Earthquake Performance and Simulation of San Francisco's Auxiliary Water Supply System

by Thomas O'Rourke

Abstract

This project involved the development, verification, and implementation of an interactive computer program with color graphics to model the Auxiliary Water Supply System (AWSS) of San Francisco. The AWSS was built as a consequence of the 1906 San Francisco earthquake to provide fire protection in coordination with the Municipal Water Supply System. Composed of approximately 200 km of 250 to 500-mm-diameter pipelines, it is the backbone of San Francisco's fire protection and critically important for emergency response after a major earthquake.

The interactive computer program, known as GISALLE, can perform accurate hydraulic analyses of the entire system and for any damage state sustained by the system as a consequence of earthquake effects. It contains a special algorithm to predict, for a given damage state, which portions of the system will be able to supply water at flow rates and pressures necessary for fire fighting. It can also predict which portions of the system will not be able to function effectively, thereby helping to plan for effective protection and restoration strategies. The program can be manipulated interactively by engineers, planners, and fire department personnel to change or add components and evaluate how these modifications affect earthquake performance of the system The computer model was verified by special fire flow tests performed by the San Francisco Fire Department.

The AWSS model was used to show city planners that damage to the buried pipeline network and unacceptable losses of water are likely in a severe earthquake. These simulations played an important role in the City's efforts to obtain a $46.2 million construction bond for improving the AWSS The bond was passed overwhelmingly by 89.2% of the voters After the 1989 Loma Prieta earthquake, the computer simulations of AWSS seismic performance were shown to compare very favorably with the actual earthquake response, and used to understand the full implications of damage sustained as a result of the earthquake.

Various strategies for improving the AWSS have been explored with the model, and communicated to fire fighting personnel and emergency planners. The recommendations resulting from AWSS simulations and the continued use of the model by engineers in San Francisco stand as significant proof that computer graphics modeling of water supply systems provides an effective way of improving both seismic performance and fire protection.

Collaboration

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Objectives and Approach

Research on the earthquake performance and simulation of the auxiliary water supply system in San Francisco is being performed to accomplish two major objectives. The first is to promote advanced computer graphics techniques for lifeline systems and validate the methods through application to a real system. The second is to demonstrate and bring about the implementation of system improvements to a real water supply which results in improved seismic performance.

The approach to this research involved computer studies and theoretical advances to create improved algorithms for simulating water supply performance under various damage states. In addition, substantial field work was required for data collection, data verification, and reconnaissance of seismic performance during the 1989 Loma Prieta earthquake.

This research task is part of NCEER's Lifeline Project. Task numbers are 86-3042, 87-3007, 88-3006, 89-3004, 90-3004, 91-3322, 92-3302B and 93-3304A.

Accomplishments

The City of San Francisco receives its water from two systems of reservoirs and pipelines: the Municipal Water Supply System (MWSS) and the Auxiliary Water Supply System (AWSS). The MWSS supplies potable water for domestic and commercial uses, as well as for fire fighting via hydrant and sprinkler systems. The AWSS supplies water exclusively for fire fighting purposes. The AWSS is the only high pressure network of its type in the U.S. It comprises approximately 200 km of buried pipe, with nominal diameters ranging from 250 to 500 mm. Approximately 85% of the system at the time of the earthquake was composed of cast iron mains with lead-caulked joints, with the remainder composed of ductile iron pipe with mechanical joints.

A computer model, known as GISALLE (Graphical Interactive Serviceability Analysis for LifeLine Engineering), was developed to simulate the AWSS. The model provides for an accurate hydraulic analysis of the system, and contains a special algorithm which evaluates each pipe segment in the system and eliminates those unable to sustain appropriate hydraulic head and flow. As a result, the program automatically reconfigures the system to show those portions capable, for a given damage state, of supplying water at flow rates and pressures necessary for fire protection. The model is equipped with interactive color graphics, and allows engineers and planners to modify or add to any part of the system by means of user friendly menus. The model generates fragility curves, based on a Monte Carlo statistical assessment of performance, that show system response as a function of damage state

