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It provides conclusions and recommendations regarding (1) a research/educational base, (2) full- or nearly full-scale data, (3) experimental facilities, (4) computer modeling, (5) use of Japanese facilities, and (6) operational funding and program management.

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Earthquake Engineering Facilities and Instrumentation

Ad Hoc Committee on Earthquake Engineering Facilities and Instrumentation
Commission on Engineering and Technical Systems
National Research Council

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This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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PREFACE

This report represents the results of a six-month study of needs and priorities for earthquake engineering facilities and instrumentation. The National Research Council undertook the study in February 1984 at the request of the White House Office of Science and Technology Policy (OSTP), with the support of the Federal Emergency Management Agency (FEMA).

The scope of the study is defined in the contract between the Federal Emergency Management Agency and the National Academy of Sciences as (1) review the need for large-scale experimental earthquake engineering facilities and instrumentation, including recent recommendations of concerned recognized bodies, (2) determine the feasibility of meeting the perceived need, and (3) assess the priorities for a U.S. program to fill the need.

As a supplement to the charge consisting of those three points, the committee was asked to consider the following questions as well as others it deemed appropriate: (1) What facilities and instrumentation might be needed and what priorities should they have, i.e., what are the trade-offs of investing heavily in one facility versus providing for several smaller-scale facilities? (2) Is there a need for a single large central earthquake engineering testing and experimental facility in the United States for which the federal government would provide substantial funding? (3) As an alternative, what would be the advantages and disadvantages of the U.S. federal government contributing to the operation of the existing Japanese facility? (4) Is a large central experimental facility feasible and practical? What are the advantages and disadvantages of a large central facility versus many smaller decentralized facilities with regard to (a) access and (b) ease of cooperative use by engineers and scientists? (5) Can computer simulation or other techniques supplant a large facility or supplement other test facility strategies to achieve much of what a large facility would provide? (6) What are the relative costs of each of the alternatives? (7) What would be the long-term plan for developing and building such a facility? (8) Would there be or is there now financial support forthcoming from sources outside the federal government? (9) Does this project have support from constituencies other than those currently identified (i.e., other than FEMA, OSTP), such as from building design and construction firms; if not, is this support important to the success of the project?

The committee consisted of 11 members drawn from diverse disciplines and backgrounds--(1) structural dynamics, (2) seismology, (3) large-scale computational methods for structural analysis, and (4) the operation of large experimental facilities. Other areas of expertise included knowledge about public appropriations for large-scale facilities and about the state of international competition in engineering design and construction of earthquake-resistant structures.

The committee's first meeting took place in February 1984 at the National Academy of Sciences building in Washington, D.C. The meeting was devoted to two activities. First, various representatives of federal agencies reported on earthquake engineering programs and on facilities that are presently available within the federal complex that might be used in the future by the earthquake engineering program. Second, strategies for the operation of the committee for the rest of its term were developed. The committee formulated seven questions--out of its charge and its own deliberations--to which 54 members of the concerned technical community were asked to respond. The seven questions were:

1. What specific, unique information can be derived from a large (20 x 20 m) shaking table facility compared with information derived from alternative smaller facilities (5 x 5 m to 10 x 10 m)?

2. Describe the experimental research activities you intend to pursue if a large national shaking table becomes available. Where would you seek funding for this?

3. What are reasons for and against conducting experimental activities at the facilities (shaking table/reaction wall) available under the U.S.-Japan cooperation program?

4. How would you rank priority of funding among the following alternatives?

   a. One large national facility (20 x 20 m reaction wall; one estimate: $145 million for construction and $25 million per year for operation).
   b. Three to four regional, modestly sized facilities (one estimate: $80 million for construction and $20 million per year for operation).

c. Upgrading of 10 to 20 existing facilities (one estimate: $15 million for construction and $5 million per year for operation).

5. To what extent do you believe that computer modeling can or cannot supplant a large facility? How can supercomputers and shaking tables complement each other?

6. What is the current practice of selecting the input motion to the shaking table? What suggestions do you have for improvement?

7. If a large shaking table facility were built, which government agency should have funding responsibility? By whom and how should it be managed?

A second meeting, aimed at a technical dialogue with the concerned technical community with respect to the seven questions, was held in San Francisco at the end of March 1984, appropriately in the Ferry Building, which withstood the 1906 earthquake and fire. A large part of the concerned technical community participated, both in terms of written response (29 responded) and in oral discussion at this meeting (19 attended). The dialogue provided for a full interchange, giving those who had responded in written form an opportunity to amplify, emphasize, or exchange ideas on the questions that were asked or on side issues that may originally have been considered peripheral.

