Mitigating Risks to Infrastructure Systems Through Natural Hazard Reduction and Design

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ABSTRACT

This paper provides a brief summary of the issues and opportunities associated with the reduction of risks to urban lifeline systems. In this paper, the term lifeline (which is commonly used to define utility and transportation systems) is used interchangeably with infrastructure. The general focus of this paper is on all natural hazards, however, earthquakes are used to illustrate most points. The basic thesis for this paper is that the cost of rebuilding lifeline systems after major natural disasters is becoming prohibitively expensive, even for large federal budgets. As our cities continue to develop and expand geographically, we increase the chance of "direct hits." Therefore, the design of our systems must consider these risks and perhaps more importantly, ways of effectively reducing these risks through land use planning, modification of hazardous site conditions, or increased design and/or retrofit.

INTRODUCTION

Recent disasters have underscored the need to assess the vulnerability of our nation's lifeline systems to natural hazard effects. Current estimates of lifeline damage as a result of the 1994 Northridge earthquake are in excess of $2 billion. While this amount may appear low relative to other types of losses (e.g., damage to buildings), it only reflects those costs associated with the repair of damaged lifeline systems. Other costs which may more accurately reflect the impact of damaged or inoperable systems, such as business losses due to

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lifeline disruption, or fire damage resulting from loss of water supplies, may be several factors higher than these repair costs. Also, it must be recognized that the Northridge earthquake was a moderate-sized event and that the Los Angeles area is capable of generating earthquakes of much larger magnitude. Therefore, the relatively good performance of lifelines in the Northridge earthquake should not promote complacency in acceptable design measures for lifeline systems.

This paper concentrates on five areas relevant to natural hazard reduction for lifeline systems. First, a brief history of lifeline earthquake engineering in the U.S. is presented in order to identify important milestones with regard to lifeline seismic design and construction. Second, a discussion of the nonlinear relationship between earthquake impacts and earthquake size and proximity to urban area is provided. As will be seen, the U.S. has been relatively fortunate to have not experienced a catastrophic earthquake in a highly urban area, at least recently. The question of how U.S. response systems would function if a Kobe type earthquake were to occur here is of particular interest. Third, a discussion of indirect versus direct economic losses associated with the failure and disruption of lifeline systems in earthquakes is presented. As stated earlier, the larger impacts associated with damaged lifeline facilities may depend on how long these critical lifeline systems are out of service. Fourth, we offer several case histories of demonstrating where mitigation has been effective in reducing earthquake losses. An important program in this respect is the CALTRANS bridge retrofit program. The cost-effectiveness of this program is reviewed against the experience of two major earthquakes in California: the 1989 Loma Prieta earthquake in the San Francisco Bay area and the 1994 Northridge earthquake in Los Angeles. Finally, several opportunities for impacting lifeline earthquake engineering design practices are discussed. The paper will show where these opportunities might build on federal initiatives. One important initiative focuses on the adoption of seismic design standards for private and public lifeline systems in the U.S.

BRIEF HISTORY OF LIFELINE EARTHQUAKE ENGINEERING IN THE U.S.

The following chronology provides a brief look at some of the more important milestones related to lifeline earthquake engineering in the U.S. As can be seen, the major impetus to examine seismic design procedures for lifeline facilities really began with the 1971 San Fernando earthquake. Even though there had been prior earthquakes in the U.S. which have highlighted the importance of lifeline systems after major disasters (e.g., 1906 San Francisco earthquake), the San Fernando event was the first earthquake to promulgate changes in design and construction.

Year Milestone

1971 San Fernando Earthquake (M6.4)
Significant damage to all lifeline systems. Start of long-term research program to study the effects of earthquakes on all lifeline systems (mostly National Science Foundation funding). Many changes to lifeline seismic design and construction initiated by this event.

1974 The Technical Council on Lifeline Earthquake Engineering (TCLEE)
TCLEE formed to address general issues regarding the state-of-the-art and practice of lifeline earthquake engineering in the U.S. Since its formation, TCLEE has sponsored four major conferences on lifeline earthquake engineering, endowed the C. Martin Duke Lifeline Earthquake Engineering award, and has published numerous monographs, design guideline documents, and special reports on lifeline earthquake engineering.

1985 Building Seismic Safety Council (BSSC) Lifeline Workshop
As a result of this workshop, an action plan for abating seismic hazards to lifelines was developed. The workshop had recommendations in four areas: public policy, legal and financial strategies; information transfer and dissemination; emergency planning; and scientific and engineering knowledge.