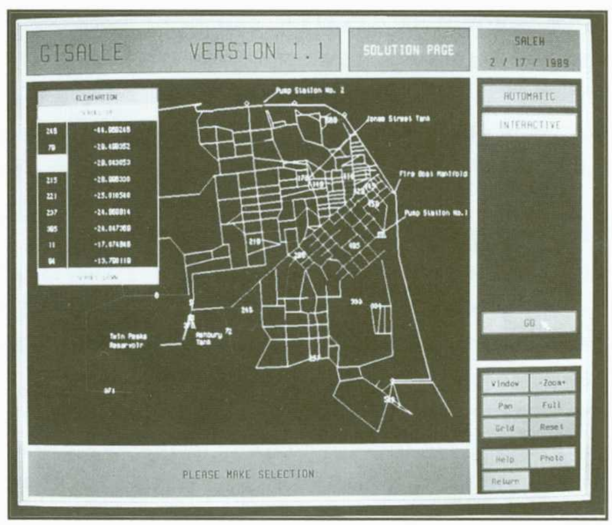
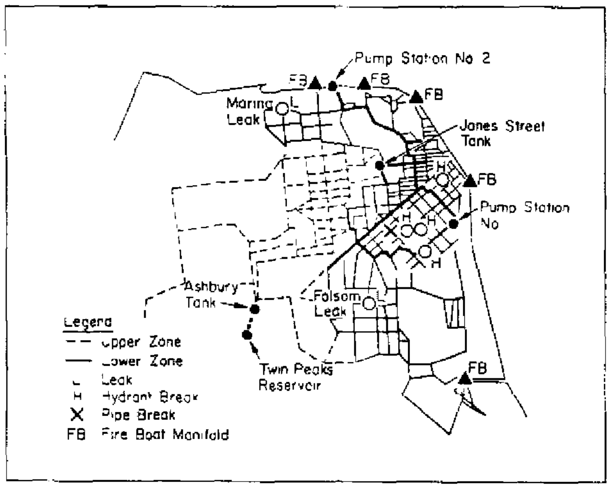


Figure 1
Computer Screen showing GISALLE representation of AWSS (courtesy of M.I. Markov)

sustained as the result of an earthquake. Earthquake effects can be simulated for any changes or additions of facilities to the system. In this way, potential modifications can be tested to decide on the best strategy for improving performance. Figure 1 shows a computer screen representation of the AWSS generated by GISALLE with a menu activated for eliminating and replacing various pipeline segments as a means of testing different network configurations.

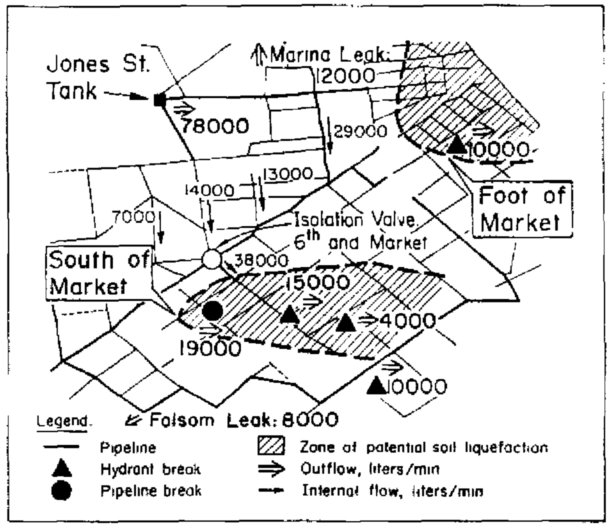
Before the 1989 Loma Prieta earthquake, the computer model was developed and its accuracy confirmed by special fire flow tests conducted



■ **Figure 2**
Conditions Used in Computer Simulation of AWSS Performance During the Loma Prieta Earthquake

by the San Francisco Fire Department. Model results were used by the Fire Department and City to promote a $46.2 million bond issue to upgrade the AWSS. The issue was passed by 89.2% of the voters.

After the Loma Prieta earthquake, computer simulations of AWSS seismic performance were shown to compare very favorably with the actual earthquake response, and used to understand the full implications of damage sustained as a result of the earthquake. Figure 2 shows a plan view of the system that was simulated to reproduce the conditions on the night of the earthquake. Water in the lower zone was supplied by the Jones St.



■ **Figure 3**
Results of AWSS Computer Simulation

Tank. The lower and upper zones were isolated from each other with closed gate valves. Pump Stations 1 and 2 were not included in the simulation to replicate the system conditions immediately following the earthquake.

