NSF/RA-770689

PB 288288

FINAL REPORT

National Science Foundation RANN Program

SEISMIC SAFETY OF ELECTRIC POWER EQUIPMENT

NSF Grant ATA73-07942 A03
(Formerly GI-39428)

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June 1977

50272-101

REPORT DOCUMENTATION PAGE	1. REPORT NO. NSF/RA-770689	2.	3. Recipient's Accession No. PB288288

4. Title and Subtitle
Seismic Safety of Electric Power Equipment, Final Report

5. Report Date
June 1977

6.

7. Author(s)
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8. Performing Organization Rept. No

9. Performing Organization Name and Address
Purdue University
School of Mechanical Engineering
West Lafayette, Indiana 47907

10. Project/Task/Work Unit No

11. Contract(C) or Grant(G) No
(C) ATA7307942 A03
(G) GI 39428

12. Sponsoring Organization Name and Address
Applied Science and Research Applications (ASRA)
National Science Foundation
1800 G Street, N.W.
Washington, DC 20550

13. Type of Report & Period Covered
Final

14.

15. Supplementary Notes

16. Abstract (Limit: 200 words)

This report summarizes a two year effort to develop a methodology for the evaluation of seismic reliability of electric power equipment. It reviews the goals of research, discusses major accomplishments, and gives recommendations growing out of the research. A plan based on the objectives of the proposed research was divided into three parts. The first involves an effort to evaluate the effect of different levels of severity of unified equipment specifications on initial costs and extent of probable power disruptions. The second deals with developing methods and procedures for proof and field testing electrical equipment, and the third involves investigating the quantity and location of equipment which can serve as backup reserve for a region in the event of a catastrophic disaster. Technical reports describing the different phases of the work are included in the appendices. These include information on the impact of the study and a brief summary of sixteen papers and ten reports resulting from the research.

17. Document Analysis a. Descriptors

Electric power plants
Earth movements
Electric power transmission
Electric power failures
Earthquake resistant structures
Seismic waves
Electric equipment
Stresses
Electrical faults

b. Identifiers/Open-Ended Terms

c. COSATI Field/Group

18. Availability Statement
NTIS

19. Security Class (This Report)

20. Security Class (This Page)

21. No. of Pages
29

22. Price
PC A03 / MF A01

(See ANSI-Z39.18) See Instructions on Reverse OPTIONAL FORM 272 (4-77) (Formerly NTIS-35) Department of Commerce

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INTRODUCTION

The following report summarizes the results of a two-year effort to develop a methodology for the evaluation of the seismic reliability of electric power equipment. The body of the report reviews the goals of the research, lists and discusses the major accomplishments of the research, and gives recommendations growing out of the research.

The appendices contain technical reports describing in detail the different phases of the work. Appendix A provides information on the impact of the study following the outline suggested in a request for information by Dr. Thiel dated December 11, 1975. Appendix B lists and briefly summarizes the sixteen papers and ten reports generated or in the process of being generated in the course of the research and indicates the distribution of each.

While this report is designated as the final report, it should be emphasized that the simulation -- the tool from which the response of the power system can be evaluated -- is still being used to generate results which are being analyzed in conjunction with the utilities. The results of this effort, which are part of two Ph.D. theses, will be submitted to the National Science Foundation upon completion of the work.

While it is impossible to credit all of the individuals and organizations which have contributed to the project, those making major contributions are gratefully acknowledged and noted.

Professor Ahmad H. El-Abiad of the School of Electrical Engineering, and Professor James T. P. Yao of the School of Civil Engineering were faculty associates on the project and contributed their valuable expertise to many aspects of project formulation and implementation throughout the course of the research. The value of the contributions of the many students who worked on the project and greatly contributed to its success cannot be overstated. In particular, the efforts of Peter Feil, Raymond Fink, Tom Fuhrman, Gregory Guthrie, Chung Ho, Donald Newsom, James Sprandel, and Rafael Torres-Cabrejos are acknowledged. In addition, the editorial assistance of Jeanne Plumb and Kathy Mapes in preparing the numerous surveys, questionnaires, and papers is acknowledged.
The assistance provided by the following utilities is also gratefully acknowledged: Bonneville Power Administration, Los Angeles Department of Water and Power, Pacific Gas and Electric Company, Public Service of Indiana, and Southern California Edison. In particular, I would like to express my appreciation to Mr. Raymond Bunten of Pacific Gas and Electric Company for his advice and his patience in working with members of the Purdue team. I would also like to thank Mr. Don Rodgers for his thoroughness and attention to detail in gathering the extensive data needed to describe the utility system.

