TIME HISTORY ANALYSIS OF SEISMIC SERVICEABILITY OF A WATER SUPPLY SYSTEM

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ABSTRACT

A new method is presented for estimating the time-dependent serviceability of water networks damaged during earthquakes. The method accounts for the uncertainty in seismic ground motion, soil conditions, current system damage state, required water demand and the finite supply of water in reservoirs and tanks. The analysis is based on the Monte-Carlo simulation method and involves a large number of hydraulic analyses of a water supply system in various damage states. The hydraulic analysis uses an algorithm that eliminates the portions of the network experiencing negative pressures. A computer code with graphic capabilities, GISALLE, developed at Cornell University is modified for calculating the time-dependent seismic serviceability measures. The Auxiliary Water Supply System in San Francisco and an earthquake of the similar intensity as the 1989 Loma Prieta earthquake are used to demonstrate the proposed method of analysis.

INTRODUCTION

Seismic serviceability is an accurate measure for evaluating the seismic performance of water supply systems. The determination of this measure posses significant difficulties because of the uncertainty in the system damage state and the water demand, and because of unavailability of a general algorithm for hydraulic analysis. Current codes for hydraulic analysis have been developed for ideal systems with no leaks. This model does not apply to actual systems in seismic regions. Two computer codes are available for finding realistic criteria of the seismic serviceability of water supply systems [1, 4]. A limitations of these codes is the assumption that the water supply in reservoirs and tanks is infinite. This restrictive assumption is eliminated in this study.

The seismic serviceability of a system depends on the local seismicity, soil conditions, system state, operational strategies, and fire vulnerability. A Monte-Carlo simulation method is used to develop measures for the serviceability analysis of water supply systems. The analysis requires to: (1) generate samples of all random parameters, (2) perform hydraulic analysis of the water supply system in various damage states, (3) develop statistics for serviceability measures and evaluate confidence level, and (4) develop time-dependent serviceability measures.

The computer code GISALLE (Graphical Interactive Serviceability Analysis of Life-Lines subjected to Earthquakes) developed at Cornell is extended to account for the limited water supply of reservoirs and tanks of a system. The code accounts for all uncertain parameters and is based on an algorithm for hydraulic analysis that can model leaks and breaks.

The extended GISALLE algorithm is applied to evaluate the seismic serviceability of the Auxiliary Water Supply System (AWSS) in San Francisco. The seismic event considered in this analysis is the 1989 Loma Prieta earthquake.

EXTENDED GISALLE CODE

The main modules of the code are shown in Figure 1. They include: definition, modification, damage, hydraulic analysis, statistical, time-history, and results modules. The modules allow *preprocessing*, *analysis*, and *postprocessing* capabilities.

The *preprocessor* module allows access to a library of undamaged water supply systems stored as data files. Figure 2 shows the graphical representation of the AWSS on the computer screen as provided by GISALLE. This is an approximation of the as-built system that does not include pipelines of diameter smaller than 10-in and some of the nodes. Pipelines of different diameters are represented by lines of thicknesses increasing with the pipe diameter. Three water supply sources are also shown in the figure: the Twin Peak Reservoir, the Ashbury Tank, and the Jones St. Tank. There are five fire boat manifolds along the bay line. Fire boats may be connected to one or more manifolds. The figure shows also pump stations 1 and 2. These stations are modeled as single pumps or combinations of pumps.

The data file provides a full description of a water supply system. It contains information on pipes, valves, and nodes. The pipes are characterized by size, length, roughness coefficient, soil condition, and nodal connectivity. A valve on a pipe is modeled by two new nodes on this pipe at 10ft distance. There are two types of valves: valves that can be closed or open and check valves that allow flow in a single predetermined direction. The nodes are specified by coordinates, elevation, specified demand, soil condition, fire risk, and connectivity to pipes. Description of nodes include additional information if nodes are connected to fixed or variable grade components. Fixed grade nodes are nodes connected to reservoirs, storage tanks or a discharge point where pressure is specified. Variable grade nodes are nodes, connected to pumps and fire boats.

The initial data file stored by the GISALLE library can be modified to correspond to a particular supply-demand scenario by a modification module containing interactive computer graphics code. The module allows to activate/deactivate or edit a particular component of the water supply system. The modification module can be skipped to call the analysis module directly.

The preprocessor module also can generate damage states and water demands in the water supply system consistent with the site seismicity, soil conditions, conflagration risk and network characteristics. Damage states are characterized by pipe and hydrant breaks. A Poisson model is used to generate randomly distributed pipe breaks in the system. A Bernoulli model is used to generate randomly distributed hydrant breaks in the system. Water demands correspond to the location of the hydrant closest to a fire. The fire ignition is modeled by a Bernoulli distribution. The fire intensity is characterized by a water demand required for fire fighting. The water demand is modeled as a random variable with a lognormal probability density function.

