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VULNERABILITY ESTIMATES OF EARTHQUAKE DAMAGED WATER SUPPLY SYSTEMS

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Abstract

A method to assess performance of damaged water- distribution networks is presented. The method estimates residual serviceability of water- supply networks under seismic damage. The presented hydraulic analysis takes in account the effect of the negative pressures that do develop in these networks. Several measures are developed for evaluating this serviceability. The measures are random variables dependent on uncertain parameters such as seismic intensity, network damage state, and water demand. The determination of the measures involves hydraulic analyses of water- supply networks in various damage states. A new algorithm is developed for the hydraulic analysis of damaged water supply networks. The algorithm eliminates the portions of the network that have negative pressures, and predicts the available flow and pressure at the demand nodes. The hydraulic analysis also accounts for the dependence of C-factors, an internal pipe roughness on the pipe diameter. This dependence is validated by fire flow tests performed for the Auxiliary Water Supply System in San Francisco - AWSS. The serviceability measures and the proposed algorithm for hydraulic analysis are applied to AWSS to evaluate seismic vulnerability. Numerical results show that the algorithm for calculating serviceability measures is robust and efficient.

Keywords: water supply; network analysis; damage assessment; simulation models; probabilistic methods

1. Introduction

Water distribution networks are buried in the ground and they stretch over large areas, which significantly increases their exposure to damage from all sorts of sources, in particular during seismic activity and ground motion. For example, the city of San Francisco was completely destroyed during a 1906 earthquake, not because of building failures due to the earthquake, but because of damages to the water distribution network. These damages left the city with no water to fight the fires that erupted after the earthquake Gilbert et al. (1907). Therefore, it is essential to be able to make provisions and to manage responses in emergency situations so as to ensure a sufficient supply of water to suppress these fires. Early use of network simulations to assess system reliability and serviceability are reported by, for example,. Shinozuka et al. (1981), Eguchi, et al. (1983), Hwang et al.(1989), Ballantyne, D., (1990), Markov et al. (1994).

Two methods commonly used for assessing the seismic vulnerability of distributed civil infrastructure systems are probabilistic seismic hazard analyses and scenario earthquake analyses. Adachi and Ellingwood (2010) examined the applicability and limitations of both methods, and illustrated them on a Mepmhis power network by considering the dependence of water distribution networks on an electrical power supply system. Analytical methods estimate stresses and strains in pipelines caused by seismic events and determine the structural reliability of piping based on probabilistic models of the seismic intensity, soil conditions, and pipeline strength. Statistical methods, on the other hand, develop correlations between component damage and earthquake intensity. A resultant correlation is then applied to generate likely damage states of water supply networks exposed to earthquakes. These methods are particularly useful in seismic regions with limited seismic records.

The seismic serviceability of a water supply network depends on the vulnerability of its components, network topology, earthquake intensity, soil conditions, fire scenario, and operational strategies. In this paper, a statistical method is presented to access the vulnerability of water supply networks. The method provides a quantitative measure of the fire-fighting capabilities of the network following an earthquake. The evaluation of the seismic serviceability of a water supply network involves a relatively large number of hydraulic analyses for the network in various damaged states.

Most methods for hydraulic analysis are based on the assumption that pipelines are always full of water e.g. Wood (1980), and do not address scenario when water pressures fall below atmospheric pressure and negative pressure develops. It is not possible to sustain significant negative pressures in a distribution network, because leaks at joints, valves, and damaged components tend to vent and subdue negative pressure. Therefore, some pipelines may not have flow or may exhibit a partial flow, in contradiction to the assumption of full flow. The method presented here is to analyze actual water supply networks with leaks and breaks.

The method describes the several phases that determine the seismic serviceability of water supply networks and water demands for fire fighting. First, damage states of the water supply network and fire scenarios are generated consistent with site seismicity, soil conditions, and pipeline characteristics. Second, hydraulic analyses are performed to determine available flow and pressure at hydrants close to simulated fires. Third, statistics are obtained on flows and pressures, and indices are developed for quantifying the network serviceability as initially reported by Markov at al. (1994) and Grigoriu at al. (1989).

