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VULNERABILITY OF TRANSPORTATION AND WATER SYSTEMS TO SCIENCE HAZARDS

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16. Abstract (Limit: 200 words)

A methodology for quantifying seismic risk to lifeline systems, specifically, water and transportation networks, was developed and demonstrated. The measure of seismic risk was defined as the annual probability exceedance function for system loss, in dollars, where system loss is the sum of repair costs and user losses. User loss was obtained by implementing a network analysis with demand functions established as the economic measure of service benefit. The area under the demand function provided a measure of the loss in user benefits. Procedures from operations research were transferred to a numerical seismic hazard simulation. Some new applications for probabilistic graph theory were developed in the process. Example applications culminated in a water system analysis based upon the Salt Lake City system, and a transportation system analysis of the eastern corridor of Pittsburgh. In all examples studied, user losses were, on the average, of the same order or magnitude as repair costs. In the absence of any specific analysis, the total lifeline loss may be roughly estimated as a doubling of the repair costs themselves.

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Pittsburgh (Pennsylvania) I.J. Oppenheim, /PI
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ABSTRACTS OF THESES

1) Debra Bresko, Seismic Risk Analysis of a Water System, 1980.

2) Kincho Henry Law, Expected Transportation Network Capacity under Seismic Hazard, 1978.

3) Ronald A. Shimizu, Estimating the Loss in Travel Benefits Associated with Transportation System Malperformance, 1978.

One further thesis (Solis) was related to this work, but was not actually supported by Foundation funds:

4) Joseph Solis, Seismic Risk Analysis of the Maximum Flow in a Network, 1980. (No abstract of this thesis is available, because all copies are at the bindery.)

Note: All theses were in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering, at Carnegie-Mellon University.

Abstract

Seismic risk for a water system is defined as the annual probability exceedance function for loss, measured in dollars. Loss is composed of repair costs plus user losses; the latter measure the disbenefit to society resulting from system malperformance. This report deals mainly with the modelling of user losses within a seismic risk analysis.

The modelling of user loss follows from the definition of user demand functions, which defines the benefit provided to users by a commodity. The loss in benefit can be calculated for any earthquake by a network analysis which consists of flow assignment so as to optimize a non-linear objective function.

The modelling of network component damage resulting from an earthquake leads to a determination of the probability of failure of each component, rather than a deterministic statement of link failure or survival. The network is termed a probabilistic graph; the exact solution for expected flow (or benefit) in one earthquake is intractable for large networks. We develop and present an algorithm which calculates upper and lower bounds on expected value of flow and benefit. The basis of this procedure is a minimum cost-maximum flow algorithm, which is widely documented.

The procedure outlined yields losses in a single earthquake. The modelling of the seismic environment is achieved by a discrete simulation of the magnitude and epicenter of earthquakes along a fault line. Ordering of the results by total loss leads to a numerical approximation of the annual probability exceedance function for total loss.

The seismic risk analysis is demonstrated on an example network based on the Salt Lake City water system. The system is modelled with 54 nodes and 75 links, and the analysis cost is modest. For a severe but reasonable estimate of the seismicity of the region, a loss of less than $1.00 per capita per year is obtained, which does not (in itself) justify a major retrofitting program. The repair costs and user losses are of the same magnitude; in the absence of a user loss calculation, it is suggested that doubling the repair cost estimation might provide a rough estimate of total losses.

Law, 1978

ABSTRACT

This report addresses the problem of a transportation system under seismic hazard. Recently, seismic risk analysis has been employed to measure the performance of a lifeline network in terms of accessibility through the network after an earthquake. However, such analyses are not flexible enough to measure the actual post-earthquake behavior of a lifeline, specifically of a transportation system. This study proposes a model which can simulate the actual performance of a transportation system, measured in terms of expected traffic flow. An advantage of such measurement is its readiness for economic analysis.