The *analysis* module determines available flows and pressures at critical hydrant locations for a fire scenario and earthquake intensity. The core of this module is an algorithm for hydraulic analysis. Currently available computer codes for the hydraulic analysis of water supply systems, are based on the assumption that the pressure remain positive at all nodes [5]. The assumption is invalid when dealing with realistic systems that are not air tight because of breaks and leaks. These codes, when applied to analysis of damaged systems, can predict unrealistically negative pressures at some nodes. Moreover, pressures at hydrants and nodes can not be specified when these codes are used. Therefore, alternative hydraulic analyses are needed for estimating the seismic serviceability of water supply systems.

The hydraulic analysis in GISALLE code can determine flows and pressures in a damaged water supply system. The solution is based on the Hazen-Williams formula and involves an iterative procedure. The computer code identifies the nodes with negative pressures at every step of the iteration procedure. A node i with negative pressure and the pipes connecting this node are eliminated from the system if the total energy at node i is greater than the total energy at all nodes j at the other end of the connecting pipes because there is no flow in this set of pipes. The node i is classified as no-flow node. A node i is classified as a partial-flow node if the energy condition is satisfied only for some nodes j.

The partial flow or open channel flow is characterized by the existence of a free water surface. The surface represents a boundary subject to the atmospheric pressure. The hydraulic analysis in this case is complex and the GISALLE code performs only an approximate partial flow analysis. The approximate method replaces partial flow pipes with full flow pipes by increasing the roughness coefficient such that the pressure at the partial flow node is equal to the atmospheric pressure.

The hydraulic analysis module has two options for elimination of the negative pressure nodes: automatic and interactive. The automatic option eliminates all nodes with negative pressure below a specified pressure threshold. The threshold is specified as a percentage level of the highest negative pressure in the system at every iteration step. The interactive subroutine allows the user to specify a different threshold for the negative pressure at each iteration. The interactive option is useful for verification of the results obtained by the automatic option.

The *postprocessor* module presents graphically: (1) results of selected hydraulic analyses, (2) fragility curves, and (3) results of time-history analyses. Figure 3 show results of a hydraulic analysis of the Auxiliary Water Supply System. The doted and solid lines represent, respectively, disconnected or broken pipelines and pipelines with nonzero flow. The pipeline flow is color coded as shown in the Figure 3 and can be used to detect parts of the system with low flow condition. Similar graphical information is available for node pressure distribution as shown in Figure 4. The postprocessor allows the user to recall the full information for each pipe and node. The pipe information includes flow in the pipe, pipe number, pipe diameter, roughness coefficient and seismic amplification factor. The node information includes node pressure, elevation, demand, seismic amplification factor for hydrant breaks and amplification factor for fire ignition.

SEISMIC SERVICEABILITY

Fragility curves are developed to evaluate seismic serviceability of a water supply system. These curves show the average seismic performance and confidence intervals of seismic serviceability as a function of earthquake intensity. Two performance indices are used to measure seismic serviceability: the damage index S_d and the serviceability index S_s. The damage index is equal to the ratio of total available flow corresponding to the damaged system to the total available flow corresponding to the undamaged system. The serviceability index can be obtained from the ratio of the total available flow of the system for a specified damage state to the total required flow. This index depends on the current demand state of the system.

The determination of the fragility curves involves four steps. First, hydraulic analyses are performed for the undamaged system and generated fire scenarios. Second, damage states are generated for the water supply system consistent with the local seismicity. The Monte-Carlo simulation method is used to generate damage states and fire scenarios. Third, the performance indices are calculated for these damage states and fire scenarios. The seeds of the random numbers used to generate damage states are recorded. Fourth, regression lines, referred as the fragility curves, are constructed based on the values of the performance indices corresponding to the damage states generated in the second phase. Exponential and polynomial regression lines, and confidence intervals for these lines are available.

Figure 5 shows a regression line for the damage index S_d. The line is based on 10 earthquake intensities in the range (VI,VII) of the Modified Mercali Intensity (MMI). Three damage states were generated for each of the earthquake intensity. The figure also shows the 95% confidence interval for S_d. The coefficient of determination R^2, and mathematical expression for the regression curve are available in the upper right window. Similar representation is available for the serviceability indices S_s.

TIME-HISTORY ANALYSIS

The time-history module provides transient values of the performance indices for a water supply system subject to earthquake. The analysis accounts for the decrease of the available water of the tanks and reservoirs supplying the system. The performance indices defined earlier can still be used to measure serviceability in this case but these indices become time-dependent.

