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A CONCEPTUAL FRAMEWORK FOR ASSESSING ECONOMIC IMPACTS OF MITIGATION STRATEGIES ON WATER SYSTEMS

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Abstract

In the face of increased development, civil infrastructure systems are increasingly vulnerable to catastrophic failures as a result of aging, overuse and poor planning when disasters such as earthquakes strike. Water supply systems are among the most vulnerable infrastructure systems and, arguably the most essential for human existence. Investment decisions regarding the retrofitting or rehabilitation of the existing systems have long-term impacts on the amount of direct and indirect economic losses that would be incurred should catastrophic events occur. Owners of public structures are faced with choices and trade-offs concerning the costs of operation and maintenance, whether recurring or uncertain, as they seek to assure that those structures perform well over their planned life cycle and the total costs over that period will be reduced. This paper describes a framework for assessing the economic consequences of key investment decisions regarding mitigation against damage to water supply systems due to earthquake effects. The framework is implemented by means of prototypical software which employs algorithms that simulate earthquake occurrences and magnitudes based upon probability distributions and models damage and costs based upon empirical studies derived from the existing literature.

Introduction

Civil infrastructure systems in the US and elsewhere in the world are becoming more vulnerable to catastrophic failures when natural disasters such as earthquakes and floods strike. Water supply systems represent a particularly critical component of infrastructure as every stage of response and recovery is dependent on the supply of adequate amounts of fresh water as well as sanitary disposal of wastewater. Exposure, aging, misuse, overuse, mismanagement and neglect are the main reasons for deterioration and vulnerability to catastrophic failures (Hudson et al. 1997). There is generally a lack of a systems approach in public sector policies for operation and maintenance (O & M) that encompasses future uncertainties such as changes in use, ownership and disaster risk (National Research Council 1991). This paper describes a systems approach governing the O&M including retrofitting and rehabilitation that would provide cognizant agencies with a basis for planning, analysis and comparison for the purpose of mitigating losses associated with natural disasters.

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Although US building codes contain natural hazard provisions, they do not require one hundred percent resilient structures due to economic concerns. In conventional standards-based design approaches, there is a trade-off between cost and resiliency. However, designers and owners of public structures are still faced with choices and trade-offs between initial construction costs and O & M costs, whether recurring or uncertain, so that those structures perform well over their assumed life cycle and the total costs over that period will be minimized.

Public structures require important investment decisions in anticipation that the returns on such investment may continue for hundreds of years. In practice, however, publicly owned structures usually have been designed on the basis of low construction costs rather than true life-cycle costs that would include future retrofitting/ rehabilitating of components due to natural disasters (Hudson et al. 1997). Those publicly owned structural systems that are designed by considering certain life cycle costs usually have a missing component, which is the assessment of vulnerability in economic terms (Chang and Shinozuka 1995; Hawk and Eng 1998).

Background

The research and development needs in the area of critical infrastructure in the US were clearly pointed out in the 1st Critical Infrastructure Protection R&D Workshop that was held in August 1999. The Clinton Administration's Executive Order 13010, issued on July 15, 1996 established the Commission on Critical Infrastructure Protection in order to develop a national strategy for protecting infrastructures from various threats and to assure their continued operation. This later led to the Presidential Decision Directive (PDD63) of 1998. Water Supply Systems were named in the Executive Order 13010 as one of the three vital human services (VHS) along with emergency and government services. National experts from academia, government, and industry were brought together in an R&D workshop to review policies and identify needs and to make recommendations pertaining to the protection of critical infrastructure. They concluded that there is a lack of understanding of how individual elements are interconnected to form complex infrastructures and a lack of strategies to help determine priorities in restoring services back to their original use should catastrophic failures occur (OSTP and NIPC 1999).

According to the findings of a recent report on the nation's infrastructure assets issued by the American Society of Civil Engineers (ASCE 2001), the nation's 54,000 drinking water systems face staggering funding needs over the next 20 years -annual shortfall of at least $11 billion for replacing aging facilities- and those funding needs do not account for any growth in the demand for drinking water. The major problem is lack of strategies to replace and maintain the aging facilities that are near the end of their useful life. One of the specific policy recommendations made by ASCE on this issue is to encourage the use of life cycle cost analysis principles to evaluate the total costs of alternative actions.

The researcher hypothesized that there is a trade off between alternative mitigation policy options given the effects of future uncertain events on water systems. A framework was developed by the researcher in order to analyze and assess the long-term effects of those events on the system under different states as prescribed by those policy options.