This report begins the modeling of a transportation system by identifying the existing key components or structures in the system. Upon the occurrence of an earthquake, the damages of components are expressed in terms of capacity reduction, measured in probabilistic terms. The component damages are then transformed into damages of network links. This approach leads to the problem generally known as "Flow in a Probabilistic Graph". The exact solution of a probabilistic graph is very complicated and usually computational infeasible. In this study, methods to estimate the upper and lower bounds on the expected network flow are suggested. In addition, the behaviors of series and parallel subnetworks are examined. An example is given by taking the eastern portion of the Pittsburgh Transportation System as a seismic target area under different earthquake intensities. An economic analysis is also included to evaluate the seismic hazard loss of the transportation system. Finally, the methodologies used in this study are discussed in detail, and recommendations for future studies are suggested.

This study was concerned with the identification of the loss in travel benefits which result from a reduction in capacity of the highway network. A simple methodology, designed for use in initial stages of transportation system malperformance evaluation, was proposed. The use of gross regional product as a surrogate for the consumers' surpluses was postulated so that a regional demand curve for travel could be constructed. In order to predict the new volume and price, a relationship between the percentage reduction in volume and the percentage reduction in capacity was proposed. Although the actual generation of the VR-CR curves is beyond the scope of this study, a general shape of the curve was postulated. Given the new volume of trips in the reduced capacity state, the loss in total net benefits could then be determined by evaluating the appropriate area under the demand curve.

The examples seem to indicate that the methodology has some potential for practical use in lifeline earthquake engineering and in other situations involvinglarge reductions in capacity of the highway network. Furthermore, the examples showed that significant losses can occur as a result of transportation system malperformance. Care should be taken to avoid the tendency to overestimate the reduction in volume of trips and thus, the overestimation of the loss in travel

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LIST OF PUBLICATIONS

NSF Project PFR 75-20977

1. Oppenheim, I.J., "Vulnerability of Transportation and Water System to Seismic Hazard -- Methodology for Hazard Cost Evaluation," ASCE Technical Council on Lifeline Earthquake Engineering Specialty Conference, Los Angeles, August 1977.

2. Britz, K., P. Edelstein and I.J. Oppenheim, "Measurement of Earthquake Performance of Transportation Systems," ASCE Technical Council on Lifeline Earthquake Engineering Conference, Los Angeles, August 1977.

3. Erel, B., G.M. Patelunas, J.E. Niece and I.J. Oppenheim, "Measuring the Earthquake Performance of Urban Water Systems," ASCE Technical Conference on Lifeline Earthquake Engineering, Los Angeles, August 1977.

4. Oppenheim, I.J., "Estimation of Water System Seismic Risk," Preprint 3349, ASCE Convention, Chicago, 1978.

5. Oppenheim, I.J., "Highway Corridor Analysis in Lifeline Engineering," Preprint 3483, ASCE Convention, Boston, 1979.

6. Oppenheim, I.J., "A Simulation of Water System Seismic Risk," ASCE Technical Council Journal, December 1979.

7. Hendrickson, C., I.J. Oppenheim and K. Siddharthan, "User Losses in Earthquake-Damaged Roadway Networks," ASCE Technical Council Journal, August 1980.

8. Oppenheim, I.J., "Lifeline Seismic Risk: Decision Making Under Uncertainty," Proceedings, ASCE Specialty Conference, San Francisco, May 1980.

9. Hendrickson, C., D. Kufert and I.J. Oppenheim, "Water System Network Analysis Under Seismic Hazard," Preprint 80-C2/PVP-62, ASME Conference, San Francisco, August 1980.

10. Carey, M., C. Hendrickson, D. Kufert and I.J. Oppenheim, "Bounds on Expected Flow Through a Probabilistic Graph," submitted to ORSA Fall Meeting, Colorado, November 1980.

11. Fenves, S.J., and K.H. Law, "Expected Flow in a Transportation Network," Proceedings U. S. National Conference on Earthquake Engineering, Stanford, 1979.

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DATA ON SCIENTIFIC COLLABORATORS

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1. Irving J. Oppenheim, Associate Professor of Architecture and Civil Engineering, Carnegie-Mellon University.
2. Steven J. Fenves, University Professor of Civil Engineering.
3. Chris T. Hendrickson, Assistant Professor of Civil Engineering.
4. Robert Anderson, Project Manager, GAI Consultants, Inc.
5. Joseph Vitunic, Project Engineer, GAI Conlsultants, Inc.
6. Robert Taylor, Senior Engineer, GAI Consultants, Inc.
7. Bilgin Erel, Project Engineer, GAI Consultants, Inc.
8. Kenneth I. Britz, Assistant Professor of Architecture, Carnegie-Mellon University.
9. Peter Edelstein, former graudate student, Department of Civil Engineering.
10. Kincho Henry Law, graduate student.
11. Ronald A. Shimizu, former graduate student.
12. Debra Bresko (nee Kufert), graduate student.
13. Krishnaswany Siddharthan, graduate student, School of Urban and Public Affairs.