The determination of time-dependent performance indices is time consuming because it has to account for changes that may occur in the water supply system. The analysis involves the following steps:

1. Generate a fire scenario using the fire module. The seed used to generate fire scenario is recorded.
2. Perform the hydraulic analysis for the generated fire and the undamaged water supply system. Available flows are recorded at tanks and fire hydrants.
3. Generated a damage state using the pipe break module and the hydrant break module. The corresponding seeds are recorded.
4. Calculate the damage index $s_{d,j}(t)$ and the serviceability index $s_{s,j}(t)$ for sample $j = 1, 2, ..., n_s$, where n_s is the total number of samples used in the analysis.
5. Calculate the time
$$t_{0,i} = \frac{c_{0,i}}{f_{0,i}} \quad i = 1, ..., n_t \tag{1}$$
to empty tank i, where $c_{0,i}$ is the tank capacity, $f_{0,i}$ is the flow from the tank i, and n_t is the number of tanks in the system. The first tank to empty corresponds to the minimum value of $t_{0,i}$.
6. Shut off the empty tank.
7. Repeated Steps 1-6. Hydraulic analysis is repeated for the same fire scenario obtained in step 1 and damage scenario obtained in step 3.

Statistics are obtained for the damage and serviceability indices as well as for the times required to empty the tanks. Figure 6 shows typical samples of the time-dependent damage index. The dotted line in the figure shows the mean value of the damage indices throughout the time.

The damage index is in this case a stochastic process $S_d(t)$ with mean

$$\mu(t) = E[S_d(t)] \tag{2}$$

and covariance function

$$\gamma(t,s) = E(S_d(t) - \mu(t))(S_d(s) - \mu(s)) \tag{3}$$

The correlation coefficient of damage indices at times t and s is

$$\rho(t,s) = \frac{\gamma(t,s)}{\sqrt{\gamma(t,t)\gamma(s,s)}} \tag{4}$$

The coefficient of variation (C.O.V.) of the time required to empty a tank i is

$$C.O.V. = \frac{\sigma_i}{\mu_i} \tag{5}$$

where μ_i is mean and σ_i is standard deviation for this time. Similar procedure is used to determine the time-dependent serviceability index.

The time-history module provides graphical presentation of the history of the performance indices. Figure 7 show the results of time-history analysis performed on AWSS. Three tanks are supplying water to the system, the Ashbury Tank, the Jones St. Tank, and the Twin Peak Reservoir. Two pumps supply water to the system with four engines running. The analyses were performed for an earthquake intensity of VII MMI. Ten samples were produced. The figure show time-history of the damage index. The index decrease in time to a constant value maintained by the pumps operation. The mean values to empty the Ashbyry Tank, the Jones St. Tank, and the Twin Peak Reservoir are graphically shown on the time axis with the letters "A", "J", and "T", respectively. Numerical values for the mean and coefficient of variation of the time to empty the tanks are shown in the upper left window. A similar presentation is in Figure 8 for the time history analysis of the serviceability index $S_s(t)$.

CONCLUSION

The GISALLE code was extended to incorporate potential changes in the available water supply of a water supply system. These changes can be caused by the complete use of water stored in one or more reservoirs and tanks. The extended GISALLE code uses the same seismic performance indices as GISALLE: the damage and the serviceability indices. However, these indices become time-dependent. The extended GISALLE code was applied to evaluate the seismic performance of the Auxiliary Water Supply System in San Francisco subject to an earthquake of the similar intensity as the 1989 Loma Prieta earthquake.

References

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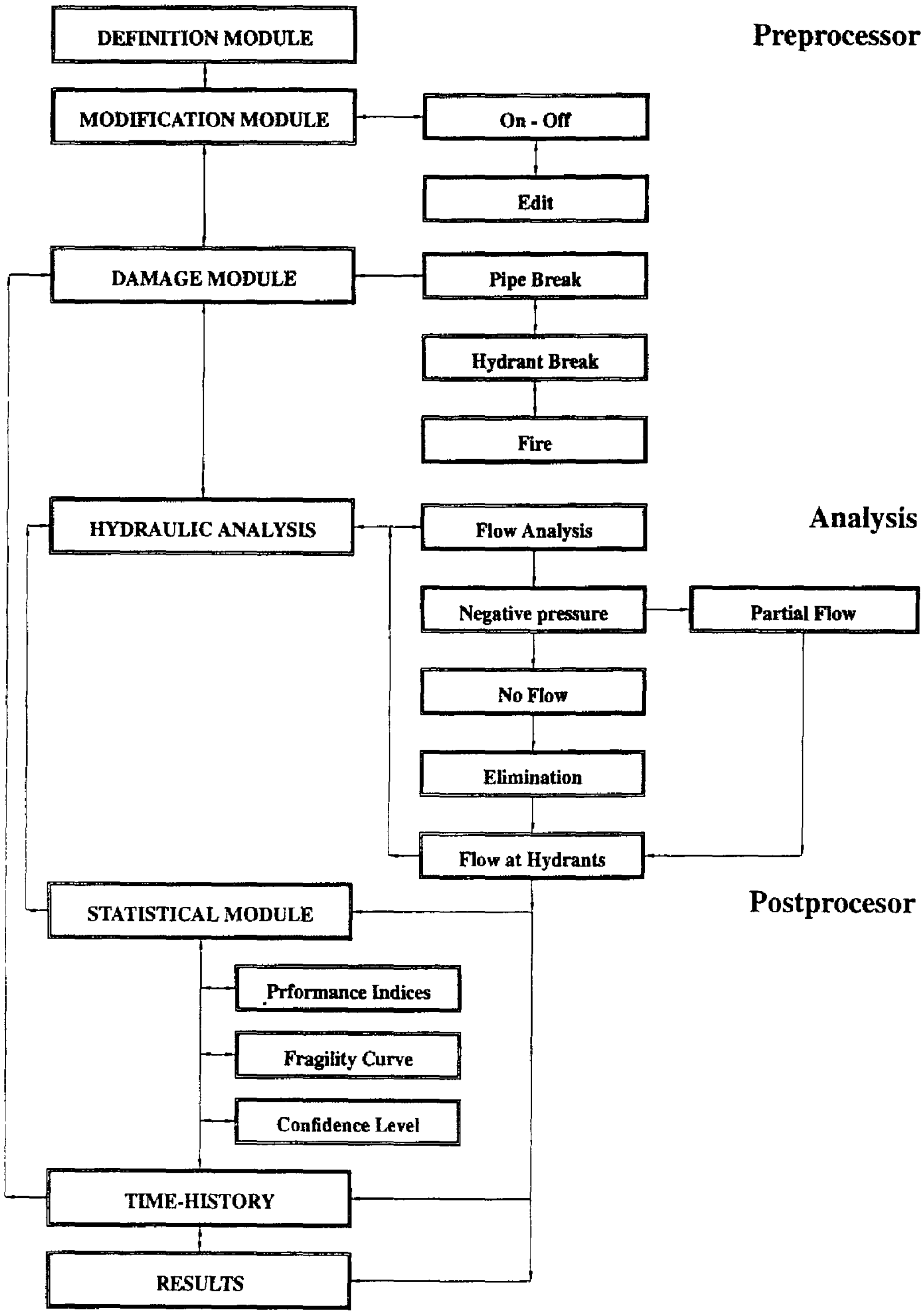

