GIS Characterization of the Los Angeles Water Supply, Earthquake Effects, and Pipeline Damage

by Thomas D. O’Rourke, Selcuk Toprak and Sang-Soo Jeon, Cornell University

Research Objectives

The objectives of the research are to: 1) develop a comprehensive database of the size, composition, and geographic location of all Los Angeles Department of Water Power (LADWP) pipelines for system modeling and reliability analyses; 2) evaluate the spatial distribution of pipeline damage and its relationship with transient and permanent ground deformation parameters; and 3) use the resulting relationships to improve both loss estimation methodologies and the identification of seismic and geotechnical hazards in the Los Angeles area. There is a fourth objective that was also achieved, although its accomplishment was not foreseen at the start of the project, but emerged as a true scientific discovery as the work progressed. This fourth objective is to improve GIS characterization by defining an explicit relationship between the mesh size used to process point source geographic data and the two-dimensional visualization of these data through mapping algorithms.

MCEER-sponsored research focuses on improved loss estimation methodologies and the application of advanced technologies to improve water system performance. It is important therefore to evaluate how water systems respond to real earthquake conditions, using information technology for comprehensive characterization of the spatially variable pipeline network, transient and permanent ground deformation patterns, and geotechnical, groundwater, and topographical features. Geographical Information Systems (GIS) are ideally suited for this type of investigation, and were used to develop a detailed and extensive inventory of the Los Angeles Department of Water and Power (LADWP) water delivery system as well as a comprehensive assessment of system performance during the Northridge earthquake.

The 1994 Northridge earthquake resulted in the most extensive damage to a U.S. water supply system since the 1906 San Francisco earthquake. Los Angeles Department of Water and Power and Metropolitan Water District (MWD) trunk lines (nominal pipe diameter ≥ 600 mm) were damaged at 74 locations, and the LADWP distribution system required repairs at 1,013 locations. The widespread disruption provides a unique opportunity to evaluate

Links to Current Research

- This research project has identified the components and facilities that most seriously affect the earthquake performance of water systems and thus are prime targets for improvements using advanced technologies. This research is an integral part of the Lifelines Program, and is also an important contributor to the Emergency Response and Recovery Program through its in-depth characterization of critical water supplies and its development of advanced GIS applicable for post-earthquake damage assessment and deployment of emergency services and system restoration resources.
The users of the research results include water utilities, such as the Los Angeles Department of Water and Power (LADWP), East Bay Municipal Utility District, Memphis Light, Gas and Water, and many other companies operating systems in areas vulnerable to earthquakes; governmental agencies, such as the Federal Emergency Management Agency (FEMA), which promote the development and application of earthquake loss estimation methodologies; and various private enterprises, such as electric power utilities, engineering firms, and insurance carriers, that are interested in advanced applications of GIS for civil infrastructure improvement and risk assessment. Research on advanced GIS technologies and risk assessment of lifeline networks not only provides for substantial improvements in seismic performance, but also establishes the platform for better management irrespective of seismic hazards. These improvements carry substantial societal benefits during normal operations through increased efficiency, safety and reliability, and through reduced maintenance and repair costs.
Figure 3 presents a map of distribution pipeline repair locations and repair rate contours for cast iron (CI) pipeline damage. The CI mains were shown to have the broadest geographic coverage, and therefore to provide the most consistent basis for evaluation of seismic response throughout the entire system (O’Rourke and Toprak, 1997). The repair rate contours were developed by dividing the map into 2 km x 2 km areas, determining the number of CI pipeline repairs in each area, and dividing the repairs by the distance of CI main in that area. Contours then were drawn from the spatial distribution of repair rates, each of which was centered on its tributary area. The 2 km x 2 km grid was found to provide a good representation of damage patterns for the map scale of the figure.

The records from approximately 240 rock and soil stations were used to evaluate the patterns of pipeline damage with the spatial distribution of various seismic parameters. The maximum strong motion readings at the Tarzana-Cedar Hill Nursery were removed from the database prior to GIS evaluation to avoid distortions from possible topographic influences. In addition,
records from stations at dam abutments were screened when a station downstream of the dam was available, again to minimize distortion from topographic effects.