This paper describes a framework that provides measured assessments of the effects of decisions made earlier in the life cycle to the overall resiliency of a water system and its future life cycle costs. Due to the fact that earthquakes have effects that are more significant on structures, especially underground networks consisting of buried pipelines, than any other hazard, the study presented here considers only earthquake risk but could easily be adapted for application towards LCC implications of other hazards.

The model is implemented by means of a computer program that allows rapid simulation of disaster effects on the life cycle cost (LCC) of the system based upon competing mitigation and response strategies.

Water Supply Failure Chain of Events

To describe what can go wrong resulting as a result of earthquakes, an illustrative approach was taken as a first step in the analysis. Shown below is the cause-effect path for disruption of water supply systems adapted by the researcher from a framework for probabilistic risk assessment of dynamic systems[2]. It illustrates the dynamics of mitigation as applied to water supply systems. Figure 1 shows the causes leading to a disruption of water supply service and Figure 2 shows the same concept together with appropriate control measures (interventions) that are applied at certain points along the causal chain to reduce the likelihood of causes leading to water supply disruption. The figures illustrate a systematic path of causes, effects, mitigating measures and potential remedies that come into play.

[2] The causal chain method (Harrald et al. 1999) has been effectively adapted and used by the researchers of the Institute for Crisis, Disaster and Risk Management of the George Washington University for maritime risk assessment.