Figure 1: GISALLE Flow-Chart

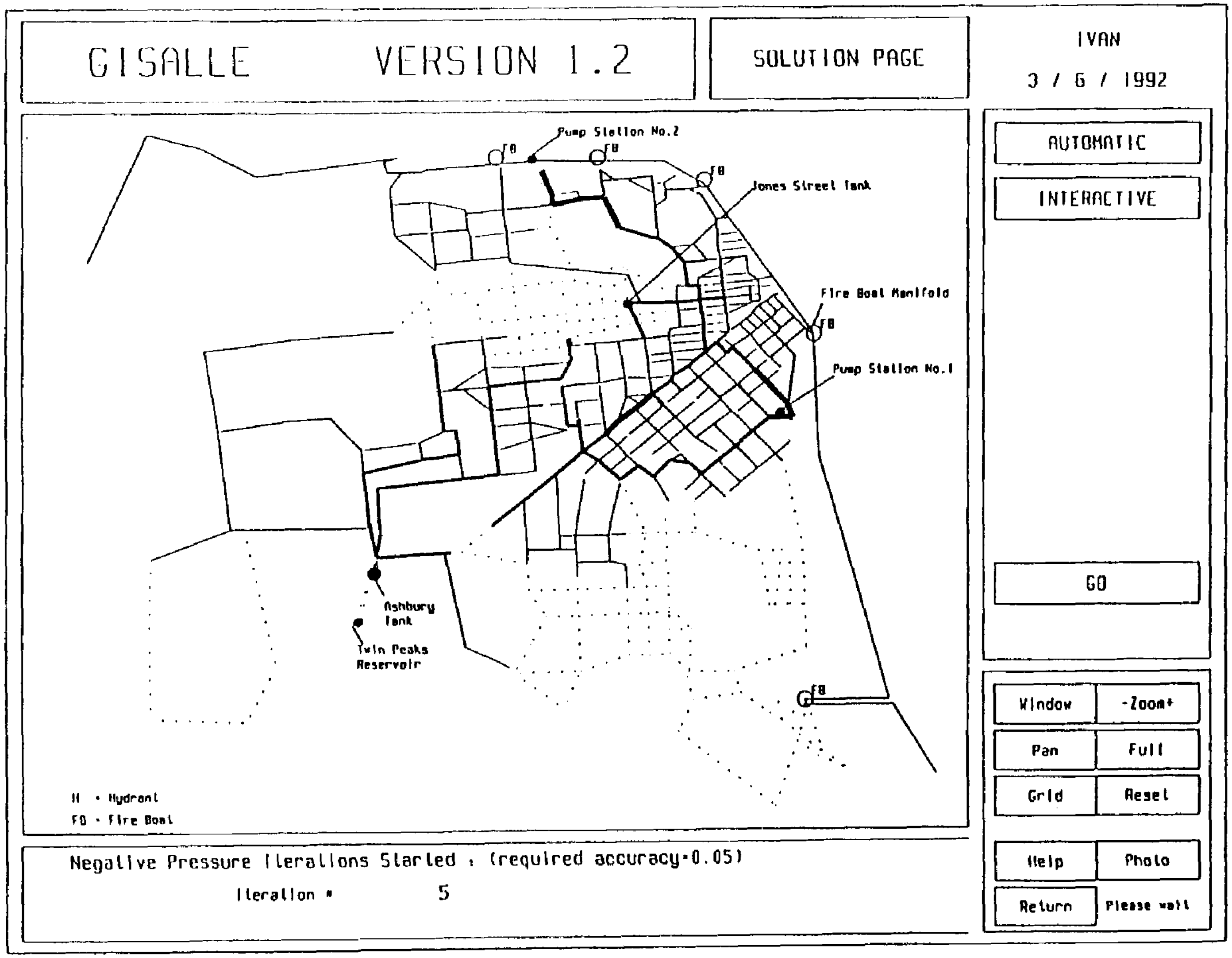

Figure 2: Computer Presentation of the AWSS

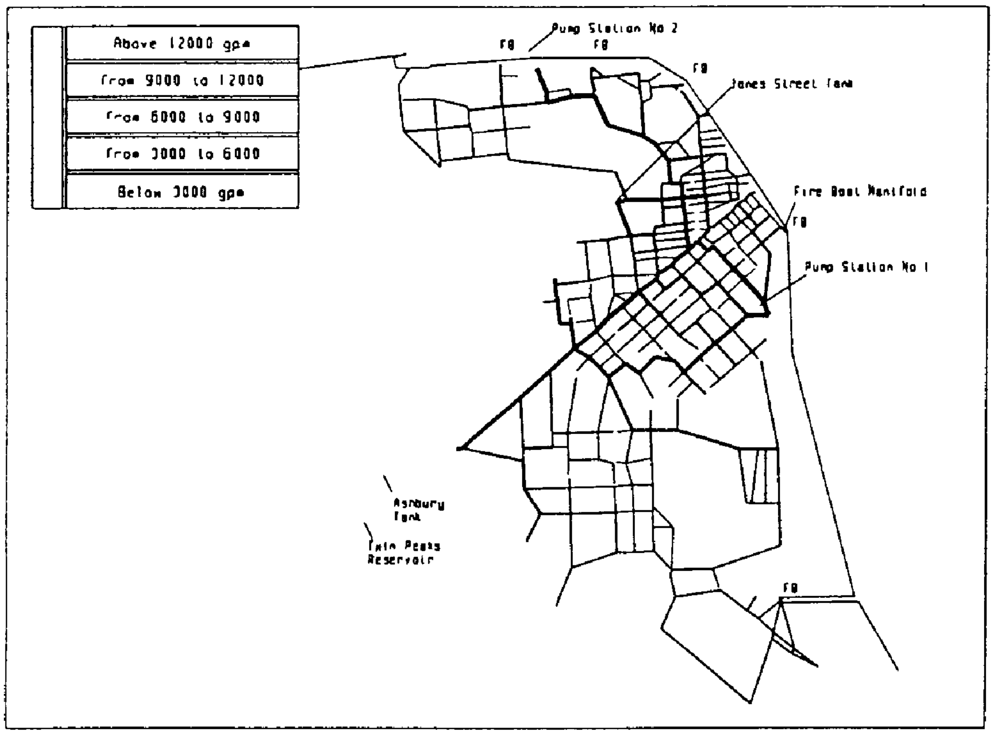