The method is implemented in a code, Graphical Interactive Serviceability Analyses of Life Lines subject to Earthquakes, "GISALLE," for evaluating the seismic serviceability of water distribution networks. The code has been applied to evaluate the seismic performance of the Auxiliary Water Supply

System (AWSS) in San Francisco. It can provide information to authorities on pipes critical to the network that may need to be reinforced and/or provide quick information on which valves ought to be closed to quickly isolate damaged areas and prevent further loss of water. The code was validated by flow tests provided by the San Francisco Fire Department and by observed network performance after the 1989 Loma Prieta earthquake. Numerical results show that the algorithm is capable of accurately and efficiently predicting the seismic performance of the AWSS.

2. Supply Model for Damaged Networks

After an earthquake, the damaged state of a water distribution network and its supply capability depends on the characteristics of the earthquake, the characteristics of the site, and the vulnerability of all the components of the network. Thus, to estimate the damage to a water supply network it is important to consider: (1) the reliability of individual network components e.g., pipelines, valves, hydrants, tanks and pump stations, (2) soil conditions on the site, and (3) the characteristics of the seismic event that may occur.

The pipes can be either intact or broken. A random variable with two possible outcomes 0 and 1 is Bernoulli random variable. Thus, the distribution of the breaks and leaks can be modeled by a Poisson process that is characterized by a mean rate of breaks per unit of pipeline length, $\lambda(I)$, where, I, is the earthquake intensity, Markov at al. (1994) and Grigoriu at al. (1989). The probability of occurrence of at least one break in a pipeline of length (L_k) during an earthquake of intensity, I, is

$$\mathrm{P_{pk}}(L_k, I) = 1 - \exp\left(-\mathrm{L_k}\,\upsilon_{\mathrm{pk}}\,\lambda(\mathrm{I})\right) \tag{1}$$

The vulnerability of the pipes in the areas where amplification of ground motion is expected is accounted with an amplification factor, υ_{pk}, assigned to each pipe k. A uniformly distributed random number, u, is generated from U(0,1) for each pipe and compared to the calculated probability of failure P_{pk} in equation (1) for this pipe. A break in the pipe occurs if $u > 1 - P_{pk}(L_{pk}, I)$. The amplification factor, υ_{pk}, can be estimated from the soil conditions in the vicinity of each pipe k because of the vast area covered by a network. It is not realistic to expect uniform damage distribution through the entire network area. Consequently, this factor can account for geological and seismic characteristics of specific area. The probability of the occurrence of landslides can be estimated based on slope, the type of the geological deposit, and groundwater conditions. Liquefaction probability can be mapped and overlain on the pipeline distribution network using a geographical information system (GIS) Ballantyne (2010). This factor can also account for differential mechanical characteristics of the pipe, such as ruggedness, a function of material strength or ductility to resist shear and compression failure; bending, a function of material strength or ductility to resist barrel bending failures; joint flexibility to allow elongation, compression and rotation; and joint restrain that prevents joint separation. The mean break rate, $\lambda(I)$, can be estimated from the repair record of pipeline damage following major earthquakes O'Rourke et al. (1991).

A broken pipe is simulated by a closed valve introduced on the pipe to prevent flow between the nodes. Two new pipes of length L/2 and of the same diameter as the broken pipe are added to each node, having fixed atmospheric pressure at their open ends. This procedure simulates a complete rupture at the center of the broken pipe. The model implemented here is conservative, since it overestimates the loss of water.

A broken hydrant is modeled with 1.5m long and 200mm diameter pipe connected to the hydrant node at one end and open to atmospheric pressure at the other end. The model is based on the assumption that a typical 3m long hydrant breaks in the middle of its length. The deterministic approach allows specifying a hydrant break at any node. The node may belong to areas with the potential of permanent ground displacement, fallen brick buildings, and other vulnerabilities obtained from the history of the site, all of which may amplify the likelihood of breaking. During simulation the random hydrant breaks are generated throughout the network according to a Bernoulli model of parameter, $v_{hi}P_{hi,}$ where $P_{hi,}$ is the probability of hydrant failure and v_{hi} is hydrant amplification factor at node, i, which may vary with location. A uniformly distributed random number, $u,$ is generated from U(0,1) for each hydrant and compared to calculated probability of hydrant failure $v_{hi}P_{hi}$. A break in the hydrant occurs if $u_i > 1 - v_{hi}P_{hi}$ *(I)*. This approach allows studying the significance of particular hydrant breaks on the overall network performance.