The committe's last meeting took place in Washington, D.C., at the end of April 1984. At that meeting the committee formulated its conclusions and recommendations.

There have been several significant studies of the earthquake engineering program over the last few years. It was never the intention of this committee, nor was it part of its charge, to attempt in any way to duplicate or redo those studies. Instead, the committee's efforts were directed to seeking out and using existing data and studies; it used information provided by prior investigators both as background information and in formulating its conclusions and recommendations. It might be said that the committee, due to the severe time constraint imposed on it, operated in the fashion of a "blue-ribbon panel" rather than in a normal, in-depth mode that is the norm for National Research Council committees.

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EXECUTIVE SUMMARY

OVERVIEW

The United States will without question experience devastating earthquakes in its future. Uncertainty exists only as to the scale of the damage and when and where such earthquakes will occur. While estimates vary of the property and human costs and the disruption to other important activities, some sense of the possible can be suggested by the following: As many as 70 million Americans in 39 states face the threat of damaging earthquakes (Federal Emergency Management Agency, 1983, p. 1). Possible loss of life from a single event could go as high as 23,000 people (Federal Emergency Management Agency, 1980, p. 4). The possible economic cost from a single major event could reach $50 billion (Federal Emergency Management Agency, 1983, p. 1). Another ramification with potentially serious national consequences is suggested by speculating on the impacts of a major southern California earthquake on the defense industry concentrated in that area.

When measured against the possible costs, serious questions arise concerning the adequacy of the present mitigation program as authorized by the Earthquake Hazards Reduction Act of 1977 (Public Law 95-124). That program, funded in fiscal 1983 at $63 million, has three elements: (1) Roughly 70 percent of the funding is devoted to understanding the causes and behavior of earthquakes. (2) Roughly 5 percent is devoted to the development of increased public understanding of and planning for earthquakes. (3) The remaining portion, roughly 25 percent, is devoted to engineering, with $8 to $10 million specifically devoted to seismic-resistant structures.

The earthquake engineering program is a preventive effort aimed at reducing the human and economic costs of an earthquake by reducing the possibility of damage or collapse of structures. Economic return on capital invested in this area is thought to be high. Given the probability of $50 billion in damage due to a single earthquake, the annual funding devoted to this prevention activity is a strikingly low 0.13 percent of the cost of such an event. The inadequacy of the funding aimed at the mitigation of damage to or collapse of structures is particularly impressive when it is recognized that federal relief and rehabilitation expenditures for any single major earthquake would likely be orders of magnitude larger than the annual funding levels presently devoted to improving the design and construction of earthquake-resistant structures.

Two factors provide at least a partial explanation for the low level of expenditures on earthquake-resistant structures. First, earthquakes are low-probability high-consequence events. That is, the long periods of time that normally elapse between major earthquake events make it very difficult to sustain the broad base of public support needed for a larger-scale program. Second, earthquakes are widely perceived as threatening only limited areas of the country. Few Americans appreciate that 39 states could experience damaging events, nor do most citizens appreciate that even local events could have disruptive consequences for the nation as a whole.

There are significant deficiencies in present understanding of how to reliably design and construct earthquake-resistant structures. It is generally believed that these deficiencies stem from a lack of reliable data on the behavior of full-scale structures subjected to forces from earthquakes. Although there is a consensus within the expert community that present research/test facilities cannot provide the needed understanding in a timely manner, there is no similar consensus on the priorities that should be assigned to the development of the various types of test facilities.

The lack of agreement on priorities reflects, in part, two conceptually different approaches. One approach proposes an acceleration of the present program of investigator-initiated research, with the Earthquake Hazards Prevention Program being essentially the sum of these individual research projects. The other approach proposes a coordinated, mission-oriented, national program aimed at providing information and understanding that will make the most rapid and cost-effective contribution to seismic-resistant structures. The latter approach starts by focusing on those information deficiencies that are likely to have the highest human and economic costs in case of a major event; it then seeks to reduce those deficiencies. This committee has taken the second approach as its basis for establishing priorities for earthquake engineering facilities and instrumentation. A summary of the study's conclusions and recommendations follows.