1986 National Center for Earthquake Engineering Research (NCEER)
In order to address socioeconomic issues related to the seismic performance of lifeline systems, the NSF awarded a multi-year contract to the State University of New York in Buffalo to form the NCEER. This center has brought together researchers from many different technical disciplines to focus on multi-dimensional issues (e.g., socioeconomic impacts caused by the disruption of lifeline service).

1989 Loma Prieta Earthquake (M7.1)
Reaffirmed need to assess and improve seismic design and construction procedures for all lifeline facilities. Particular attention given to the performance of highway bridge structures.

1990 Port of Los Angeles (POLA) Seismic Workshop
The purpose of this workshop was to develop a set of guidelines to be used by the port to address seismic design issues in the design and construction of new landfill areas within the port. This workshop reflected the culmination of many months of preparation and meetings among scientists, engineers and policy makers.

1990 Public Law 101-614 (Reauthorization of the National Earthquake Hazards Reduction Program)
Passage of this law required the Director of the Federal Emergency Management Agency (FEMA), in consultation with the National Institute of Standards and Technology (NIST), to submit to Congress a plan for developing and adopting seismic design and construction standards for all lifelines.

1991 Lifeline Standards Workshop
The purpose of this workshop was to (1) obtain comments and suggestions for revising draft plans prepared in response to Public Law 101-614, examining lifeline issues, and (2) obtain priorities for various standard development and research activities.

1991 Workshop sponsored by the National Science Foundation and the National Communications System
This was one of the first workshops to focus on the effects of earthquakes on communication lifeline systems. This workshop was followed by a second meeting in 1992 where different approaches to communication lifeline modeling was discussed.

1994 Northridge Earthquake (M6.7)
Performance of lifelines significantly improved compared to prior earthquakes in this region (e.g., 1971 San Fernando earthquake). However, continued concern over the performance of highway bridges structures.

NONLINEARITY OF EARTHQUAKES

In the U.S., we have been relatively fortunate to have not experienced a major earthquake (M7 or greater) in a highly urbanized area. The closest earthquake to this situation was the January 17, 1994 Northridge event. This earthquake occurred directly beneath the San Fernando Valley, a suburban area of Los Angeles. However, because of the depth and size (M6.7) of the earthquake, damage was generally limited to this area alone. A larger event, particularly one that occurs along one of the blind thrust ramps in the Los Angeles area (e.g., the Elysian Park ramp that is located directly under downtown Los Angeles) would definitely cause an order of magnitude more damage than observed in the January 1994 event.

California has been host to a whole series of moderate and large earthquakes. Table 1 shows a reverse chronological list of earthquakes that have affected California in the last twenty years or so. As is evident from this list, there are three events that dominate the loss picture. These are the 1971 San Fernando, 1989 Loma Prieta, and 1994 Northridge earthquakes. The total economic loss (just repair costs) for all earthquakes since the San Fernando event is about $29 billion (in 1994 dollars). The three earthquakes mentioned previously account for approximately 97% of this total. The total number of deaths and injuries for all earthquakes are 190 and 16,000, respectively.

The response and recovery from these California earthquakes has been quite effective, particularly from the standpoint of lifelines. In most cases, service was restored to affected populations in a matter of days and weeks. For example, as shown in Table 2, the longest restoration associated with a damaged lifeline system (not including transportation systems) in the Northridge earthquake was 12 days (natural gas system). Further, it is clear from Table 2 that the outages which were observed in the Northridge earthquake affected a very small percentage of the serviced population. It is also interesting to note in Table 2 that those lifeline systems that are eligible for federal assistance (LADWP, MWD, L.A. City and CALTRANS) account for about 95% of the total losses in the table. Therefore, restoration of these systems is not just a Los Angeles or California problem, but also a federal problem.

Table 1. Significant California Earthquakes, 1971 to Present

LOCATION	YEAR	MAGNITUDE	DEATHS	INJURIES	DAMAGE[2] ($ MILLION)
Northridge	1994	6.8	57	9,000+	20,000
Big Bear	1992	6.7	-	-	48.5
Landers	1992	7.6	1	402	48.5
Cape Mend	1992	7.1	-	356	51.5
Joshua Tree	1992	6.1	-	10	.04
Sierra Mad	1991	5.8	1	30+	36
Upland	1990	5.5	-	38	11.2

