characterized by r^2 that are comparable, although the highest r^2 is associated with maximum PGV. Fig. 6(d) shows the maximum PGV regressed against the geometric mean for 162 strong motion records for the Northridge earthquake.

In the remainder of this paper, the PGV cited will refer to the maximum PGV. If the forthcoming regression equations for PGV are to be used in conjunction with attenuation relationships based on the geometric mean, Fig. 6(d) can be applied to estimate maximum PGV, from predicted geometric means.

As reported by O'Rourke and Jeon[15], statistics were compiled for the repair rates of CI, DI, and AC distribution lines, and regressions were developed for repair rate vs. PGV. The compilation of statistics for steel distribution pipelines showed that there were many different types of steel pipeline grouped within this category. Figs. 7(a) and (b) present pie charts for the lengths and earthquake repairs associated with the different types of steel pipelines. At least six different kinds of pipeline were identified after a careful review of the records.

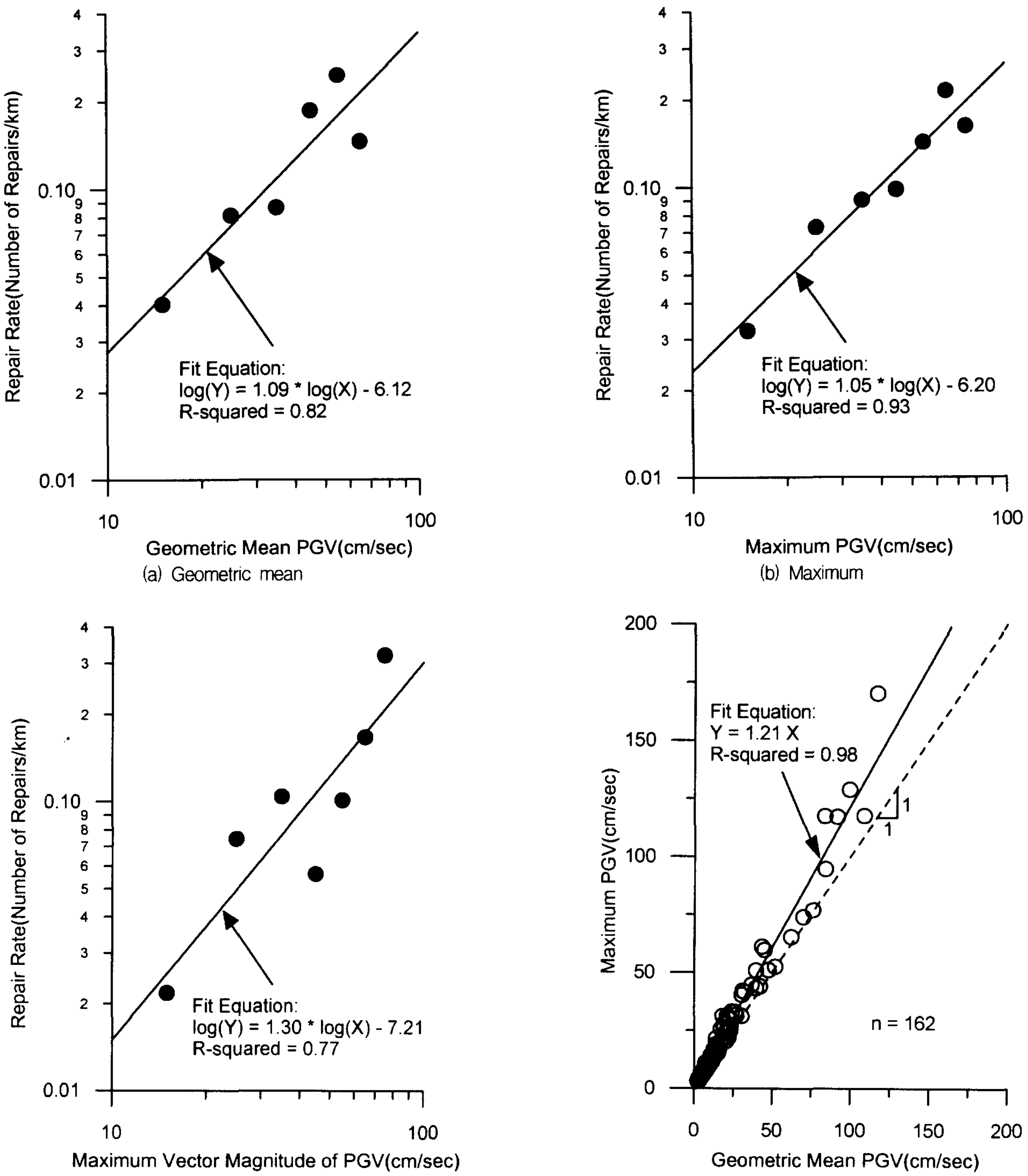
Matheson and Mannesman steel pipelines were installed primarily in the 1920s and 1930s. Most were installed without cement linings and with minimal coating. In addition, their wall thickness is generally less than that of other steel pipes with similar diameter. Matheson and Mannesman steel pipelines are vulnerable to corrosion, as are steel pipelines with threaded couplings. In the latter case, corrosion tends to concentrate at the threaded cross-sections. These types of pipelines did not perform well during previous U.S. and Japanese earthquakes.[5],[9],[12]