It should be noted that many aspects of the research are not reflected in the contents of this report -- for example, the time and effort required to establish rapport with the participating utilities. The utilities exercised great caution in releasing information describing the detailed workings of their power systems, a prudent measure in light of the need for system security. A great deal of effort was also required to grasp the salient characteristics of a large operating utility so as to model it in a reasonable fashion. The complexities are not typical of those encountered in an academic environment.

GOALS OF THE RESEARCH

The "Abstract of Proposed Research" contained in the proposal is repeated below.

"The objective of the proposed research is to establish a unified and rational procedure for establishing earthquake-resistant design specifications, methods of analysis and testing to ensure a proper balance between the security of electrical power equipment and total cost. The research will consist of three parts. The first part will evaluate the effect of different levels of severity of unified equipment specifications on initial costs and extent of probable power disruptions. One aspect of uniform specification is that the majority of the equipment will be overdesigned. The cost of overdesign may be nominal for some equipment and significant for others. Thus, equipment should be classified as to whether it falls under the unified specifications or it should be designed to meet local requirements. The second part of the research will deal with developing methods and procedures for proof and field testing electrical equipment. The third part of the research will investigate the type, quantity and location of equipment which can serve as backup reserve for a region in the event of catastrophic disaster."

An introductory paragraph of the "Proposed Research" states "because the need for a realistic and implementable approach is deemed necessary, only an outline of the proposed research procedure can be given at this time. The detailed formulation must be done in conjunction with the power system people and consultants. Indeed, even the general outlines described here might have to be modified as the problem definitions and research evolve."

The evolution of each of three parts of the research originally proposed is now briefly discussed.

The first objective, "evaluate the effect of different levels of severity of unified equipment specifications on initial costs and the extent of probable power disruption," has been approached with a slightly different emphasis from what was originally conceived. The change in emphasis involved eliminating the evaluation of cost trade-offs for different seismic specifications. This type of information was not available to the research team, and indeed, is not even available to the utilities for use in their decision process for establishing seismic specifications. This is commented upon later in the report. The major objective of developing a methodology for evaluating the effects on system performance of changes in seismic specifications has been achieved, although by a different method than originally suggested.

Originally, it was suggested that a decision theory failure tree approach would be adopted. There were several major reasons for abandoning this approach in favor of the simulation which was used. First, it became apparent that the evaluation of system performance depended on the location within the system of the lines and equipment which are damaged. Just the knowledge of the probability of failure of certain facilities was not adequate. The relative importance of different facilities depends on how the system is configured, which, due to planned redundancy and flexibility, could take quite varied forms for a given system. The evaluation had to reflect performance of specific types of equipment, not just its generic form. Fourth, the system response could be strongly dependent on the location of the earthquake's release of energy relative to the power system. Thus, the methodology would have to evaluate system behavior relative to each of a series of earthquakes. Finally, the realistic evaluation of performance had to reflect the duration of disruption as well as its extent.

The second research objective, "Develop methods and procedures for proof and field testing electrical equipment," has been approached as originally conceived and expanded upon. That is, a transportable computer-based vibration testing system was to be developed to meet the following objectives as re-stated from the research proposal.

1) To supplement and extend existing methods of testing and data analysis to gather information to construct and evaluate models of the effects of vibration on electrical equipment.

2) To develop systematic and economical methods for proof testing field installations so as to reduce the cost of testing and thus justify their use as standard practice.

3) To assist the power companies in developing an "in-house" expertise in testing power equipment.

4) To investigate and make recommendations for areas requiring basic research with emphasis on methods for modeling porcelain.

The effort on the last item listed above has been greatly expanded. The difficulty in obtaining fragility data for power system equipment and the importance of the failure of porcelain members in evaluating equipment fragility suggested that research to evaluate the dynamic response of porcelain should be pursued rather than just recommended.

The third research objective, "investigate the types, quantity and location of equipment which can serve as backup reserve for a region in the event of catastrophic disaster," has been de-emphasized. In later discussions with the utilities it was learned that spares must be distributed throughout the system to maintain normal operation needs. Thus the redistribution of spares for the earthquake problem was an unrealistic option.