An open hydrant can be introduced at any node of the network. It is represented by a 3m long and 200mm diameter pipe placed at this node, and with a pressure of at least 140kPa at the free end. This pressure is typically required by fire insurance underwriters as the minimum acceptable pressure.

The modeling of other network components is also availble. The valves are modeled as 3m long pipes inserted between two nodes. They can be check valves or closed. Check valves are modeled as closed pipes if water flow is against the operating direction. The pipes are characterized by size, length, roughness coefficient, soil condition, and nodal connectivity. The nodes are characterized by coordinates, elevation, specified demand, soil condition, fire risk, and connectivity to pipes. They include additional information if the nodes are connected to fixed- or variable-grade components. The fixed-grade nodes are nodes connected to reservoirs, storage tanks, or a discharge point where pressure is specified. The variable grade nodes are nodes connected to pumps and fireboats. The seismic vulnerability of the additional components can be assessed by varying amplification factors assigned to them. For example, the reliability of tanks and pumps can be introduced by the amplification factor assigned to the corresponding connection pipes to allow for the study of the effect of potential regional soil liquefaction.

Particular pipes can be upgraded from their strength to earthquake-resistant pipes that sustain no damage during seismic events. Thus, the procedure can be used to detect the most critical system components from the sensitivity of the system performance with respect to a particular component. A particular component is critical if its upgrade to a seismic resistance component results in a significant increase of the system's performance. Methods such as this can be invaluable in emergency situations and also can be used to optimize an upgrading strategy based on sensitivity studies and economical considerations.

This method also allows simulation of deterministic and random water demand for fire fighting in the network. The deterministic approach is used when locations of fires and fire intensities are either estimated or known apriori,and the network is analyzed for a given fire scenario. Random demand is used to generate fire ignition and intensity consistent with the site's fire vulnerability, conflagration risk, earthquake intensity, and soil condition. The fire ignition corresponds to the location of the closest hydrant at which a water demand is required. The fire intensity typically depends on earthquake intensity, degree of structural damage, and character of building content and can be related to building floor area, Scawthorn (1987), to estimate the amplification factor.

The fire ignition is modeled according to a Bernoulli model of parameter $v_{fi}P_{fi}$ where P_{fi} is the probability of having open hydrant at node i and v_{fi} is fire amplification factor assigned to node i which may vary with the variation of fire vulnerabilities throughout the network area. It is possible to localize fires by setting fire amplification factors to zero in all other areas. The model generates a sequence of n_n trials where n_n is the total number of nodes with fire potentials. The trials are identical, mutually independent, and each trial results in either an open or a closed hydrant. For example, the model generates a set of uniformly distributed random numbers, $u,$ from U(0,1) and compares them to calculated probability of fire $v_{fi}P_{fi}$ at each node i. The fire ignites if $u_i > 1- v_{fi}P_{fi}$ *(I)*. The fire intensity is characterized by a water demand required for fire fighting. The demand is modeled as a random variable with a lognormal probability density function (PDF) to prevent negative demands in case of small demands.

3. A Hydraulic Analyses Model for Damaged Networks

Available hydraulic heads at joints and flows in pipes are crucial for predicting the performance of water-supply networks. These parameters satisfy a system of nonlinear algebraic equations that have to be solved numerically. Commonly used methods are based on the assumption that pipelines are full of water even when the water pressure falls below the atmospheric pressure. The assumption is unrealistic, because water distribution networks are not perfectly tight to the atmosphere. Water leaks that occur at pipe joints behave like air-inlet valves. Thus, negative water pressure cannot occur in networks. The consideration of leaks drastically increases the nonlinearity of the flow and head equations, because some pipes may have no flow or free surface flow and as the result also network serviceability is effected because some areas may be left with no water.