CONCLUSIONS AND RECOMMENDATIONS

Research/Educational Base

Conclusion

Whether viewed over the short or long term, an essential ingredient in the nation's earthquake hazards reduction capability is a strong research/educational base in earthquake engineering. The present capabilities in the United States are at best minimally capable of meeting the nation's mission-oriented earthquake engineering needs. Specifically, the experimental facilities presently in universities are old and getting older and have limited versatility. There is an urgent need to modernize university-based research/test facilities.

Recommendation

The highest priority for the federal government's earthquake engineering program should be the enhancement of the research/educational base in universities. The committee has made this its highest-priority recommendation because it wishes to ensure that none of the other recommendations in this report dilute or otherwise diminish the current level of support for earthquake engineering research. The goal of federal support for universities should be the development of a research/training program that produces improved technical information as well as designers and constructors who have an increased capacity to build seismic-resistant structures. The attainment of this goal requires university faculty who have the understanding and experience to educate the professional engineers of the future in this field. A number of the presently existing research/test facilities at the most involved universities should be updated on an accelerated basis. These research facilities should be equipped with state-of-the-art technology and equipment. Additionally, a supplemental program should be created to identify other appropriate commercial and governmental experimental facilities that are underused and to develop cost-effective plans for the productive use of such facilities.

Full- or Nearly Full-Scale Data

Conclusion

There is near unanimity within the earthquake engineering community that a need exists for data on the behavior of earthquake-excited full-scale multistory structures from the initiation of structural damage to collapse. The most rapid contribution to the design and construction of more seismic resistant structures will come from full- or nearly full-scale data.* The need is particularly urgent for masonry and concrete structures, both because they represent such a large portion of both existing and new construction and because less is known about their behavior under actual earthquake conditions. It is generally agreed that reliable extrapolation of data on failure modes for concrete and masonry structures obtained from small-scale models is exceptionally difficult, and perhaps impossible, in the foreseeable future. Full-scale data are needed on the behavior of (1) structural components, (2) whole structures, and (3) the interaction of structures and nonstructural elements. Clear definitions are lacking of the kinds of generic data that would be most useful to designers and builders. Those data urgently need to be defined.

Recommendation

The federal government should undertake a program to provide for the rapid definition of the types of structures and the kinds of generic data from those structures that would make the largest contribution to seismic-resistant design and construction. Concurrently with the formulation of that definition, the federal government needs to move rapidly to ensure that the necessary data can be collected. To collect such data, it will be necessary to subject full- or nearly full-scale structures to simulated earthquake forces across a range from damage initiation to collapse.

Experimental Facilities

Conclusion

The irreducible need for full-scale data on the behavior of earthquake-impacted multistory structures requires that the nation have experimental facilities able to test such structures across a range from damage initiation to collapse. At present, no adequate facilities for testing full-scale structures exist in the United States. A variety of alternative experimental/test

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*This issue relates to the size of test structures, which is discussed more fully in the narrative section of this report.

facilities have been proposed. These include shaking tables, reaction walls, instrumented buildings in earthquake-prone areas, explosive tests, and tests on prototype structures. It is very important to note that there is a broad range of disagreement within the scientific and technical community on these various proposed experimental techniques and the instrumentation appropriate to each of them. The majority opinion among experts, however--although by no means the consensus opinion--is that a facility with a large shaking table and appropriate reaction wall is likely to yield the most useful data over the shortest period of time. Three reservations are regularly expressed concerning large shaking tables: (1) they cannot directly provide data on soil-structure interaction, (2) some experts question their cost effectiveness, and (3) they may not be operationally feasible at sufficiently large scale.

Recommendation

The federal government should undertake, on an accelerated basis, planning aimed at developing a major national earthquake engineering experimental/test facility. The goals of that facility should be to provide the data and understanding necessary for rapid improvement in the design and construction of seismic-resistant structures. Following are three alternative approaches to the development of a national facility. They are summarized in the committee's order of priority.

Experimental Facilities: Priority 1 The federal government should immediately initiate a conceptual engineering design study of a national earthquake engineering experimental/test facility capable of both dynamically and statically testing full- or nearly full-scale multistory buildings to destruction in a simulated earthquake environment. The engineering design study should focus on a large shaking table of a size substantially larger than is presently available in the United States and possibly larger than is now available in Japan. The engineering design study for the large shaking table should be used as a source of data for making a careful comparison with alternative full- or nearly full-scale methods of obtaining the needed experimental data. The ultimate goal of the design comparison study is the development of an experimental/test facility that will provide design and construction professionals with the tools needed to allow them to build buildings and other structures capable of resisting destructive earthquakes at a cost commensurate with the earthquake risk.