ACCOMPLISHMENTS OF THE RESEARCH

The following list of accomplishments has been grouped into three categories, one for each of the major research goals. It should be noted that for some items, it is ambiguous as to which category is appropriate, as much of the research is highly interrelated. Letters corresponding to appendices which relate to each goal are given in parentheses after each section.

Developing a Methodology for Evaluating the Effects of Earthquakes on System Response

The development and implementation of a method to evaluate the effects of earthquakes on power systems has required that many tasks not previously attempted be done and the work of others be adapted to make it useful to the present application. Some of the accomplishments listed below relate to parts of the simulation while others relate to the gathering of information or developing of methods to get data required for the simulation.

1. A methodology has been developed and implemented to evaluate the effects of earthquakes on electric power systems using digital simulation methods. In the methodology, an earthquake is represented by multiple point sources along that part of the fault which releases energy. Laws of ground motion attenuation, and amplification introduced by soil layers, support structures and electrical equipment itself are used to determine the levels of vibration the equipment experiences. The levels of vibration are

translated into probabilities of failure via fragility curves. Specific items of equipment are determined to have failed, consistently with their probabilities of failure. The power system is reconfigured, utilizing inherent system redundancy, to optimize delivery of power. The post-earthquake recovery process is modeled to the time at which the system is substantially recovered. Information provided by the simulation includes measures of the efficiency of recovery strategies, the extent and duration of customer disruption, and statistics on equipment damage. To bring the simulation to fruition, several major developments were required, some of which are described below. (C, L, N, O, R, Y)

2. Earthquakes have been modeled in a manner suited to the computational speed and level of accuracy required by the simulation. Spectra for a site are provided which take into consideration its distance from and position along the fault. Energy release is attributed to several point sources along the fault, rather than to a single epicenter. It should be noted that the fault need not be in a straight line. The distance from the fault is used, rather than from the epicenter (as is typically used); this is important for modeling close to the fault, as is often required on the West Coast. (I, Y)
3. Modeling of earthquake effects has incorporated the amplification due to soil layers and equipment support structures in determining excitations to which equipment is to be subjected. (I, Q, T, Y)

4. Equipment damage throughout the system has been represented as the failure of specific items of equipment. The levels of vibration which each piece of equipment experiences are computed. Through the use of fragility curves with these levels of vibration, the probability of failure associated with each mode of failure is determined. The status of each piece of equipment is determined consistent with its probabilities of failure. The modes in which equipment fails are identified so that failure may be related to the manpower, support equipment, and spare parts required to effect repair. (G, I, Q, T, Y)
5. A format for encoding power system facilities has been developed. This format allows the system to be accurately described by a relatively small number of modules. (A system having equipment at 206 sites was coded into 1317 modules of which 445 were transmission lines.) Each module is a group of equipment which performs a well-defined function on the system level. This characteristic of the format not only simplfied the task of encoding the system, but also provided the system with a structure that enabled rapid analysis in the post-earthquake reconfiguration of the system. (Z)
6. A method for local reconfiguration of a power system after extensive earthquake damage has been developed. It should be noted that while many utilities across the country have computer-controlled dispatching (allocation of generation to minimize cost or pollution with a given system configuration), none have a means for computer reconfiguration of the system.

The reconfiguration involved determining possible configurations at each site, using the functioning equipment efficiently, and recording the new configuration and any options which might be exercised later during the global rerouting. (Z)

7. A method for global rerouting of power in a severely damaged system has been developed. The rerouting involved selecting which equipment should be connected at each module where there are failed circuit breakers. Generation is then allocated and the system is partitioned in order to eliminate overloads and to force full loading of lines and transformers in critical areas. Overloads which cannot be solved by this method are eliminated by reduction of the load in the critical area. (Z)

8. The post-earthquake recovery process has been modeled, incorporating strategies for the allocation of manpower, support equipment, and spare parts. The efficiency of various strategies is measured by the time required to restore the system to comparable overall levels of service. Statistics are also gathered on the number and duration of customer outages, and on the levels of service customers receive. (L, Y)

9. A survey (Delphi study) was conducted to have experts assess the vulnerability to earthquake damage and potential for improved earthquake resistance of several elements of power systems, and evaluate measures for mitigating earthquake damage. (M, U)

10. A detailed study of available data on loads just prior to and following the San Fernando earthquake of February 9,

1971, was conducted to ascertain the reduction in power demand following the earthquake and the rate of its recovery to pre-earthquake levels. (N)