Victaulic couplings are bolted, segmental, clamp-type mechanical couplings whose housings enclose a U-shaped rubber gasket.[1] The gasket tends to deform and lose its initial water-tight characteristics under prolonged service. Riveted steel pipelines are older installations, which are prone to corrosion. Contact between the rivets and laminated steel of the pipe body promotes galvanic action between the two dissimilar metals.

A welded slip joint is fabricated by inserting the straight end of one pipe into the bell end of another and joining the two sections with a circumferential fillet weld. The bell end is created by the pipe manufacturer by inserting a mandrel in one end of a straight pipe section, and expanding the steel into a flared, or bell casing. The pie charts in Fig. 7 show that this type of steel pipeline(refered to as welded) was the predominant type operated during the earthquake.

The histogram in Fig. 7(c) indicates very high repair rates associated with Matheson, Manneson, and threaded steel pipelines. The lowest repair rates are associated with welded steel pipelines. Because of their broader coverage and greater aggregate length, regression analyses were performed for this type of steel pipeline.

Fig. 8(a) shows the repair rates for steel(steel distr.), CI, DI, and AC distribution lines regressed against PGV. The regressions indicate that the highest rate of damage for a given PGV was experienced by steel pipelines. This result at first seems surprising because steel pipelines are substantially more ductile than CI and AC pipelines. Steel distribution



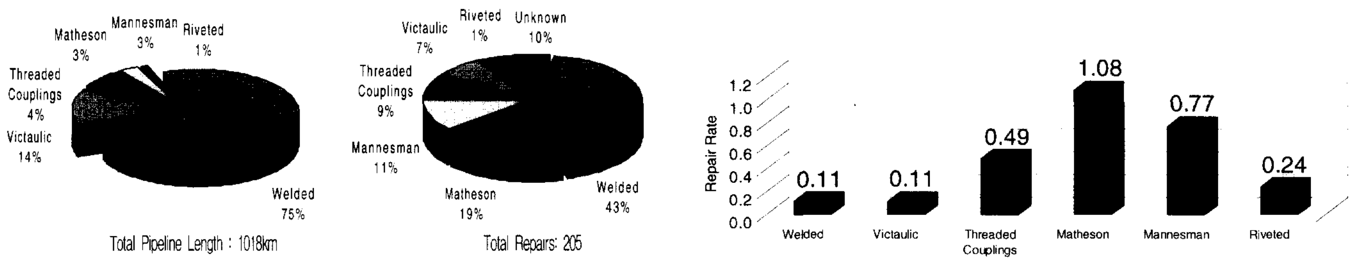
(a) Geometric mean

(b) Maximum

(c) Maximum vector magnitude

(d) Maximum vs. geometric mean

Fig. 6 CI repair rate regression with geometric mean, maximum, and maximum vector magnitude of PGV, and relationship between the maximum and geometric mean PGVs