Figure 3: Graphical Presentation of the Flow Distribution

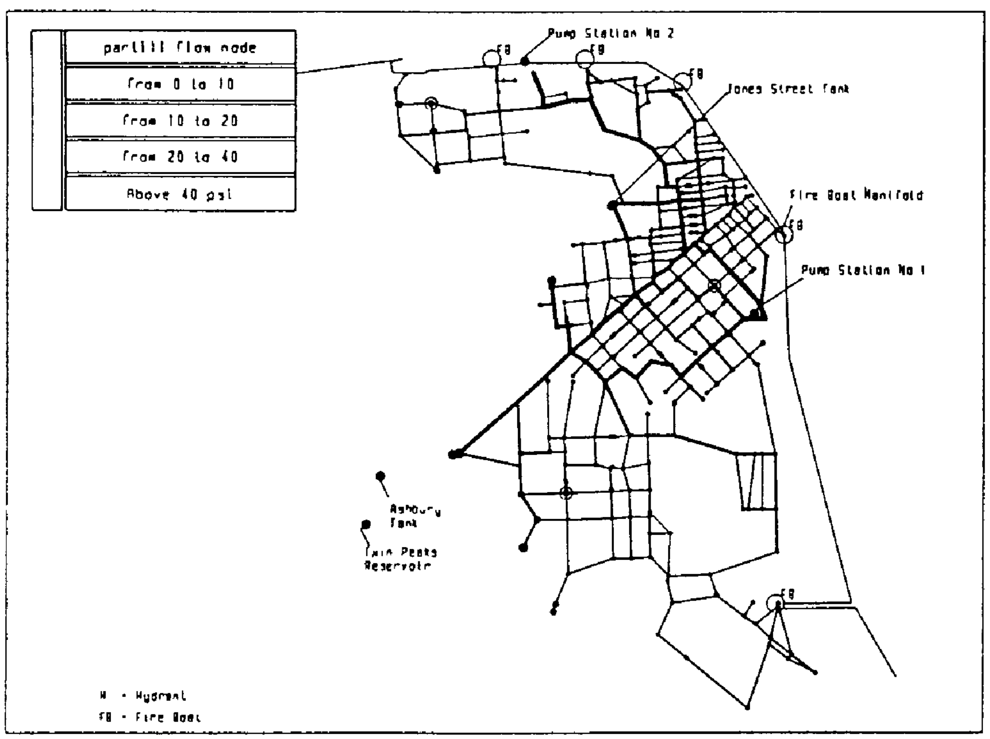

Figure 4: Graphical Presentation of the Pressure Distribution