11. An extensive literature survey was conducted to determine equipment fragility. In addition, a questionnaire was mailed to utilities, manufacturers, and consultants (74 individuals) to get definitive fragility data. An extensive bibliography was also developed. (Q, W)

Improving Methods for Analysis and Field Vibration Testing of Power System Equipment

12. Field tests have been conducted to evaluate system software and hardware for semi-automated vibration testing of substation equipment. Testing, which was carried out in the Midwest, raised the awareness of one utility to the earthquake problem. (H, X)

13. A specialized finite element program has been developed for the analysis of substation facilities. This program is a modified and simplified version of SAP IV which is more suitable to the intended use. The program facilitates the design of substation structures so as to account for equipment resonances -- a procedure not generally used, even in high seismic risk areas. Requests for this program have been received from some utilities. (AA)

14. A method has been developed to analyze porcelain elements used as structural members. The method enables the probability

of failure to be determined for porcelain members subjected to earthquake excitations. A simplified design procedure using the above method of analysis is being developed. (AA)

15. The application of items 13 and 14 above have enabled fragility data to be obtained for some power system equipment which was not otherwise available. (Q)

<u>Recommendations for the Quantity and Location of Spares and Emergency Standby Equipment</u>

16. The evaluation of the response of power systems to date has not identified the need for emergency standby equipment. A situation in which a power system had regions in which bulk power was predominantly carried by underground high voltage transmission lines may find emergency standby generators of some value. This situation does not exist for the system which was modeled. (Y)

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations are based on the work carried out over the course of the research. While many individuals have contributed to this effort, the views expressed here are those of the author and should not imply that those contributing to the study approve or agree with them. A draft of this report has been distributed to those utilities which have contributed to the project for their review and comment. They have also been given the opportunity to include in the report comments relative to the conclusions and recommendations, but have not submitted comments for inclusion.

The following material is organized into four groups of related conclusions and recommendations. The letters in parentheses at the end of each paragraph are references to the papers or reports in the appendices from which the conclusion or recommendation is most closely drawn. Additional, more detailed, conclusions and recommendations are contained in the individual reports. Some of the comments, however, are based on discussions conducted over the course of the study and are not contained in any of the reports or papers.

Mitigating the Effects of Earthquakes on Electric Power Systems (Delphi Study)

Expert opinion obtained in the Delphi study identified and ranked eight measures for mitigating earthquakes effects on electric power systems. In order of importance they were 1) establish seismic criteria for facilities, 2) establish seismic specifications for equipment, 3) use seismic risk analysis for site selection, 4) have qualified field inspection during construction and installation, 5) perform dynamic analysis in equipment and facility design, 6) improve quality assurance by suppliers, 7) use cost-benefit methods in establishing specifications, and 8) perform low-level field vibration testing. While some of the measures have been partially instituted by some of the West Coast utilities, almost nothing has been done outside of the West Coast to mitigate earthquake effects on other than nuclear power generation facilities. (M,U)

A comparison between the ranking of the importance of earthquake mitigation measures and their cost-effectiveness obtained in the Delphi study indicated that the determination of cost-effectiveness is a vital element in the determination of their importance. This points to the need for the availability of information on incremental costs to decision-makers. For most power system equipment, this information is not supplied by equipment manufacturers. (M,U)

Participants in the Delphi study overwhelmingly favored that designs and facility inspection be "certified," where "certified" is interpreted to mean reviewed by an individual qualified in earthquake-resistant design. By and large, this has not been formally adopted, even on the West Coast. This raises the problem of finding and identifying an individual with the required expertise. The multi-disciplinary character of earthquake engineering means that none of the classical engineering professional groups is totally qualified, a structural engineer's training probably being the most appropriate. This problem has been raised with the Earthquake Engineering Research Institute. (M,U)

Recommendation:

Means should be sought for stimulating action to implement cost-effective measures to improve earthquake resistance in areas which have low seismic awareness.

Recommendation:

Information on incremental costs for providing improved earthquake resistance should be provided to decision-makers.

Recommendation:

It is suggested that some means be found for identifying individuals (similar to being registered as a professional structural engineer in California) who are competent in the various phases of earthquake engineering expertise so that organizations seeking expertise in one of these areas can have a means for judging an individual's training and/or experience.