[2] Normalized to 1994 Dollars

LOCATION	YEAR	MAGNITUDE	DEATHS	INJURIES	DAMAGE[3] ($ MILLION)
Loma Priet	1989	7.1	63	3,757	6,500
Imp Co	1987	6.6	-	94	3.2
Whittier	1987	5.9	8	200+	430
Chalfant	1986	6.0	-	-	.5
Oceanside	1986	5.3	1	28	.9
Palm Spr	1986	5.9	-	-	6.6
Morgan H	1984	6.2	-	27	13.2
Coalinga	1983	6.4	-	47	42
Eureka	1980	7.0	-	8	2.7
Owens Val	1980	6.2	-	13	3.0
Livermore	1980	5.5	1	44	17.5
Imp Valley	1979	6.4	-	91	50.6
Gilroy-Hol	1979	5.9	-	16	0.8
Santa Barb	1978	5.7	-	65	13.8
Oroville	1975	5.9	-	-	0
Pt. Mugu	1973	5.9		-	3
San Fern	1971	6.4	58	2,000	1,766
TOTAL			190	16,226	29,049.54

In a large event in an urbanized area, the response and recovery efforts may increase by many times. Unfortunately (or maybe fortunately), we don't know how response and recovery systems will respond when demand for resources greatly exceeds available capacity, because we have not experienced a catastrophic event in the U.S. in recent times. In order to understand the resiliency of these systems, we need to learn from foreign earthquakes.

The earthquake which occurred in Japan exactly one year after the Northridge earthquake probably represents the closest example available of a "nonlinear" earthquake. Nonlinear earthquakes are defined as events where the demand for resources greatly exceeds available capacity. Because manpower and repair resources will be overextended, restoration times will be stretched and delayed. Resources will eventually have to come from areas very distant from the affected areas. In addition, damage to local and regional transportation systems may also add an additional dimension to response times.

Table 2. Lifeline Performance During the January 17, 1994 Northridge Earthquake (Preliminary Data)

LIFELINE	POPULATION W/O SERVICE	RESTORATION TIME	DAMAGE ($Million)
LADWP (Power)	100%	90% in 1 day	136
SoCal Edison	25%	99.9% in 1 day	0.5
LADWP (Water)	~15%	8 days	44
MWD	-	-	5

[3] Normalized to 1994 Dollars

LIFELINE	POPULATION W/O SERVICE	RESTORATION TIME	DAMAGE ($Million)
LA City (Sewer)	-	-	36
SoCal Gas	3%	12 days	60
PacBell	8 communities	-	26
GTE	<1%	-	3.5
CALTRANS	-	-	1,450
TOTAL			1,761

In order to demonstrate this point, Table 3 and Figure 1 are presented. Table 3 shows an illustrative regional earthquake damage index. This index is nothing more than a qualitative attempt to describe the risk a particular region or area may have given certain geographical and earthquake parameters. For example, within this context, it is assumed that risk or subsequent post-earthquake damage can be describe by two parameters: earthquake magnitude, and proximity to urbanized region. The underlying theory here is that significant damage or risk only occurs when unfavorable values of each parameter occur at the same time. That is, risk is high if the earthquake, whether large or moderate, occurs in a densely populated area.

In order to provide some quantitative scale to these indices, a simple and somewhat arbitrary set of descriptions are provided for each range of damage indices. In effect, what is being suggested here are the results of a general or crude seismic risk analysis.

Table 3. Regional Earthquake Damage Index

PROXIMITY TO URBANIZED REGION	MAGNITUDE RANGE				
	<5	5 to 6	6 to 7	7 to 8	>8
Remote	0	1	3	5	7
Close	2	4	6	8	9
Direct Hit	2	5	7	9	10

0 - No Impact
1-3 - Newsworthy, Minor Regional Damage
4-6 - Front Page News; Moderate Regional Damage
7-8 - Newsweek; Major Damage
9-10 - "Nightline"; Catastrophic Damage

Figure 1 shows a plot of repair costs per customer for various earthquakes, including the recent Northridge and Kobe events. The repair costs are associated with damaged electric power systems and represent very coarse estimates at best. Therefore, the figure is more illustrative than scientific.