The method presented here is based on the assumption that air is admitted into pipelines when one or more nodal pressures are significantly below the atmospheric pressure. The unknown parameter flows and hydraulic heads satisfy a set of nonlinear algebraic equations, which can be solved by iteration. The number of equations is equal to the total number of nodes and pipes in the network.

Deterministic hydraulic analysis of the network is performed as follows. The flow Q_k in pipe $k = 1,\ldots,n_p$ connecting nodes i and j, where $i, j = 1,\ldots, n_n$, with pressures P_i and P_j, at corresponding nodes are the unknowns. Thus, there are $n_p + n_n$ unknowns pipes and nodes satisfying the same number of nonlinear equations, Davis (1942), Morris (1963). The first set of equations is based on the conservation of energy, as follows:

$$Q_k - b_k p_i + b_k p_j = \gamma b_k (E_i - E_j),\ k = 1,2 \ldots, n_p \tag{2}$$

in which

$$b_k = \frac{1}{\gamma K_k |Q_k|^{a-1}} \tag{3}$$

E_i, E_j = the elevations of node i and j; K_k = a constant dependent on units, the roughness coefficient and diameter of the k^{th} pipe; constant independent of units $a = 1.852$ for the Hazen-William equation, and γ = the specific weight of water. The second set of equations is based on continuity of flow, as follows:

$$\sum_k Q_k = Q_i^*,\ i = 1, 2, \ldots, n_n \tag{4}$$

in which Q_i^* is the required external flow at node i, and summation, *k,* extends over all the pipes converging to node i.

The analysis presented here accounts for the fact that air is admitted in the pipeline network when the pressure at a node is less than atmospheric pressure. The system of Eq. (2), and Eq. (4), are solved by iteration. First, initial values are assumed for the flows Q_k. The pressures p_i can be obtained by solving Eq. (2), and Eq. (4), simultaneously. Then, these pressures can be used in Eq. (2) to obtain new values of the flows Q_k. The iteration is continued until (1) the difference between the flows Q_k in consecutive iterations is smaller than a specified value, and (2) the objective function, *e*, is minimized, provided that demand flows are specified at hydrant h.

$$e_1 = \sum_{h=1}^{m} |Q_h - Q_h^*| \tag{5}$$

be minimized, with the constraints $P_h \geq P_h^*$, $h=1,...,m$, where Q_h^* is the required flow at hydrant *h*, P_h^* is the required pressure at hydrant *h*.

During the iteration, the method identifies the nodes with negative pressures. A node *i*, with pressure $p_i < 0$ and the pipes connecting it to nodes *j* are eliminated from the network if $E_i + p_i/\gamma > E_j + p_j/\gamma$, for all j because there is no flow in this set of pipes. The node is classified as a no-flow node. A node, *i*, is classified as a partial-flow node if $p_i < 0$ and the inequalities $E_i + p_i/\gamma > E_j + p_j/\gamma$ are satisfied for some *j*. Thus, the analysis of partial flow is not fully implemented. The hydraulic analysis returns the information on the pipes eliminated from the network, the flows in the active pipes, and the pressures at the remaining nodes.

The solution of the damaged network includes several phases. First, the nodes with negative pressure are identified and divided into two categories: no-flow nodes and partial-flow nodes. The no-flow nodes and the pipes converging to these nodes are eliminated sequentially, starting with the node of highest negative pressure. Flows and pressures are recalculated after each step of elimination. The no-flow nodes may isolate a part of the network, in which case that part is taken out from the network. Second, partial-flow nodes are considered. For example, let *i* be a partial-flow node and *j* be a node connected to *i* so that $H_j > E_i$. Then, the pipe connecting nodes *i* and *j* has partial flow. The effect of the partial flow is approximated by changing the roughness coefficient of the pipes connected to the partial flow node until $p_i = 0$. This is a heuristic approach to simplify the mathematical model. Thus, the explicit calculation of an open-channel flow profile is avoided. While adjusting any no-flow or partial-flow node, the previously adjusted nodes are checked to ensure that they continue to meet the criteria for no-flow node and partial-flow nodes. A separate sensitivity analysis of the elimination sequence was performed, and found that the elimination sequence does not have a significant impact on the final results. Thus, the elimination sequence starting with the node of the highest negative pressure was adopted. The algorithm involves lengthy computations because of repeated flow analyses of the entire network.