Figure 1: Causal Chain Framework for Water Supply Disruption

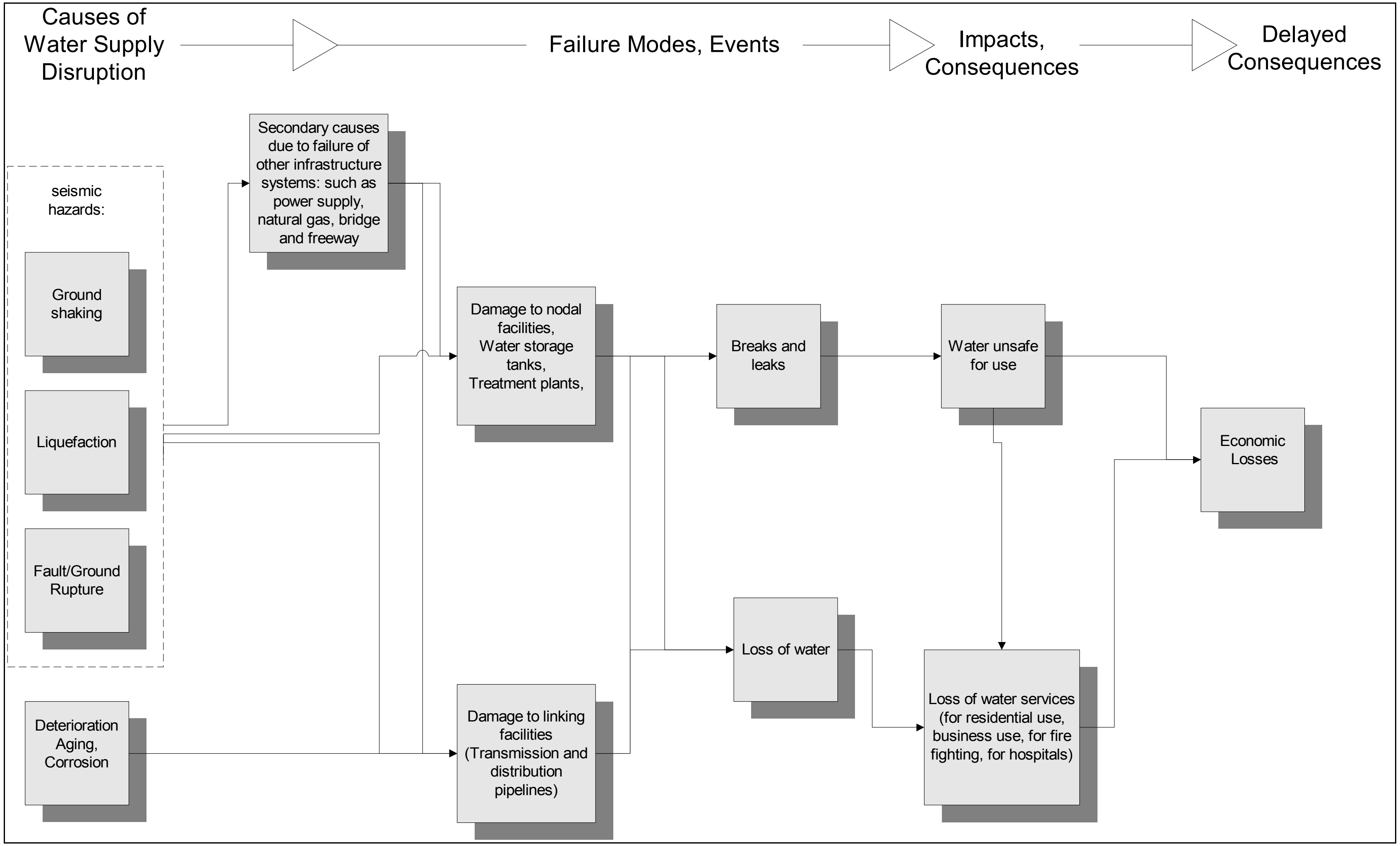
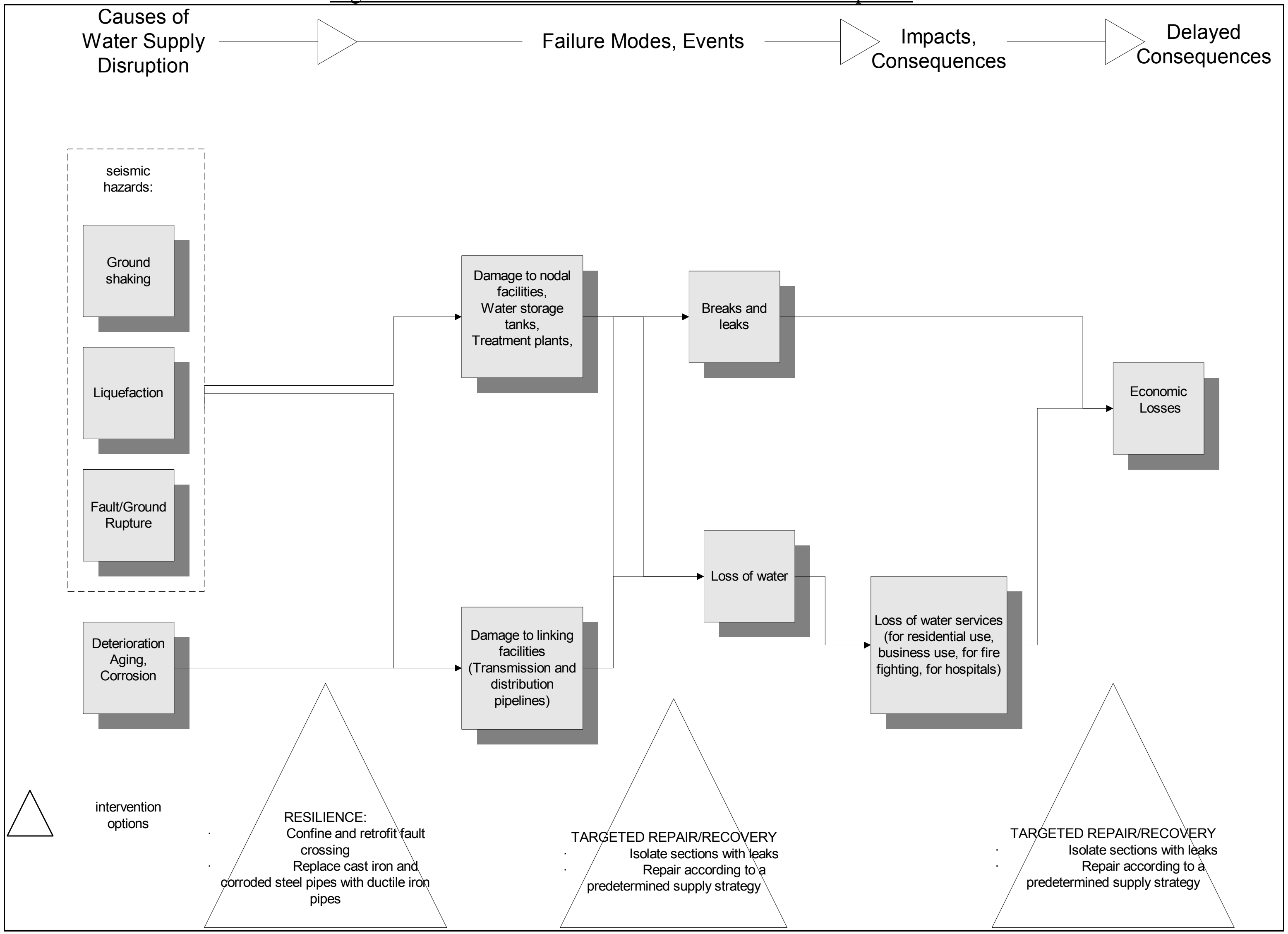