Data Related to the Simulation

There is a need for better reporting of the effects of earthquakes on power systems, both within the United States and for overseas earthquakes. While Earthquake Engineering Research Institute and the National Academy of Engineering oversee earthquake damage assessment activities, reports on lifeline damage (and power systems, in particular) are often much more sketchy than reports on structural damage. Also, the information is often published in civil engineering-related journals, rather than those journals which would be more likely to be read by utility industry personnel. While the United States utilities have sent observers to sites of destructive earthquakes, their findings are often not widely distributed. There is also a need for fuller disclosure of United States earthquake damage.

The extensive effort made to obtain information about the fragility of electric power system equipment through contact with the manufacturers, utilities, and consultants who work on such matters produced relatively little information. While fragility is an important element in the study of power system response, deficiencies in this data have far broader implications. The present system of setting seismic specifications for equipment should be based on the principle of cost-effectiveness. If the incremental cost for different earthquake resistance is not known, this principle cannot be utilized. (Q,W)

While information on fragility and equipment failure modes is difficult and costly to obtain, the information which is known is, by and large, kept confidential by the equipment manufacturers. It should be noted that the utilities have instituted some self-imposed restraints in circulating information on dynamic equipment response developed in their own research programs out of the concern that the working relationship with the equipment manufacturers, such as it is, would be adversely affected by such disclosures. The situation suggests that a utility industry trade association which could gather and disseminate information might help improve the utilities' ability to rationally set equipment specifications using cost-effective methods. Contacts with Electric Power Research Institute and Energy Research Development Administration have not been able to stimulate any interest in this aspect of the problem or the earthquake hazard in general. It would appear that the earthquake problem (other than for nuclear facilities) does not appear on either organization's list of priorities. EPRI, a nonprofit corporation funded by member utilities to address the research needs of the industry, has not and does not plan to address earthquake-related problems (other than those related to nuclear generating facilities). A query of the utilities indicated that procedures for requesting EPRI action were generally not known and that the utilities have not requested EPRI to address earthquake problems as they relate to transmission and distribution facilities. (Q,W)

Recommendation:

It is recommended that an appropriate communication media be established for distributing the results of earthquake damage studies. It is hoped that the activities of the Technical Council on Lifeline Earthquake Engineering will address this deficiency.

Recommendation:

It is suggested that the site and the type of support structure for each piece of damaged equipment be recorded, as well as the amounts and the specific types of damage suffered by each type of equipment. This information could then be made available to utilities, manufacturers and the research community for analysis to improve equipment response.

Recommendation:

It is recommended that the date of the manufacture and the name of the manufacturer be identified for all equipment which is damaged and that accessibility of this information to the industry be required, possibly by filing with the state utility commission.

Recommendation:

It is suggested that a national -- or at least regional -- utility industry-based organization address the earthquake-related research needs of the utility industry.

Recommendation:

It is suggested that procedures be developed for technical staffs of utilities to communicate their research needs to Electric Power Research Institute. In addition, a means should be developed for determining the responsiveness of EPRI in meeting the utilities' research needs.

Following the San Fernando earthquake, there occurred a much larger reduction in power demand and a longer period for recovery than originally anticipated by utility personnel. Power demand in some areas (disregarding the large dropping of load immediately after the earthquake due to the action of sudden pressure relays in transformers) was typically reduced to 55% of pre-earthquake levels in the damaged areas, and the recovery extended over a two-week period. This data was obtained from the San Fernando Valley earthquake for areas which were primarily residential for a limited number of reporting stations. (N)

Recommendation:

> It is recommended that in future earthquakes the extent and duration of reduced power demand be observed, noted, and made available to the technical community.

The study area covered by this research is one of the most intensely studied areas from an engineering seismology point of view. Notwithstanding this, information such as depth to bedrock is often not known. Many of the areas for which there is data have been studied in such detail that much of the data is not of engineering value, although such detailed study may be of value to those outside the engineering community. Thus, there is a need for basic engineering seismology information for major cities in high seismic risk areas. (I)

Recommendation:

> It is suggested that a better balance, from the engineering point of view, be achieved between the highly detailed engineering seismology data obtained in some areas and the lack of basic data in equally important areas.

The present simulation of the response of power systems to earthquakes has considered the effects of the interaction with other lifeline systems in a very rudimentary way, or not at all. Restoration of power facilities will require the transportation of heavy equipment within the service area. The present simulation has dealt with this problem using very rough approximations. While utilities have extensive communication systems which are independent of telephone systems, the response of these systems and the effects of their malfunction have not been included in the present study. The experience from the Managua earthquake indicates that a failure in communications can affect system performance. (L)

The simulation methodology can be applied to other lifelines with some modification. One lifeline with particular potential for such application is transportation, since the links in this network are individually of such importance that the operational status of specific links should be evaluated in order to evaluate system response.