The following two individuals have collaborated, but were not formally supported by Foundation funding:

14. Malachi Carey, Assistant Professor of Economics, Carnegie-Mellon University.
15. Joseph Solis, former graduate student, Department of Civil Engineering.

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TECHNICAL DESCRIPTION OF PROJECT AND RESULTS

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Project objectives were to develop and demonstrate a methodology for quantifying seismic risk to lifeline systems. The specific cases of water and transportation systems were to be used, as they are the principal responsibility of civil engineers. The basic measure of seismic risk, which is fully rational in probabilistic and economic terms, is the function which gives the annual probability of suffering an earthquake which causes any specified level of system loss to be exceeded. System loss is defined as the dollar quantity composed of 1) repair/replacement costs and 2) user losses. It is the very existence of user losses (sometimes labelled indirect losses) which implies the title of lifeline. Lifelines are urban service systems upon which the inhabitants of a region depend for continual service. Were that service interrupted, various consequences would result. Those consequences could include (for instance) forced evacuation, loss of employment, loss in quality of the environment, and so on. The <u>measurement</u> of user benefit is a practice well-established in other disciplines. From the outset, we proposed to use those measures of benefit as the indicators of system performance, defining user loss as the decrease in system benefit in the post-earthquake state as compared to the steady state.

System loss in any single earthquake is therefore defined as the sum of repair/replacement costs and user losses. In all applications, available damage predictions were used to relate component damage to ground motion intensity. Calculation of repair/replacement costs in any earthquake is therefore a straightforward task. The basic research task was to develop analysis procedures for calculating the (loss of) user benefit in any single earthquake. This was accomplished by using a systems modelling, implementing procedures developed in operations research. A first quantity for such an analysis is the demand function, relating the marginal benefit per unit of commodity to the volume of that commodity delivered to any user or set of users. A network analysis model then determines the equilibrium distribution of the commodity to the group of users. In a damaged water system a hydraulic network must be modelled to yield the flow available to each user (or group of users) in the system. In a damaged transportation system a traffic assignment model must be used to solve (at equilibrium) for the number of travellers between any origin-destination pair. Either of these calculations requires a sophisticated modelling of network performance. The loss in user benefits is obtained directly from the flow totals, after integration over the duration of the repair period. Note that such a procedure yields the user loss in a single earthquake, to be added to the repair/replacement cost in arriving at the total system loss in that one earthquake.

In a seismic risk analysis, we are concerned only with the probability of exceeding any particular loss level, on an annual basis. There are any number of earthquakes (of differing epicentral magnitude and location) which could cause any level of loss. The seismic risk measure must therefore permit an integration over all possible causal earthquakes, specifically over both magnitude and location. Conventional integration procedures, which form the core of all single-site seismic hazard and seismic risk analyses, are not appropriate when dealing with a network for which an even greater mix of earthquakes could yield the same "loss" level. Therefore, a numerical simulation of the earthquake environment was proposed. All possible earthquakes were represented by a finite number (typically 200) of individual earthquakes. Each individual earthquake had a finite annual probability of occurrence, representing earthquakes within a certain narrow magnitude range with an epicenter located narrowly near specific co-ordinates. This numerical procedure was shown to efficiently approximate the "exact" results obtained from explicit integration over all magnitude and location pairs. Having represented the seismic environment by (say) 200 individual earthquakes, it is necessary that the network be analysed in each such event. This yields a list of 200 different loss levels, each with an annual probability of occurrence. By re-ordering the list in descending order, the annual probability exceedance function is easily approximated. This practice requires, however, that the system (network) analysis be sufficiently expedient to be embedded within the seismic hazard simulation, and be repeated, typically, 200 times. In the example problems studied, this was shown to be practical.