Figure 2: Causal Chain Framework with Intervention Options



Model for Simulation

A model was formulated and developed by the researcher in order to analyze and assess the long-term effects of uncertain seismic events on the water system under different states as prescribed by the following policy options:

Option 1: Do nothing now, wait until an earthquake strikes, and for failures to occur. Invest in targeted recovery only. (i.e. Repair the system as damage occurs).
Option 2: Do not wait for the earthquake and consequent failures to occur. Act now and upgrade the existing components that are deemed as weak against seismic forces (such as replacing corroded steel pipes with ductile iron or PVC pipes).
Option 3: Do not wait for the earthquake and consequent failures to occur. Act now and invest in redundant systems (pipelines and or alternative storage tanks) parallel to the existing facility.
Option 4: Invest in increased manpower and equipment to respond effectively in the event of an earthquake and decrease the time to restore the system (that would allow to lessen the unwanted economic impacts due to disruption of water service)
Option 5: Some combination of the above

The alternative strategies may consist of either one of the above or a combination depending on the system under consideration and depending on system O&M budgetary constraints. For each system under each option, the performance objectives should be stated. These performance objectives are used as postulates in order to be tested against the simulated failure results.

Computerized algorithms allow rapid simulation of disaster effects on life cycle cost (LCC) of the system based upon a wide range of potential economic and seismic input variables. The software simulation tool (LCCSim-Water1.0) performs the following functions:

- Simulates the occurrence of seismic events based upon a Poisson distribution of independent arrivals over the remaining economic life cycle of the water system
- Simulates the magnitude of seismic events based upon an exponential distribution
- Processes damage assessment on a link by link basis based upon pipe material, joint type, size, and soil type
- Performs present value cost analysis based upon direct and indirect costs, escalation factor, labor cost indexes and interest rate
- Conducts two different and separate modes of simulation 1) a one-time scenario simulation 2) repeated simulations in a Monte Carlo fashion of up to 1000 trials, over an extended time frame based upon a common set of water supply system data, earthquake distributions, damage models, and cost models.

This model includes only water transmission and distribution pipelines with different pipe characteristics (in terms of materials, size and age) and the effects of soil characteristics on pipes (corrosive or non-corrosive). It does not cover facilities that include storage tanks, treatment plants, pumping stations. Computing case specific damage patterns to these facilities that may include structural failures and mechanical failures (e.g. reliability issues of pumps) are left for future studies. Dams or source water facilities such as lakes, rivers, streams and wells are also left outside the scope of this study.

Historical evidence has shown that for buried pipelines, seismic hazards are twofold: 1) wave propagation hazards and/or 2) permanent ground deformation hazards. Wave propagation hazards (PGV) are characterized by the transient strain and curvature in the ground due to traveling wave effects. PGD (such as landslide, liquefaction induced lateral spread and seismic settlement) hazards are characterized by the amount, geometry and spatial extent of the PGD zone. The fault-crossing PGD hazard is characterized by the permanent horizontal and vertical offset at the fault and the pipe-fault intersectional angle (O'Rourke and Liu, 1999). The simulation model assumes that the damage to pipelines occur due to both PGV and PGD. The model simulates the damage patterns on water supply and distribution pipelines by means of the semi-empirical correlations between observed seismic damage and a measure of ground motion that were developed by Kamiyama et al. (1999) and Youd and Perkins (1987).

Data Requirements

The model requires data on seismicity of a sample region, system data parameters and cost data.

Relevant historical seismic data is obtained from the National Earthquake Information Center's seismology online database based upon input parameters of longitude and latitude, a timeframe that can extend backward over 200 years and a radius of activity that is relevant to the water supply system under consideration. The query result is a long list of earthquakes that occurred within the specified area with occurrence dates, latitude/longitude parameters of the epicenter, and magnitudes. This information condenses readily into average earthquake arrival rates and average earthquake magnitudes for use as input to the earthquake simulation module of the water supply system life cycle costing tool that will be developed for the proposed study.