To illustrate this concept of nonlinearity, data from different earthquakes have been plotted in Figure 1. The following represents the author's opinion of damage index levels for the various earthquakes:

Earthquake	Magnitude	Proximity to Urbanized Region	Repair Cost ($) per Customer	Damage Index
1971 San Fernando (SF)	6.4	Direct Hit	$30	7
1986 Palm Springs (PS)	5.9	Remote	$1	1
1989 Loma Prieta (LP)	7.1	Remote	$7	5
1994 Northridge (NOR)	6.7	Direct Hit	$100	7
1995 Kobe (KOBE)	~7	Direct Hit	$1500	9

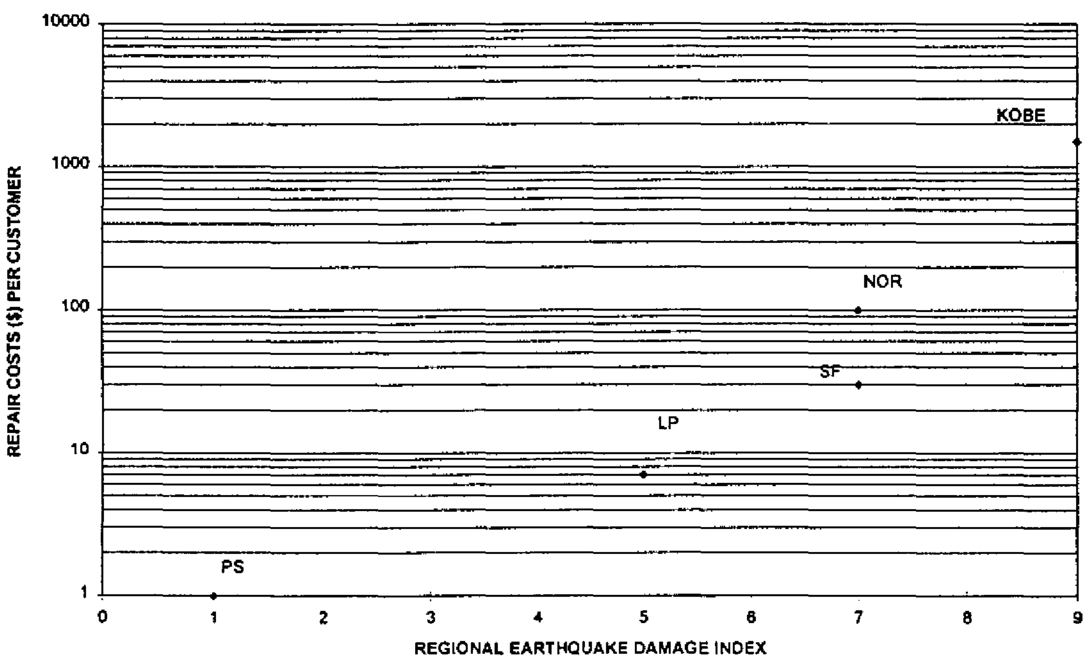

Figure 1. Repair Costs ($) per Customer for Several Recent Earthquakes - Electric Power Systems

Figure 1 shows that there is a tendency for these normalized repair costs to increase in a nonlinear fashion with the simplified damage index. All of the U.S. events are well below the Kobe earthquake, both in terms of normalized repair cost and index. Therefore, perhaps the Kobe event may suggest where the trend may end up if we were to experience a major earthquake (M7 event or higher) in a highly urbanized area of the U.S. Obviously, a more thorough analysis of this nonlinear effect should be conducted using actual and more detailed data on each of the earthquakes. However, it is hoped that this simple illustration points out the need to examine lifeline damage and restoration issues for large urban earthquakes.

INDIRECT ECONOMIC LOSSES

The failure of lifeline systems in natural disasters can be devastating, hampering both response and recovery. Recent events, such as the 1994 Northridge and 1995 Kobe earthquakes, have demonstrated that indirect impacts associated with the failure of lifeline systems may far outweigh the direct costs associated with system repair. As a result, the problem of quantifying possible indirect losses is currently receiving increased attention.

Table 4 shows a comparison of direct and indirect losses caused by damage to oil supply pipelines in the New Madrid Seismic Zone (NMSZ). As part of a National Center for Earthquake Engineering Research (NCEER) project on the New Madrid Seismic Zone, EQE International performed several analyses to estimate the effects to local and regional economies from a disruption of oil supply in a M8+ NMSZ earthquake.

Table 4. Comparison of Direct and Indirect Losses Caused by Damage to Oil Supply Pipelines in the New Madrid Seismic Zone (Eguchi et al., 1993)

LOSS TYPE	AMOUNT ($MIL)	% OF TOTAL LOSS	RATIO TO DIRECT LOSS
Repair Costs	75	2.3	1.0
Environmental	310	9.6	4.1
Refinery/Petroleum Industry	720	22.1	9.6
Local/Regional Economy	2,147	66.0	28.6
Total	3,252	100.0	-

The basic conclusion from this study was that repair costs are but a fraction of the total loss associated with the failure and disruption of these oil pipeline systems. In Table 4, repair costs account for approximately 2.3 percent of the losses contained in the table. The largest loss will probably be associated with local and regional economies that will suffer because of a disruption of oil supply. Contingency factors such as alternative supplies, however, have not been factored into the analysis. Nevertheless, disruption of oil supply will have a significant regional impact in the postulated NMSZ event.