Modelling of water or transportation systems by efficient network models is an interesting development or application of existing theories; those steps alone should be of great interest to other researchers or users. However, substantial progress on a research topic within network modelling was achieved. If, in any earthquake, we propose that we cannot specify the survival or failure of any component, but only its probability of survival, the network in question becomes what is known as a probabilistic graph. The general analysis of a probabilistic graph is intractable. Instead, analysts typically use bounds on the quantities of interest. In this research program a number of new capabilities for probabilistic graph analysis were displayed. Most significantly, a totally new lower bound procedure for expected flow was developed. It is noteworthy in that it is designed for problems (such as systems in the aftermath of an earthquake) where component failure probabilities are high; most existing methods have been developed for communications or power networks in which failure probabilities are many orders of magnitude smaller. (Note also that the upper bound procedure is well-established.) In another new use for probabilistic graph theory, both upper and lower bound solutions were applied to the problem of user benefits, which is a much more difficult network measure to obtain than, say, flow. These findings should be of interest to researchers in a number of other fields.

The transportation system analysis was applied to a sample network based upon the eastern corridor of Pittsburgh. The analysis was performed using eastern seismicity estimates, and was then repeated using the higher seismicity typical of western locations. Modelling of transportation system performance is a very challenging analytical task. While the procedure worked perfectly for the system under study, it proved impractical (in terms of computational cost) when applied to a somewhat larger network. As a result, it will be essential that prospective users assemble a skeletal network model responsive to the computational demands that can result.

The water system analysis was applied to a sample system based upon the Salt Lake City water network. In this analysis a rather large model was generated, and computational costs remained very modest. Using this type of model it appears that sizable water system studies could be undertaken.

Results generally showed that user losses (in dollars) were less than repair/replacement costs in minor earthquakes, and surpassed them in major earthquakes. Significantly, when annual expectations were taken (as is appropriate for economic planning purposes, as demonstrated within project activities) the annual expected loss contained components of repair cost and user loss of the same order of magnitude. This suggests that, in the absence of rigorous analysis, the expected system repair costs may be doubled to yield an estimate of total system loss on a yearly average. Note however that there are certain conditions which can alter that balance, and induce user losses much higher than repair/replacement costs. A study of the methodology and examples should familiarize future users with those possible counterexamples.

All project findings have been transferred, as far as possible, into publications. The attached list should serve to refer any reader to material containing a fuller description of the many points referred to in this summary. Users may want to request one report which is unlikely to be published in its full form, and that is the project report by D. Bresko, "Seismic Risk Analysis of a Water System," which describes the analysis of the Salt Lake City based example.

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LIST OF SEMINARS AND OTHER ACTIVITIES

First referring to the publications list, items 1, 2, 3, 4, 5, 8, 9, 10 and 11 were presented to the engineering and research community in public conference sessions. In addition to those talks, numerous occasions were taken to present research objectives and findings in seminar form. Many of these presentation were not made at NSF expense. The full list of seminars or public presentation is as follows:

1. UCEER, Vancouver, 1976.
2. Massachusetts Institute of Technology, 1976.
3. Rensselaer Polytechnic Institute, 1976.
4. Lehigh University, 1977.
5. University of California, Berkeley, 1977.
6. UCEER, Boston, 1978.
7. Utah State Seismic Safety Advisory Council, 1980.
8. University of California, Berkeley, 1980.

The activities of the researchers have also taken on an international interest. Representatives from three major Japanese research groups have visited Carnegie-Mellon University to meet with and correspond with researchers. They are:

1. Dr. H. Kameda, Kyoto University
2. Dr. T. Tazaki, Public Works Research Institute
3. Dr. T. Katayama, University of Tokyo

Another activity appropriate to mention is the ASCE Research Committee, and specifically the Task Committee on Research Needs in Lifeline Earthquake Engineering. The Principal Investigator was the chairman of that Task Committee, and (at ASCE expense) held a workshop at UCLA in September 1978, which culminated in an ASCE report which was then published as follows:

1. Task Committee on Research Needs, I.J. Oppenheim, chm., "Research Needs in Lifeline Earthquake Engineering," Journal of the Technical Councils, ASCE, December, 1979.