Life Cycle Cost Parameters

The model considers the initial, recurring and emergency response costs in two categories similar to the categories that Hudson et al. (1997) used:
1. Agency costs, and
2. Non-agency costs

Agency costs are those costs that appear in agency's budget. They include:
1. Initial capital costs of construction (for the purposes of this research, only for redundant system construction)
2. Costs of maintenance, rehabilitation, renovation, and reconstruction (M, R&R): *Periodic (planned) maintenance*: *Cleaning and lining* (includes cost of excavation, bypass piping, valve replacements) and *Cathodic protection* (includes costs of testing, mobilization, anode material, installation, power lines, rectifiers, O&M labor and power), *Repairing of leaks and breaks, Pipe replacement*
3. Salvage return or retention residual value (may be a negative value) at the end of the analysis period,
4. Engineering and administrative costs
5. Costs of borrowing (if projects are not financed from current revenue)

Non-agency costs would typically be incurred by either users of the system or by non-users. For the case of water systems, they would include the following:

Non-agency costs (User Costs):
6. Disruption due to breaks and leaks
7. Disruption due to M, R & R activities

The decisions taken at some point in time will show their effects in the form of dollar losses, given future earthquakes. The model allows adjustments for inflation indexes based on Engineering News Record's (ENR) Building and Construction Cost Indexes and an escalation rate is also factored in for forecasting future cost figures. The LCC is expressed in terms of present worth (PW). PW gives the amount of money required now to fund the alternative strategy for the entire analysis period. The discount rate is considered as the minimum real or net rate of return, after inflation, to be achieved by public sector investments (Office of Management and Budget 1972).

A detailed study on cost estimates for maintenance, repair and replacement of water distribution systems have been conducted by USACE (Walski 1984). The model draws upon the empirical relationships obtained by regression methods of that study. The cost modeling portion of the model relies upon certain constants that have dependencies on current labor and material costs and therefore provides the means for controlling or updating these constants or even treating them as variables impacting a long term LCC analysis.

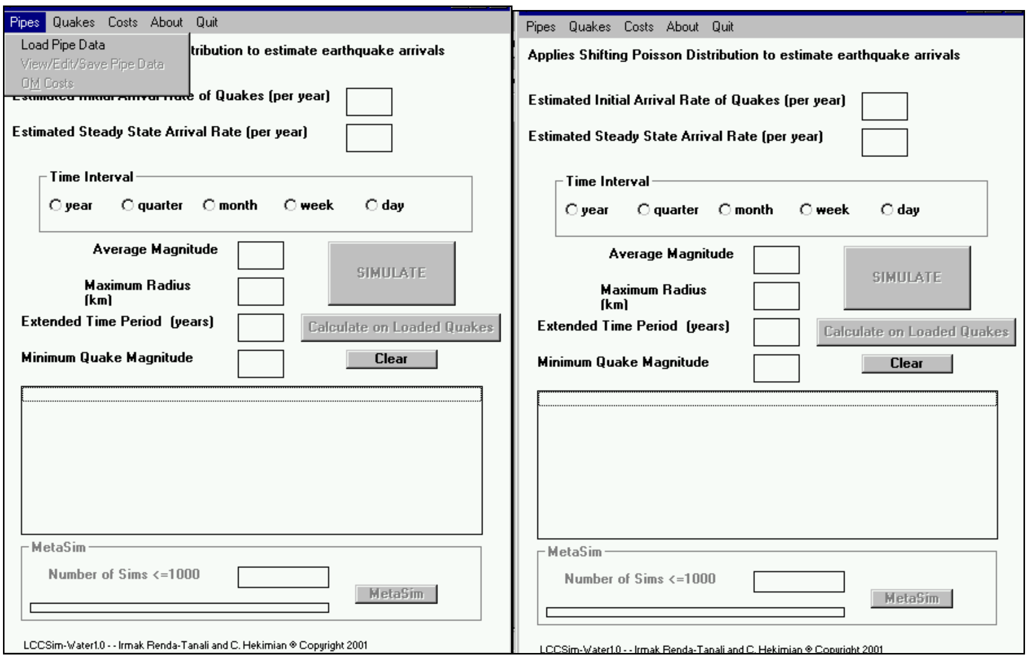
Inputs

In order to conduct the simulation of earthquake occurrence and the associated costs, the user enters the following input parameters related with the earthquake occurrence and damage prediction:

1) Pipe data
2) Estimated initial arrival rate of quakes per year (from historical records)
3) Estimated steady state arrival rate of quakes per year (from historical records)
4) Time interval that defines the granularity (default parameter is 'days')
5) Average magnitude (from historical records)
6) Maximum radius (based on a rule based judgment)
7) Extended time (the remaining life cycle of the existing system or the future time period that an economic analysis needs to be conducted)
8) Minimum quake magnitude (defining the magnitude threshold below which an earthquake is assumed to cause negligible damage)