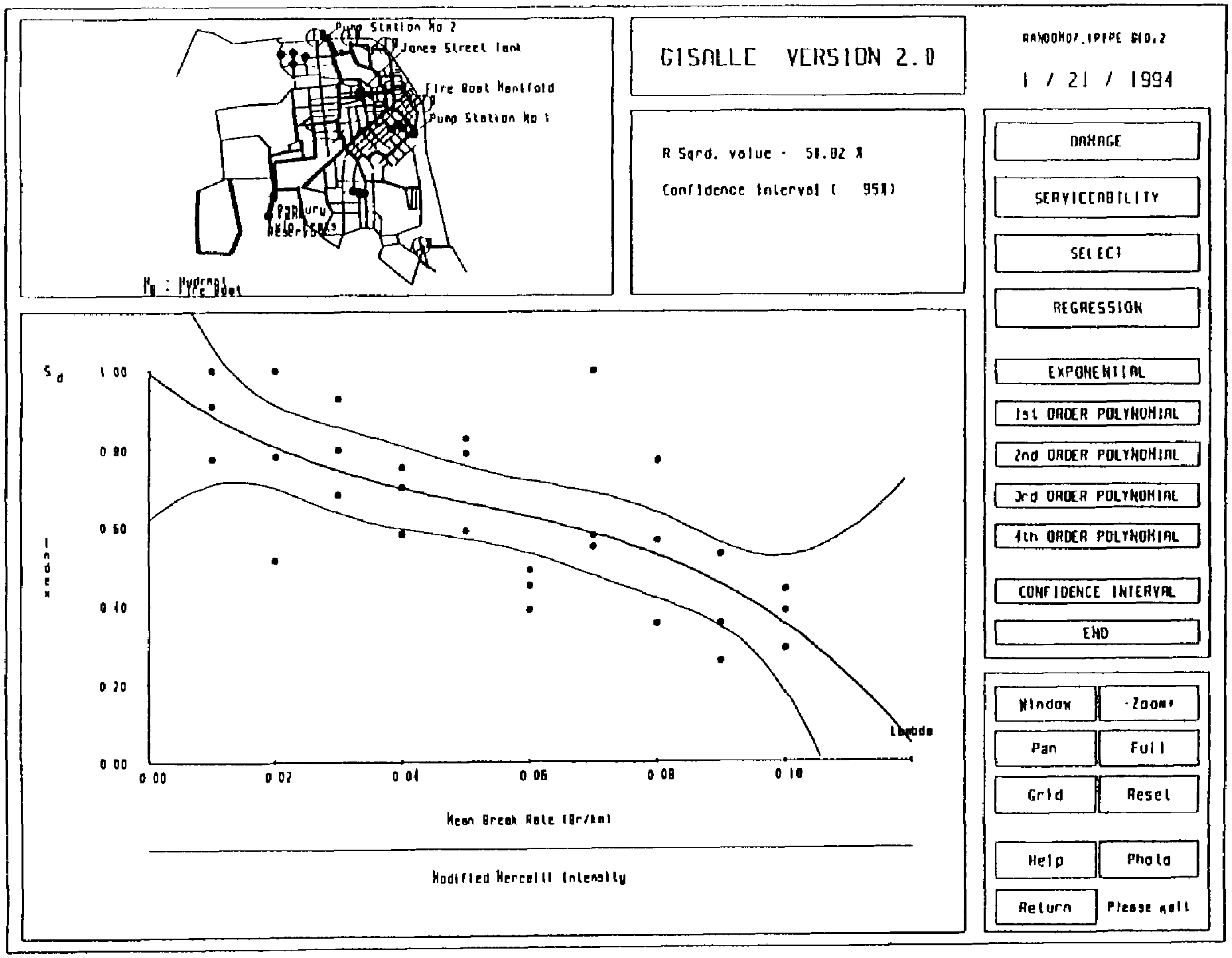

Figure 5: Computer Displays of Fragility Curve and 95% Confidence Level for Damage Indices S_d