4. Serviceability Estimates

One way for providing a measure of the seismic serviceability of a water supply network is to quantify the fire capabilities of the network following an earthquake. The evaluation of the seismic serviceability involves a relatively large number of hydraulic analyses of the network in various damage states. Here, two serviceability measures in the form of indices are considered. The first index is defined as the ratio of the total available flow of the network Q_T in the specified damage state to the total required flow Q_{T^*}.

$$S_s = \frac{Q_T}{Q_{T^*}} \tag{6}$$

This index depends on the current demand and the network capacity. The second index can be obtained from the ratio of Q_T to the total available flow in the undamaged network Q_{TO},

$$S_d = \frac{Q_T}{Q_{T0}} \tag{7}$$

The indices are related to a network as a whole, yet they can provide a measure of serviceability for a particular region if the water demand is limited to that region only. The indices can be time dependent because of changes in the supply-demand scenario following an earthquake. Both indices correspond to a specified set of (m) hydrants used to withdraw water from the network. The total available flow Q_T represents the sum of the available flows at these hydrants. It is generally required by fire departments that the pressure at all hydrants be greater than 140kPa. The total available flow is a random variable depending on the network damage state

$$Q_T = \sum_{h=1}^{m} Q_h u(p_h - p_h^*) \tag{8}$$

in which, Q_h and p_h are the available flow and pressure, p_h^* is the required pressure at hydrant h, and u is the unit step function which is one for $p_h - p_h^* \geq 0$ and zero otherwise.

A Monte-Carlo simulation method is used to calculate probabilistic characteristics of the serviceability indices in Eq. (6), and Eq. (7). The method involves several phases. First, a damage state is generated for the water supply network. Second, the values of the indices S_s and S_d are calculated for this damage state. Third, statistics are developed for S_s and S_d from their values corresponding to various damage states generated in the first phase. Fourth, regression lines are constructed based on S_s and S_d values corresponding to the damage states generated in the second phase. Exponential and up to fourth-order polynomial regression lines can be developed and selected confidence levels can be obtained for each of the lines.

The determination of the flows Q_h in Eq. (8), is not unique when the number of operating hydrants is greater than one. An optimization algorithm is used to find the flows Q_h from the condition that an objective function

$$e_1 = \sum_{h=1}^{m} |Q_h - Q_h^*| \tag{9}$$

be minimized, with the constraints $P_h \geq P_h^*$, $h=1,\dots,m$, where Q_h^* is the required flow at hydrant h.

The serviceability indices S_s and S_d in Eq. (6), and Eq. (7), are used to develop fragility curves. These curves constitute regression lines fitted to values of S_s and S_d corresponding to a set of earthquake intensities. A least-square regression algorithm is used to find the flows Q_h based on a polynomial regression model to fit the observed responses.

An interval estimation of the mean response is used to predict how close the mean response is likely to be to the true response. For example, a 95 percent confidence interval implies that the true value of the mean response will fall within this interval, with a probability of 0.95. In general, the higher the confidence level, the wider the confidence interval. Thus, once the data on damage and serviceability indices is calculated, fragility curves are developed based on statistics of these indices.

5. Validation of the Method

The method was validated with the fire flow tests that were performed on the AWSS in San Francisco. The 1989 Loma Prieta earthquake scenario was used to evaluate the prediction capabilities for simulating flows and pressures throughout the network, given a particular demand and access to particular reservoirs.

The AWSS is the backbone of the city's fire protection. It operates at a pressure of about 1000 kPa. Figure 1 shows a plan view of the network, with contour lines indicating elevations in various portions of the network. The cast iron pipeline network is separated into two zones: the Lower Zone (shown with solid lines), and the Upper Zone (shown with dashed lines). The two zones can be connected to increase the pressure in the Lower Zone. The AWSS has three major sources of water: reservoirs, pump stations, and cisterns. The reservoirs include(1) the Twin Peak Reservoir with a capacity of about 38,000 m^3 (2) the Ashbury Tank with a capacity of 19,000 m^3 controlling the pressure to the Upper Zone and (3) the Jones Street Tank (JST) with a capacity of 28,000 m^3.