Figure 3 below shows the input data view of LCCSim-Water1.0:

<u>Figure 3: Input Data View of LCCSim-Water1.0</u>



Outputs

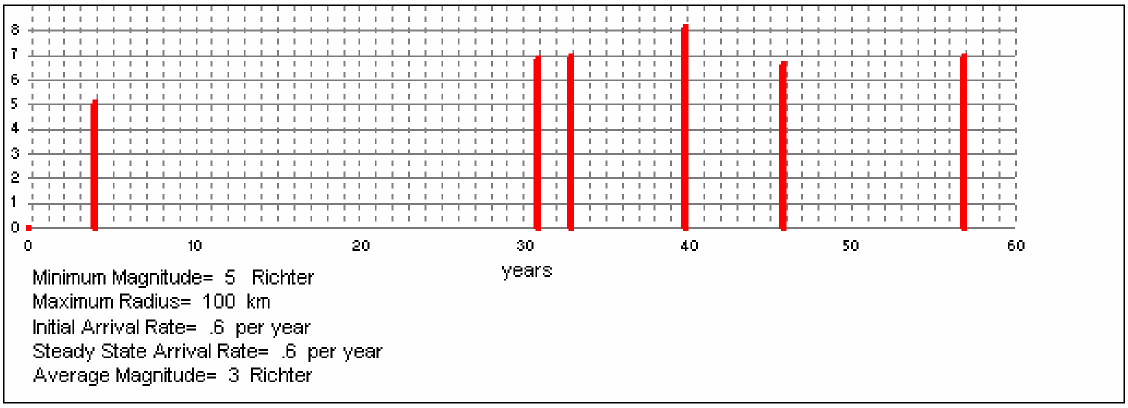
One-time Simulation

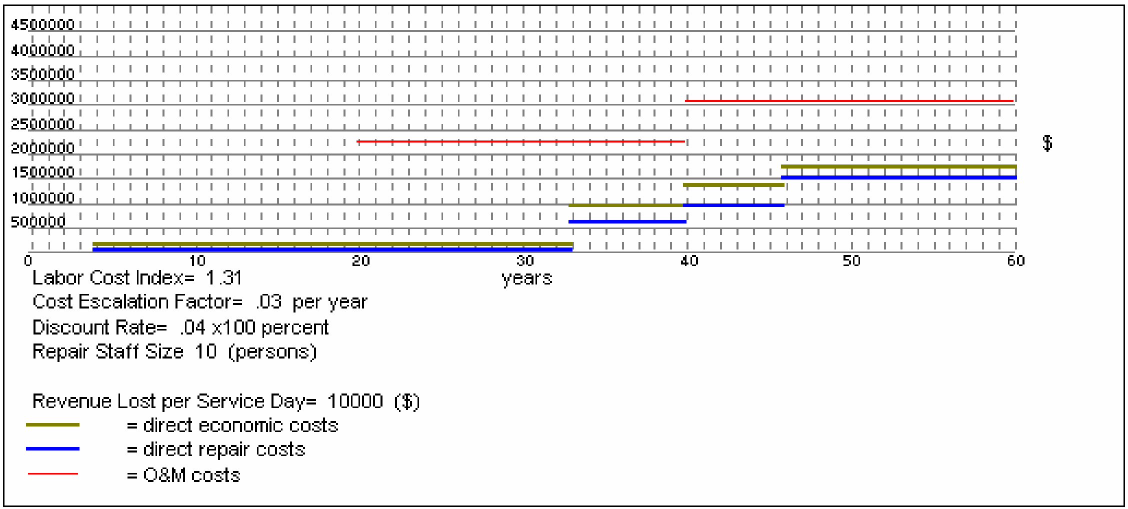
A simulation is run once for the remaining system life cycle, generating earthquake occurrences, magnitudes and distances from epicenter, all based upon their own probability distributions. Damage to pipelines is calculated based upon tabulated data and formulae governing peak ground velocities (PGV) and permanent ground deformations (PGD). The pipe damage in breaks/feet for each link is processed by the repair cost model. The total number of breaks for each link is calculated and its associated costs. The output includes the following:

1. The year and day on which each of the earthquakes occur, the corresponding magnitudes and distances from the source
2. For each earthquake within the system life span:
   2a) damage to the pipes, i.e. the number of breaks per thousand feet on a link by link basis
   2b) damage to the pipes, i.e. the number of breaks per thousand feet for each pipe type
   2c) total number of breaks for each pipe type
   2d) repair costs for each pipe type
   2e) direct economic losses (in dollar values) for each pipe type
   2f) total repair costs
   2g) total direct economic losses
3. Total direct costs of earthquake related loss
4. Total direct economic losses (in dollar values)
5. Total O&M Costs
6. A time-line plot of earthquakes showing date and magnitude
7. A plot of cumulative costs over the entire life cycle

Figure 4 shows the timeline plot of a sample scenario run and corresponding cumulative costs over a life cycle for a sample system.