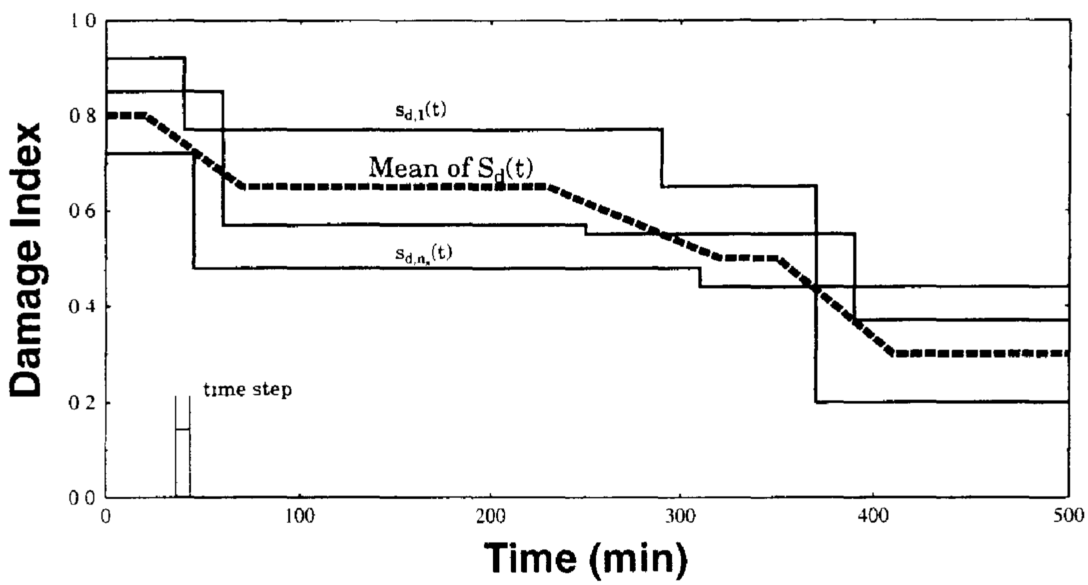

Figure 6· Time-History Analysis of Performance Indices

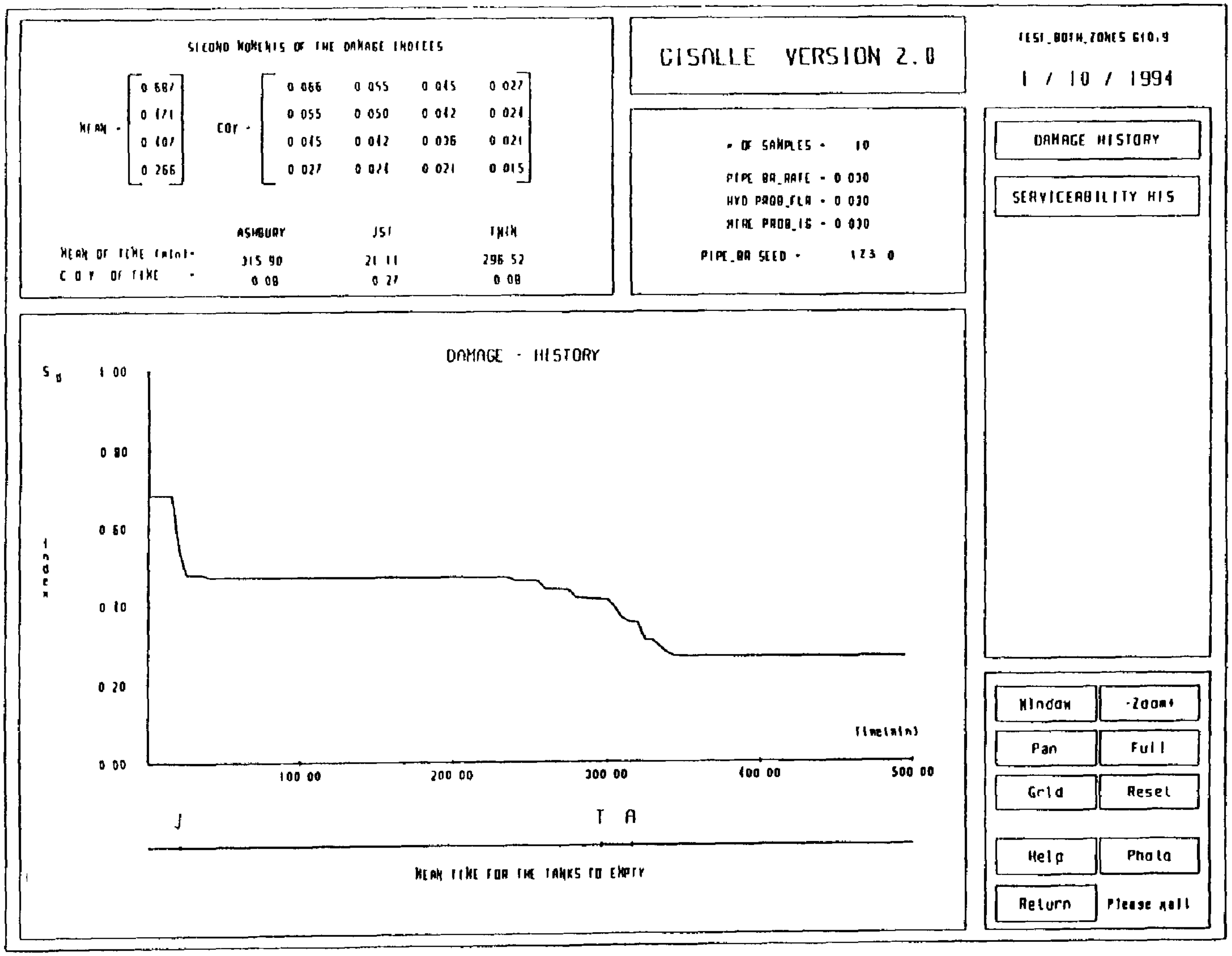

Figure 7: Graphical Presentation