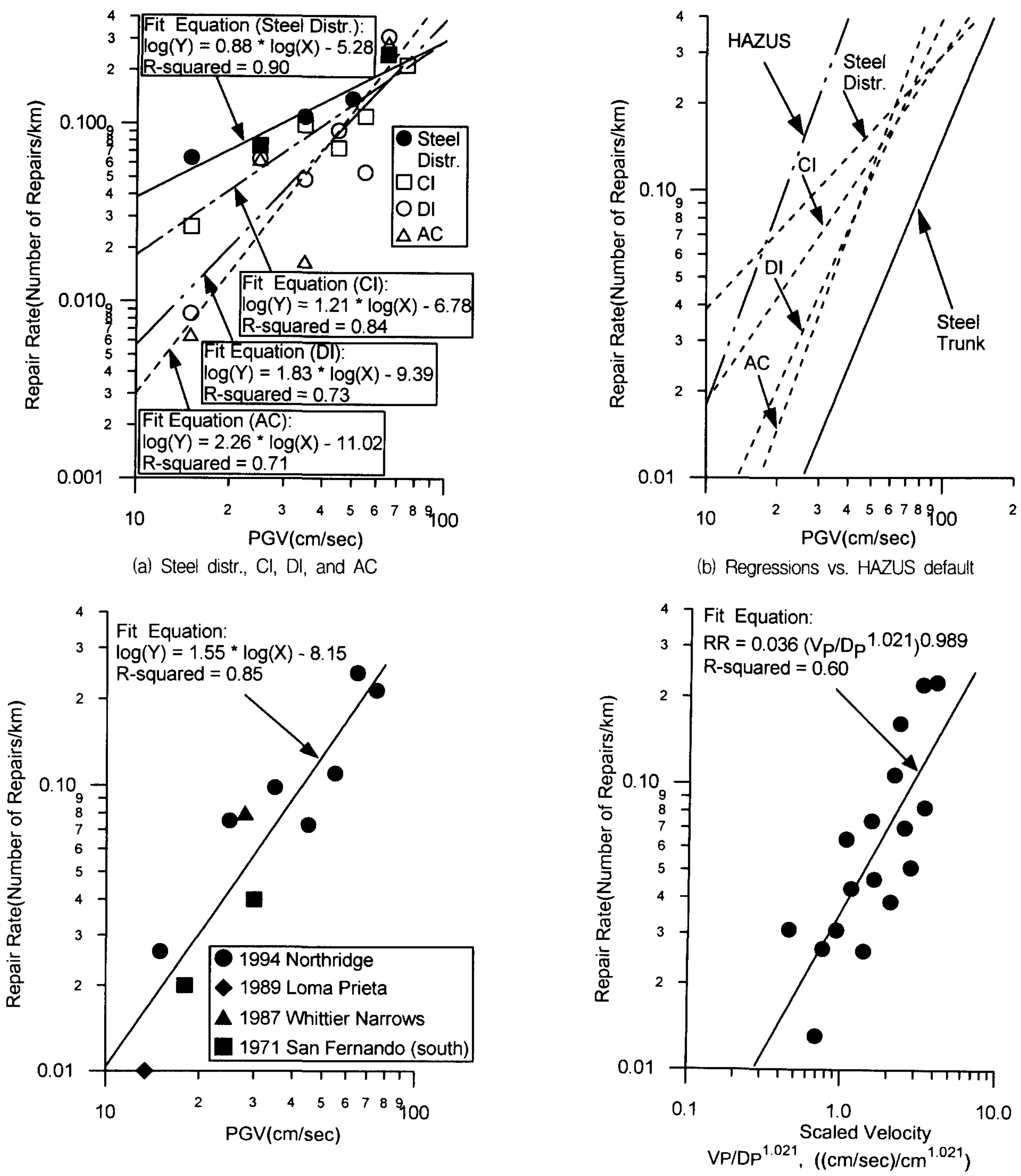
(a) Steel pipeline length

(b) Steel pipeline repairs

(c) Steel pipeline repair rate

Fig. 7 Pipeline lengths, repairs, and repair rates for various types of steel pipeline in service during the Northridge earthquake pipelines in Los Angeles, however, are used to carry the highest water pressures, installed in areas of relatively steep slopes susceptible to landslides, and are subject to corrosion that has been shown to intensify their damage rates in previous earthquakes.[8] Comparatively high repair rates for steel pipelines were reported by Eidinger[6] after the 1989 Loma Prieta earthquake.

Fig. 8(b) compares the regression equations derived from the GIS database for the Northridge earthquake with the default regression currently used in HAZUS.[10] The regression for the steel trunk lines(nominal diameter$\geq$600mm) was developed according to similar procedures followed for the distribution pipelines. The steel trunk lines are constructed with welded slip joints. Virtually all the regressions developed from the Northridge GIS database plot significantly below the HAZUS default. This trend is especially true for steel trunk lines that show repair rates 10 to 20 times lower than those estimated with the HAZUS default.



(a) Steel distr., CI, DI, and AC

(b) Regressions vs. HAZUS default

(c) Combined CI database

(d) Scaled velocity

Fig. 8 Regression for the repair rates of various types of pipelines vs. PGV and scaled velocity

Fig. 8(c) presents the linear regression that was developed between CI pipeline repair rate and PGV on the basis of data from the Northridge and other U.S. earthquakes. By taking advantage of additional data, this regression provides a more comprehensive representation of repair rate trends. It is not significantly different from the regression in Fig. 6(b), thereby implying a consistency between the Northridge earthquake trends and previous earthquake statistics.

As explained by O'Rourke and Jeon[15], the regression relationship for the repair rate, RR, can be expressed as

$$\mathrm{Log\,RR} = \mathrm{Log\,K} + \alpha\,\mathrm{Log\,V_p} - \mathrm{Log\,D_p} \tag{1}$$

in which K, α, and β are constants, V_P is PGV, and D_P is the pipe diameter in cm. Eq. (1) can be rewritten as

$$\mathrm{RR} = \mathrm{K}(\mathrm{V_p}/\mathrm{D_p^{\alpha/\beta}})^{\alpha} \tag{2}$$

in which $V_p/D_p^{\alpha/\beta}$ is referred to as the scaled velocity that represents PGV normalized with respect to diameter. The exponent of D_P is a scaling factor that accounts for the statistical relationship embodied in the database. This relationship is, in turn, a function of the strong motion and pipeline system characteristics.