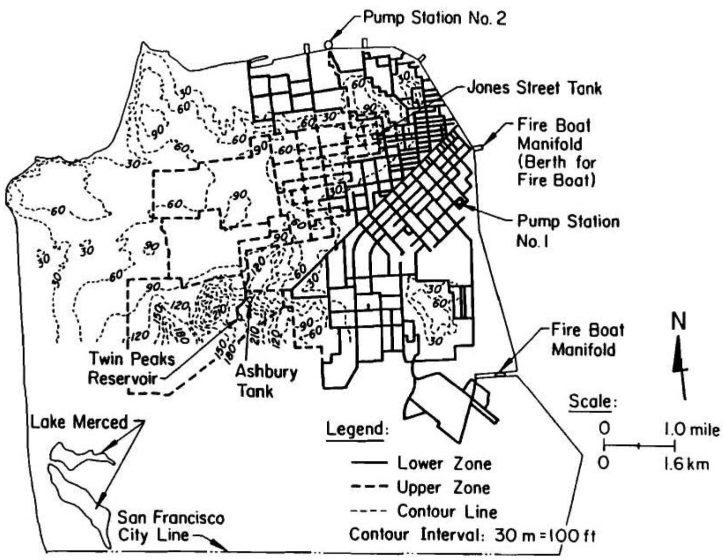

Figure 1. Auxiliary Water Supply System (AWSS)

Numerous valves and check valves can be opened or closed to control the network flow. Check valves allow water to flow in a single direction only. The AWSS has no connections to industry and houses. The only outlets for drawing water from this network are fire hydrants.

The San Francisco Fire Department performed several tests on the AWSS, some of which were specifically designed to validate the method. The tests used for validation include three tests in the Lower Zone, five tests in the Upper Zone, and one test which merge both zones. Reservoirs were the only source of water in all tests. Pressures were monitored at number of hydrants during the tests. The test data was compared with analytical results from the code to evaluate the accuracy of the computer simulations and to estimate the relationship between C-values and pipe diameter.

Table 1, gives results of this method for simulation of fire flow tests. In Tests 1 and 2, pressures were monitored at two locations. There is a good agreement between measured and calculated pressures for the tests in which the Upper and Lower Zones are not connected. However, some discrepancies occur when the two zones are connected. These discrepancies can be attributed to differences between the values of *C* in the Upper and Lower Zones. The test, which merged both zones, was performed 20 years later than the other eight tests.

Table 1. Results of the field tests and computer analyses

Location	Test No.	Field (kPa)	Code (kPa)
Both Zones	1*	296 48	162 66
Lower Zone	2* 3 4	310 517 90 924	310 517 96 93
Uper Zone	5 6 7 8 9	538 345 228 552 296	531 338 179 620 303

*Presue monitored at two locations

6. Conclusion

The method presented here was developed for evaluating the serviceability of water networks. The method is general and can be applied to the seismic serviceability analysis of any water supply network, regardless of its damage condition. The method has four major stages that allow network operators to (1) define and modify the network, (2) generate an analysis of a damage state consistent with the site seismicity, (3) perform hydraulic analyses and calculate serviceability measures, and (4) develop fragility curves and other indicators of seismic performance. It allows a network operator to explore in the real time the most vulnerable network components and regions and investigate potential strategies for mitigation more efficiently and more effectively. It can be used to estimate potential damage and short- and long-term resilience assessment to seismic events.

The method was validated by field data obtained from fire-flow tests performed by the San Francisco Fire Department and from data obtained from the Loma Prieta Earthquake. Predictions of the code are consistent with field data in both case studies. These results suggest that the method can be a useful tool for assessing the seismic serviceability of a water-supply network and can be used to improve the seismic performance and to optimize the emergency response of these networks.

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