of the Time-History for Damage Indices

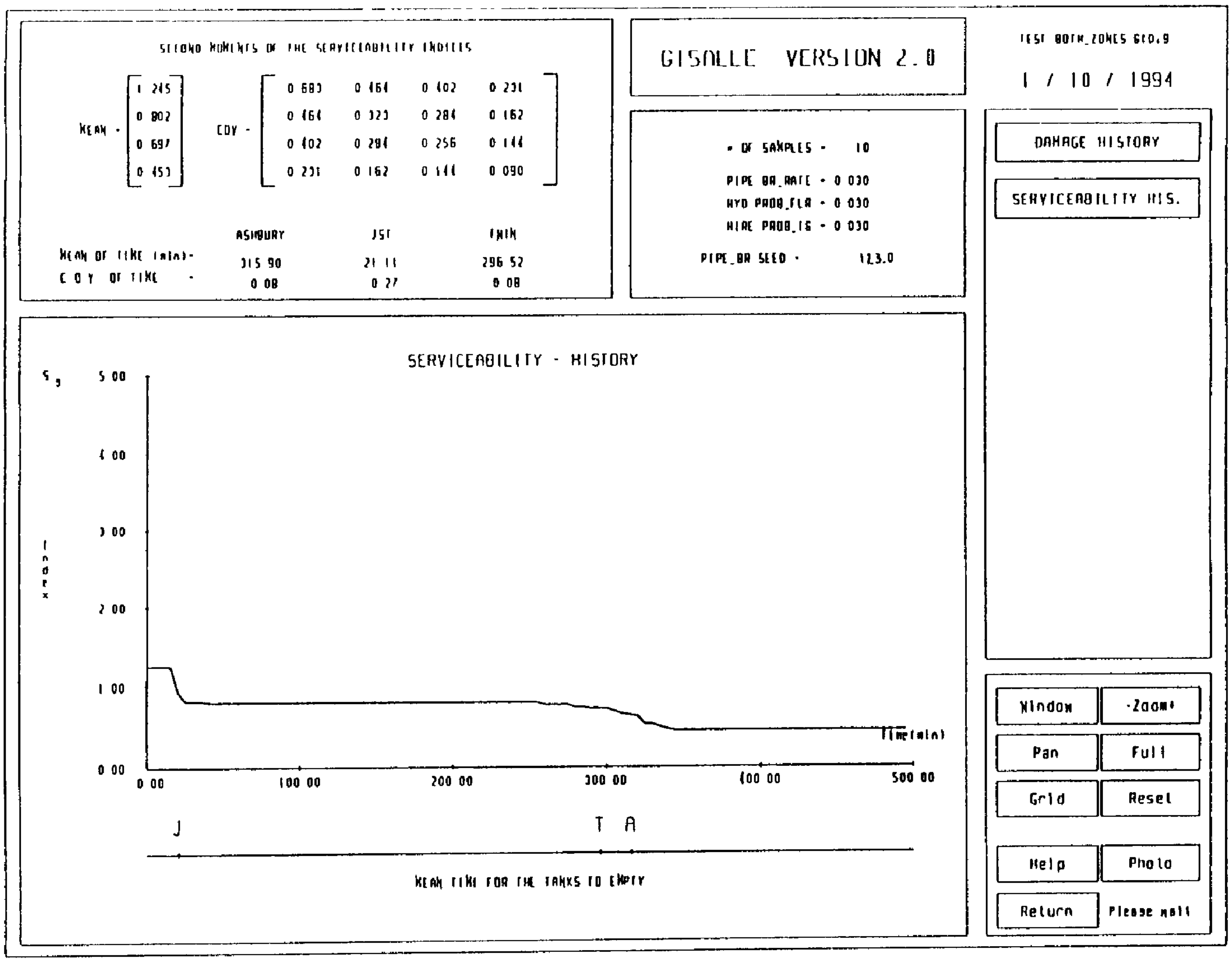

Figure 8: Graphical Presentation of the Time-History for Serviceability Indices