Figure 4 shows the CI pipeline repair rate contours superimposed on zones of peak ground velocity. By evaluating the zones of ground velocity with GIS, as illustrated in Figure 4, it was possible to correlate the pipeline repair rates in all the zones characterized by a particular velocity with the velocity pertaining to those zones. As explained by O’Rourke (1998), similar evaluations were made of pipeline damage relative to spatially distributed peak acceleration, spectral acceleration and velocity, Arias Intensity, Modified Mercalli Intensity (MMI), and others 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 peak ground velocity. Figure 5a presents the linear regression that was developed between CI pipeline repair rates and peak ground velocity on the basis of data from the Northridge and other U.S. earthquakes. Figures 5b and 5c show repair rate correlations for welded steel trunk lines and for cast iron, ductile iron, and asbestos cement distribution lines. Figure 5d compares the regressions developed in this research work with the default relationship used in HAZUS (NIBS, 1997), which is the computer program that implements the current earthquake loss estimation methodology sponsored by FEMA. The FEMA correlation does not distinguish between trunk or distribution lines, nor does it allow for predictions based on pipe composition. The data pertaining to the FEMA
Figure 5. Pipeline Repair Rate Correlation with PGV for CI, DI and AC Distribution and Welded Steel Trunk Lines
correlation were analyzed before the current generation of GIS technologies, and are strongly influenced by repair statistics for the Mexico City water supply after the 1985 Michoacon earthquake (Ayala and O’Rourke, 1989). Inspection of Figure 5d reveals that the current default relationship in HAZUS is very conservative, and results in predicted repair rates that exceed those provided by the regressions developed in the MCEER-sponsored research by over an order of magnitude for steel trunk lines and by a factor of two to three for distribution mains subjected to velocities greater than 20 cm/s.

After the Northridge earthquake, pre- and post-earthquake air photo measurements in the Van Norman Complex were analyzed as part of collaborative research between U.S. and Japanese engineers (Sano, 1998; O’Rourke et al., 1998). The area near the intersection of Balboa Blvd. and Rinaldi St. has been identified as a location of liquefaction (Holzer et al., 1996) where significant damage to gas transmission and water trunk lines was incurred. Ground strains were calculated in this area from the air photo measurements of horizontal displacement by superimposing regularly spaced grids with GIS software onto the maps of horizontal displacement and calculating the mean displacement for each grid. Grid dimensions of 100 m x 100 m were found to provide the best results (Sano, 1998).

As illustrated in Figure 6, ground strain contours, pipeline network, and repair locations were combined using GIS, after which repair rates corresponding to the areas delineated by a particular contour

**Figure 6. Procedure for Calculating Repair Rate in Each Strain Range**

**Figure 7. Distributions of CI Repair Rate and Ground Strain**
interval were calculated. Figure 7 shows the repair rate contours for CI mains superimposed on the areal distribution of ground strains, identified by various shades and tones. In the study area, there were 34 repairs to CI water distribution mains and two for steel water distribution pipelines. There were five water trunk line repairs in the area. The repair rate contours were developed by dividing the map into 100 m x 100 m cells, determining the number of CI pipeline repairs in each cell, and dividing the repairs by the length of the distribution mains in that cell. The intervals of strain and repair rate contours are 0.001 (0.1%) and 5 repairs/km, respectively. The zones of high tensile and compressive strains coincide well with the locations of high repair rate.

In Figure 8, the relationship between ground strains and repair rates is presented graphically using linear regression. The repair rate in each ground strain range, 0-0.1, 0.1-0.3, and 0.3-0.5%, was calculated as explained previously. Ground strain contours obtained both from the air photo measurements and LABE survey were used. As shown in this figure, repair rates increase linearly with ground strain. A high $r^2$ value shows that a large percentage of the data variability can be explained by the regression line.