Figure 4: Timeline Plot of a Sample Scenario Run





Monte Carlo Simulation of Life Cycle Costs

A Monte Carlo function processing up to 1000 one-time simulations at once is facilitated for the purpose of LCCA. Each simulation generates earthquake occurrences, magnitudes and distances from epicenter, all based upon their own probability distributions. Damage to pipelines is calculated based upon corresponding peak ground velocities (PGV) and permanent ground deformations (PGD). The damage output in breaks/feet for each link is then processed by the repair cost model. Each unit break is multiplied by the entire length of the link and by the unit cost of repair. The output includes:

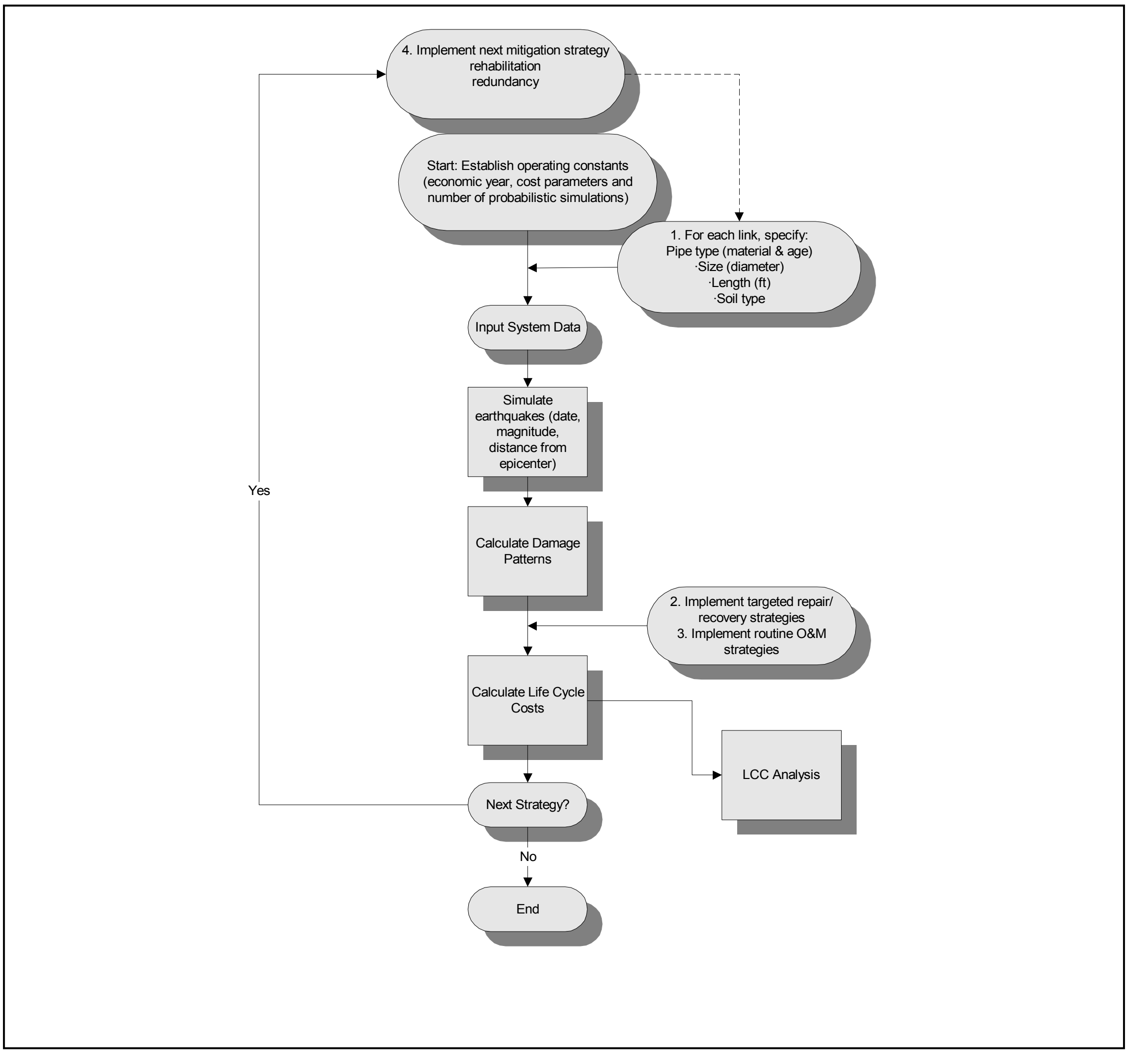
1) The average radii (over X number of simulations)
2) Average magnitude with its variance
3) Average number of breaks per foot for each pipe type
4) Average total number of breaks
5) Average total repair cost per foot of pipe
6) Average total repair cost
7) Average total direct economic loss
8) Total cost of O&M
9) Average total costs