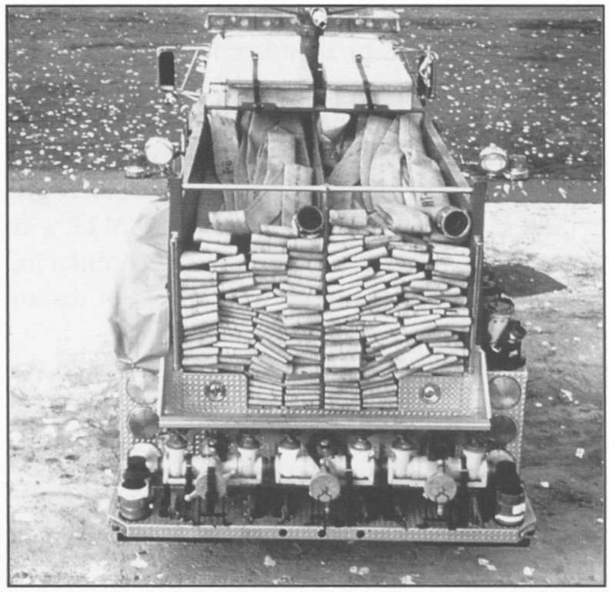
Figure 3 shows the results of the analysis in graphical format. Open arrows denote water egress either from the Jones St.Tank or damaged components. The solid arrows denote internal flow. Zones of potential soil liquefaction in the South of Market and Foot of Market areas also are shown.

The South of Market area had been recognized as a zone of potentially unstable ground, called an infirm area, and had been isolated from adjoining portions of the network by closed gate valves. Only one open gate valve was provided in this zone at the intersection of Market and 6th Sts., as illustrated in the figure. This gate valve was designed to be operated remotely with utility-supplied electric power. Because of electric power loss at the time of the earthquake, the valve could not be closed remotely. Consequently, water flow through this gate valve equals the sum of water losses from the broken main and two broken hydrants in this particular infirm area of the system.

The total flow rate from the Jones St. Tank was approximately 78,000 liters/min. Given that the normal operating capacity of the Jones St.Tank is approximately 2.72 million liters of a maximum 2.84 million liters, the time required to empty the Jones St. Tank would have been about 35 minutes. This estimated time to loss of tank agrees with observations during the earthquake.

There are important lessons from this case history. Not only was the computer simulation model, GISALLE, able to reproduce the damaged system performance, but it actually had been used in planning studies before the earthquake to predict correctly that the in-ground piping system would not be reliable under severe seismic disturbance. Partly as a result of these forecasts, a Portable Water Supply System (PWSS) had been developed, which consisted of vehicular hose tenders, each carrying about 1.5 km of 125-mm-diameter hosing and above-ground hydrants. Three hose tenders were dispatched to the Marina, where they were able to contain and extinguish the fire using water pumped from San Francisco Bay by the city's fireboat. Figure 4 shows an aerial view of the fire which erupted at the corner of Divisadero and Scott Sts. in the Marina. Figure 5 shows a portable hose tender with hosing and above-ground hydrants visible at the back of the truck. The computer simulations indicate that graphical hydraulic network modeling is sufficiently advanced for effective use in system management and emergency preparations. The computer simulations also emphasize the substantial effect that hydrant breaks can have on water lost from the system.

■ **Figure 4**
Fire in Marina which was suppressed with the PWSS (courtesy of EQE, Inc.)



■ **Figure 5**
Special Hose Tender with above-ground hydrants and hosing of the PWSS (courtesy of C. Scawthorn)

The failure of the remotely controlled isolation valve to be activated by utility-supplied electricity emphasizes the importance of identifying critical interfaces between systems and providing suitable back-up for emergency conditions. The isolation valve now is connected to a battery pack that can be activated by radio transmission.

In summary, the local benefits for the San Francisco community from this project are:

- $46.2 million seismic upgrading of its emergency water supply
- Emergency preparations which were able to contain and extinguish the Marina fire despite the fact that the in-ground water supply had failed in this area.

Moreover, various strategies for improving the AWSS have been explored with the model and communicated to fire fighting personnel and emergency planners. The recommendations resulting from AWSS simulations and the continued use of the model by engineers in San Francisco stand as significant proof that computer graphics modeling of water supply systems provides an effective way of improving both seismic performance and fire protection.

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