Recommendation:

It is suggested that the response of other lifeline systems to specific events, as opposed to a probability of failure associated with earthquakes, be evaluated.

Substation Design Related to Mitigating Earthquake Effects

While the major California utilities have institutionalized measures to improve earthquake response of new facilities by adopting seismic specifications for their facilities and equipment, the situation outside of California leaves much to be desired. Most utilities in the Northwest, while aware of the earthquake problem, have not been active in mitigating hazards. Awareness of the problem outside of the West Coast is very low. While the Institute of Electrical and Electronics Engineers is preparing guidelines for seismic specifications for substations, the impact of such measures outside of high awareness areas is likely to be negligible, since the motivation and expertise to effectively act upon the guidelines is lacking. It should be noted that it is only in the post-San Fernando period that the California utilities have developed a capability and motivation to perform dynamic analyses on substation facilities, and even here, the treatment is quite uneven across the utilities. The long return period for major earthquakes outside of the West Coast makes it difficult to justify the expense needed to develop the required expertise in earthquake resistant design.

Recommendation:

It is recommended that a set of specific measures to improve the resistance of facilities to earthquakes be formulated with ample documentation to demonstrate their cost-effectiveness. Clearly, such measures would have to be low-cost if they were to be adopted in the Midwest and other areas for which there is appreciable seismic risk although return period may be long. Fortunately, many such measures can be instituted to significantly reduce earthquake damage.

Recommendation:

It is recommended that there be a directed effort to raise the awareness and inform utilities in low earthquake-awareness areas of measures which can improve the earthquake resistance of their systems, workshops probably being the most appropriate means.

Available information on the dynamics of substation structures and equipment is often not utilized in system design. The similarity of substation facilities for different utilities, both in function and form, and the similarity of service loads, both electrical and mechanical, for many regions of the country suggests that a standardization of design would enable problems such as earthquake resistance of structures to be more economically and effectively implemented.

Recommendation:

It is suggested that the feasibility of establishing standardized substation structures, at least on a regional basis, be investigated.

Initial results from the simulation of a "typical" utility system indicate that for large earthquakes (Magnitude 7) service is restored within 3 days. For very large earthquakes (Magnitude 8.3) some customers were without service for as much as a week. It is expected that the above results could vary from system to system. (Y)

Recommendation:

It is recommended that the methodology be used by utilities in seismically active areas to evaluate their system and provide a means for improving its response.

Problems Needing Further Attention

While the completion of the theses work will see the methodology described and the simulation tuned and executed to evaluate system performance, the model will not have had extensive use so as to gain as much information as possible from the effort already expended. (Y,Z)

Recommendation:

> The simulation should be further used to gain as much information as can reasonably be obtained and analyzing results from the simulation in conjunction with utility personnel rather than implementing major changes in the methodology.

In the course of the research, it was observed that the technical staffs of the utilities are generally in favor of more attention to earthquake resistant design and feel that their perceptions are not shared by the decision-makers. It is not apparent whether correct decisions are being made using the data which is available. It is at least clear that with the present lack of information on incremental costs, it is impossible to make decisions on the basis of cost-effectiveness.

Recommendation:

> An effort should be made to identify the decision-makers in industry and evaluate their perceptions of earthquake-related problems and their need for data to make informed decisions on the allocation of resources between competing needs.

Historically, utilities have not been faced with liability problems following major catastrophes. In recent years, however, there is evidence to suggest that this situation may be changing, as indicated by the problems with medical malpractice and product liability. Should this trend continue, problems may develop relative to the flow of information about earthquake-induced equipment damage. Since this type of information is one of the primary means by which earthquake resistance can be improved, its continued free exchange should be protected.

Recommendation:

It is recommended that means be found to ensure that the exchange of information relative to earthquake-induced equipment damage not be impeded by liability-related litigation.

While the number of underground high voltage transmission lines is relatively small at the present time, environmental pressures are contributing to their increased utilization. These facilities have the character that once damaged, restoration is a lengthy process in which the entire length of the cable is rendered inoperative. To date, the vulnerability of these types of facilities to earthquakes remains untested.

Recommendations:

It is recommended that high voltage underground facilities be evaluated for their earthquake resistance and that the cost-effectiveness of the incorporation of intermediate junctions allowing sectionalization of the cable be evaluated.