The simulation results can be used in order to:

1. Predict future system damage patterns
2. Predict future costs of operating and maintaining the systems
3. Compare competing mitigation strategies
4. Conduct sensitivity analysis

Figure 5 presents the algorithmic structure that was implemented for the one-time simulation. The Monte Carlo simulation feature allows the algorithms to be applied repetitively up to 1000 times while collecting the mean values and the deviances from the mean.

Figure 5: The Algorithm



Conclusions

The results of the research can be applied directly to decisions regarding retrofit of operational water supply systems in seismically active areas so as to support the concept of mitigation. The system effectively serves as a linkage between high level planners and operations level water supply systems responders. The model provides a repeatable and traceable avenue of accountability for decisions regarding water supply system repair and retrofit based upon clearly defined parameters. This model makes two unique contributions: 1) The research's perspective is that of the owner of a critical infrastructure and the results of the modeling will support the strategic decisions required as the infrastructure owner determines how to best deal with the risk of extreme events. 2) The perspective and methodology described in this paper, although demonstrated for water supply systems and earthquake risk, are applicable to other critical infrastructure and other threats including the threat of deliberate sabotage or attack. Methodologically, it integrates the disciplines of emergency management, engineering economy, and engineering towards a time critical problem. The analytical tool combines existing models for earthquake occurrence, ground motion and deformation, pipeline fragility, associated direct and indirect costs due to pipe damage and loss of service, and costs related to routine operation and maintenance. The system delivers life cycle cost specific data pertinent to decisions regarding repair and retrofit of water supply system components on a routine basis or after a catastrophic failure due to natural or man-made hazards in a seismically active region. The tool employs stochastic techniques that provide instant life cycle cost model results over extended time periods in such a way that critical response and recovery decisions can be made in the context of complete overall system life cycle. The integrated model supplies projected life cycle costs associated with competing investment strategies as directed towards system strengthening measures. The integration of the results of several models provide timely decision support for most advantageous return on mitigation investment. The perspective and methodology described in this paper, although demonstrated for water supply systems and earthquake risk, are applicable to other critical infrastructure and other threats including the threat of deliberate sabotage or attack.

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Note

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Author Biography

Irmak Renda-Tanali: Ms. Tanali is a Research Associate at the George Washington University, Institute for Crisis, Disaster, and Risk Management. She has conducted basic and applied research for various organizations in the fields of emergency, disaster and risk management and organizational management since 1998. She has recently served as a principle graduate research associate in the collection and synthesis of human needs data in the aftermath of 1999 Turkey Earthquakes, and in observing and documenting the inter-organizational response to the September 11, 2001 terror attacks (both funded by the National Science Foundation) and in evaluating the United States Army Corps of Engineers' ESF #3 support to the September 11, 2001 disasters at the World Trade Center and Pentagon. She has also collaborated in the development of the *Disaster Time Line* and the *Terrorism Time Line* with Ms. Claire B. Rubin.

Ms. Tanali's past work experience is in the field of engineering design and construction. She was formerly the vice president and project manager of an engineering design and consulting firm in Ankara, Turkey.

Ms. Tanali holds a B.S and an M.S. degree in Civil Engineering and an M.B.A. Her interests include Engineering Economy, Project Management and Disaster and Risk Management. She is a Doctoral Degree Candidate at the Department of Engineering Management and Systems Engineering of The George Washington University. Ms. Tanali is currently working on her Doctoral Dissertation entitled "*Life Cycle Cost Analysis of Water Systems as Critical Lifelines"*.