With GIS, it is very easy to divide a spatially distributed data set into arbitrarily sized areas. If the areas are delineated by a framework of equally spaced, vertical and horizontal lines, the resulting grid can be characterized by a single dimension representing one side of each area, $n$, and the number, $N$, of areas comprising the total area of the system, $Nn^2$. The choice of $n$ can be regarded as a means of visually resolving the distribution of damage.

Some practical questions emerge. Is there a useful relationship between $n$ and the visualization of zones with high damage? An additional question may be asked about what values of $n$ represent the best choices for visualizing damage patterns?

In this research project, a relationship was discovered between the area of the map covered by repair rate contours and the grid size, $n$, used to analyze the repair statistics. If the contour interval is chosen as the average repair rate for the entire system or portion of the system covered by the map, then the area in the contours represents the zones of highest (greater than average) earthquake intensity as reflected in pipeline damage. The area within the contour lines...
divided by an area closely related to the total area of the map, $A_c$, is referred to as the threshold area coverage, TAC (Toprak et al., 1999). Alternate thresholds may also be defined on the basis of the mean plus one or two standard deviations.

A hyperbolic relationship was shown to exist between TAC and the dimensionless grid size, defined as the square root of $n^2$, the area of an individual cell, divided by the total map area, $A_T$. This relationship is illustrated in Figure 9, for which a schematic of the parameters is provided by the inset diaphragm. The relationship was found to be valid over a wide range of different map scales spanning 1200 km$^2$ for the entire Los Angeles water distribution system affected by the Northridge earthquake to 1 km$^2$ of the San Francisco water distribution system in the Marina affected by the Loma Prieta earthquake (Toprak et al., 1999). The data points refer to maps of various dimensions from which the relationship was developed.

This relationship can aid GIS users to get sufficiently refined, but easily visualized, maps of damage patterns. Because the relationship is independent of size and will work at the scale of the entire system or any practical subset thereof, it can be used for damage pattern recognition, and for computer “zooming” from the largest to smallest scales to identify zones of concentrated disruption. This relationship has great potential for data management to support emergency response decisions and planning for optimal post-earthquake recovery.

### Conclusions

The GIS-based research focused on the LADWP system has resulted in the largest U.S. database ever assembled of spatially distributed...
transient and permanent ground deformation in conjunction with earthquake damage to water supply and other lifeline systems. The research has led to a better delineation of local geotechnical and seismological hazards that are shown by the zones of concentrated pipeline damage after the Northridge earthquake. The research has resulted in correlations between repair rates for a variety of trunk and distribution pipelines and seismic parameters, such as peak ground velocity. These correlations are statistically reliable and have improved predictive capabilities compared with the default relationships currently used in computer programs developed by FEMA for earthquake loss estimation. The research has led to the discovery of a relationship between the two dimensional representation of local damage and the grid size used in GIS to analyze the spatial distribution of data. For practical purposes, this relationship is independent of scale and therefore ideally suited for damage pattern recognition and computer “zooming” from largest to smallest scale to target areas for emergency response and recovery.

The research has resulted in a comprehensive GIS characterization of the LADWP pipeline network, earthquake damage patterns, and spatial distributions of seismic parameters, permanent ground deformation, geotechnical hazards, topography, and groundwater tables. This characterization will be used in forthcoming systems analysis and reliability assessments of the LADWP water supply network. Because of its unprecedented size, complexity, and accuracy, this GIS data set is currently being used in studies at the NSF-supported Institute for Civil Infrastructure Systems to explore relationships between physical infrastructure systems and the social, economic, and political databases that coincide with them.

An evaluation of the earthquake damage statistics of the LADWP system has disclosed critical components that are most susceptible to earthquake damage and have the greatest impact on system performance. Based on the findings of this work, future research will focus on the welded slip joints of steel trunk lines that are susceptible to compressive failure under transient and permanent ground deformation. Research will concentrate on characterizing the load-deformation behavior of these joints and the use of externally applied fiber reinforced composites (FRCs) to increase their load carrying capacity as part of either retrofit or new construction activities.

**References**


*Continue with next chapter*