COST-EFFECTIVE MITIGATION STRATEGIES

With the recent wave of natural disasters in the U.S., it is becoming imperative that repair programs and strategies include mitigation elements. That is, we, as a nation, should attempt to improve the resistance of our lifeline structures to natural hazard effects at every opportunity possible. It has been shown in many examples that damage to structures or systems can be reduced if prudent planning is implemented.

One of the best examples of cost-effective mitigation measures is the CALTRANS program which was started immediately after the 1971 San Fernando earthquake. In a recent report entitled "The Continuing Challenge: The Northridge Earthquake of January 17, 1995," which was prepared for the California Department of Transportation by a Seismic Advisory Board formed by the Governor of California, a summary of the CALTRANS seismic retrofit program is presented. Two of the major conclusions of the report were (1) "All structures in the region of strong shaking [in the Northridge area] that were retrofitted since 1989 performed adequately ...", and (2) "The Board's conclusion is that if the seven collapsed bridges had been retrofitted, they would have survived the [Northridge] earthquake with little damage."

The cost-effectiveness of the retrofit program is further justified by the data contained in one of the tables of the report. This table, which is reproduced here, states that the total estimated cost of retrofit, by category of structure, for all seismically-vulnerable bridges is about $2.4 billion. This total should be compared to the estimated cost of repair to CALTRANS bridge structures that were damaged as a result of the Northridge earthquake ($1.5 billion). If the conclusions of the CALTRANS report are valid, repair costs during Northridge could have been eliminated, or at least greatly reduced, if that money had been spent to complete the retrofit program. This is one solid example of where mitigation activities are cost-effective. Other examples for other lifeline systems also exist.

Table 5. The Caltrans Bridge Retrofit Program Status as of June 1, 1994 (Caltrans, 1994)

CATEGORY OF STRUCTURE	ESTIMATED TOTAL COST ($ MILLION)	CONSTRUCTION COMPLETE	CONSTRUCTION UNDERWAY	REMAINING
Single Col. Retrofit	$120	87%	13%	0%
Multiple Col. Retrofit	$1,650	2%	7%	91%
Toll Bridge Retrofits	$650	0%	0%	100%
Total	$2,420			

FEDERAL AND INDUSTRY LIFELINE INITIATIVES

The federal government has historically played a major role in facilitating research and seismic evaluation programs for lifelines. With the reauthorization of the National Earthquake Hazards Reduction Program, Congress mandated that the Federal Emergency Management Agency (FEMA), in consultation with National Institute of Standards and Technology (NIST), develop a plan for assembling and adopting national seismic design standards for all lifelines, public and private. This plan has been developed and will be released before the end of 1995. Important in this plan is the recommendation that public and private partnerships be developed in order to effect implementation. As key elements of the plan, several pilot projects will be conducted to demonstrate the cost-effectiveness of various mitigation strategies. Overall, this plan will be consistent with FEMA's new initiative for an improved hazard mitigation strategy.

CONCLUSIONS

Several major conclusions are drawn from this qualitative look at lifeline engineering and the mitigation of risks to lifelines from natural hazards.

1. Lifelines have been shown to be extremely vulnerable to certain natural hazards and failure of these systems can result in significant direct and indirect loss.
2. Numerous milestones have observed which describe the progress of lifeline earthquake engineering in the U.S., all of which begin essentially with the 1971 San Fernando Earthquake.
3. In the U.S., we have been relatively fortunate in that recent damaging earthquakes have been moderate in size and/or have not occurred in highly urban areas. By using the Kobe earthquake as a guide for how restoration may be affected by inadequate resources, we may investigate the "nonlinear" effects of earthquakes.
4. Consideration of the indirect losses that may result from the failure or disruption of a lifeline service may add many times to the loss associated with the repair of a damaged system.
5. Mitigation of future risks through cost-effective retrofit or design strategies has been shown to be effective, as demonstrated by the performance of CALTRANS facilities during the 1994 Northridge earthquake.
6. One important initiative that is being administered by FEMA and NIST has the potential for improving significantly the earthquake performance of lifelines in future events. This initiative calls for the development and adoption of seismic design standards for all public and private lifelines.

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