Fig. 8(d) shows the linear regression between repair rate and scaled velocity. Combining the PGV and D_P into a common parameter offers a new tool for loss estimation. Scaled velocity combines the effects of PGV and nominal diameter, and thus accounts for the two most important variables affecting earthquake damage to pipeline of a particular composition.

The regressions in Fig. 8 were developed after the data were screened for lengths of pipeline that represent approximately 1.5 to 2.5% of the total length or population for each type of pipe affected by the earthquake.[15] This procedure reduces the influence of local erratic effects that bias the data derived from small lengths of pipeline. The use of this filtering procedure leads to statistically significant trends. The regressions are applicable only for PGV $\leq$ 75cm/sec. For the Northridge earthquake, zones with PGV exceeding 75cm/sec generally correspond to locations where PGD, from sources such as liquefaction and landsliding, was observed. Hence, this screening technique tends to remove damage associated with PGD, resulting in correlations relevant for TGD.

4. Conclusions

One of the most significant difficulties in characterizing seismic hazards for lifelines, especially buried lifelines, is the identification of PGD and TGD zones, and the characterization of TGD effects in areas where constructive interference of waveforms and ground strain concentrations may occur. TGD in the form of surface waves in sedimentary basins, vibration of relatively narrow soil-filled valleys, and liquefaction-induced ground oscillation may induce locally high ground strains, especially near basin and valley margins where soft sediments impinge on less deformable geologic media. In all PGD zones, there are some TGD effects. As a consequence, PGD and TGD effects tend to merge, making a clear distinction between the two very difficult at some locations. To resolve accurately the locations and areal coverage of PGD zones, sufficient data are required to characterize the subsurface deposits and delineate the potential boundaries of movement. The spatial variability of soil, surface gradients, subsurface geometry of deposits, and groundwater coupled with sparse information at most locations poses a substantial challenge for the seismic zonation of lifelines. Fortunately, increased use of GIS and computerized databases make it possible to collect and store large amounts of information for a particular region. As site explorations are performed in the future, the ensuing information can be added to existing databases to improve subsurface characterization.

Regression analyses for predicting pipeline damage are performed by assuming that seismic and subsurface parameters are known without error. For example, when the pipeline repair rate is regressed against PGV, it is assumed as a premise of the regression analysis that PGV is known precisely.

It should be recognized that procedures are available to account for the variability of the different parameters in regression analyses.[18] Moreover, methods, such as kriging (e.g., Ripley[16]), inherently account for spatial variability, and can be adapted to delineate confidence limits and probabilities of exceedance for a particular parameter in two-dimensional space. In the future, it will be advantageous to explore the variability of all regression parameters to reflect properly the spatial uncertainties of seismic and site conditions.

Lifeline systems are composed of diverse components and facilities that may differ from one system to another. To apply regressions or correlations that were developed with emphasis on a particular system, one must be satisfied that the characteristics of that system are representative of others for which the predictions are being made. The statistics of pipeline performance from GIS investigations of water distribution systems after the Northridge earthquakes shows several consistent trends. For both earthquakes, water main damage was inversely proportional to nominal diameter, directly proportional to PGA, and the ratios of repair rates for DI and CI pipelines are comparable for smaller diameter lines.

For steel distribution pipelines, however, the repair rates are significantly different. The repair rates for steel distribution pipelines after the Northridge earthquake are higher than those of CI pipelines, whereas the opposite trend applies for the Kobe earthquake. The relatively high susceptibility of steel piping to damage during the Northridge earthquake may be explained in part by utility practices, such as using steel pipe for the highest internal pressures and deploying steel pipe in areas with relatively steep slopes. Increased susceptibility to corrosion also appears to play a role in steel pipeline performance.

Pipeline system complexities apply to operational strategies and company procedures. It is necessary, therefore, to be aware that practices can vary among different utilities and that local differences may affect the suitability of empirically-based predictions.

Pipeline damage data from the Northridge earthquake are useful not only for developing predictive regressions for different types of piping, but for identifying areas of seismic hazards. When compared with default predictions currently embodied in the National Loss Estimation Methodology, the regressions presented in this paper show substantially lower repair rates. Damage statistics from recent earthquakes and improvements in GIS technology provide the opportunity for comprehensive assessment of system performance and the characterization of spatial variability at a level of detail previously unattainable.

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