The primary purpose of this highest-priority recommendation is to determine whether one or more of the alternative methods is more cost effective than a shaking table as a source of needed data. One of the first needs of the study recommended here will be to establish the size and capability of the shaking table and related equipment required to adequately test full- or nearly full-scale high-risk structures. The recommended design comparison study should realistically assess the cost and performance parameters of needed facilities and should establish specific testing needs and priorities, with anticipated results, for at least three to four years of experimental testing. Both the design of the shaking table and the collection of the data on alternatives are needed in order to compare the cost effectiveness of the different approaches. It should be stressed that both the design study and the analysis of alternatives should proceed concurrently. Although simultaneous study of other alternatives is recommended, they are not given the same weight because, of all options, the large shaking table is the one with the least available engineering data. It is also the most complex and expensive. Detailed studies of other methods are not of high priority because more reliable engineering data and real world experience are available in most cases. It is important to note that very few of the alternative major test methods described in the narrative section of this report can provide sufficiently large forces to permit investigation of the failure modes of real structures. The shaking table offers most promise in this regard and, therefore, is the test method of first choice. Should the shaking table prove to be the most cost-effective way to acquire needed data, the design study would become phase one in the construction of a large shaking table. Alternatively, if an approach other than the shaking table is judged to be most cost effective, the development of a national facility based on that approach or a combination of approaches should be initiated.

Experimental Facilities: Priority 2 The federal government should undertake the immediate development and construction of a major national earthquake experimental/test facility consisting of a mid-size shaking table, a reaction wall, and possibly other test devices. The recommended facility should be developed so that the capability would exist for constructing a large shaking table in the future, if it is determined that such a shaking table is required and can be effectively constructed and operated. This recommendation has the advantage of proposing a shaking table of a size that clearly can be built within present state-of-the-art capabilities. It therefore reduces the risk resulting from the present uncertainty concerning the national capability to design, construct, and operate a large shaking table. The data generated by the facility recommended here would be useful, and the operation of the facility would provide experience upon which further evaluation of a full-scale shaking table could be based. It needs to be pointed out that this recommendation would not produce significant quantities of full- or nearly full-scale data.

Experimental Facilities: Priority 3 The federal government should immediately undertake the design and construction of a national earthquake engineering experimental/test facility consisting of a large shaking table (larger than presently exists in the United States and perhaps larger than any existing in Japan) and an appropriate reaction wall. This recommendation assumes that full-scale test data are urgently needed and should be obtained in the shortest possible period of time. It requires a national commitment to construct a large-scale experimental/test facility on a high-priority basis. The choice of this priority would require a federal commitment to devote the necessary resources to develop and construct this shaking table and to ensure its full use in an appropriate long-range program.

Computer Modeling

Conclusion

Computer models will ultimately be the vehicles used to ensure that a broad range of seismic-resistant structures are appropriately designed and built or retrofitted. Computer modeling of linear structural behavior has already achieved a high degree of reliability. The major need at the present time is for computer models that can predict the earthquake responses of structures in the nonlinear regime. Computer models that are reliable in the nonlinear regime require basic new developments in computational mechanics and a new body of experimental data before they can be developed and validated. Once developed, computer models can reduce the number of needed experiments, but computer models cannot substitute for or replace data derived from full- or nearly full-scale tests.

Continued and vigorous support of computer modeling is an essential ingredient if the nation is to significantly improve the seismic-resistant character of structures. The operation of a national earthquake engineering experimental/test facility will require powerful computer capabilities to handle data acquisition and processing and to facilitate research and development related to computer modeling of structures. A clear need is for the national facility to develop the computing tools necessary for practitioners to use effectively the new earthquake engineering data as it is generated. Finally, state-of-the-art computer modeling capabilities need to be sustained at universities where the next generation of earthquake engineers will be trained.

Recommendation

The federal government should ensure that universities involved in earthquake engineering research have both state-of-the-art computing capability and adequate support for the development of nonlinear computer methodologies. Provision of state-of-the-art computing capability should be an integral part of a national earthquake engineering experimental/test facility. Wherever carried out, the development of computer models should be integrated with experimental programs, and their potential for reducing the costs of experiments should be carefully considered in the planning of new or upgraded experimental facilities.

Use of Japanese Facilities

Conclusion

The Japanese presently have earthquake engineering experimental/ test facilities that are substantially larger in scale and more complex in nature than those existing in the United States. Cooperative use of the Japanese facilities by U.S. and Japanese researchers has the potential to offer full-scale data without the need for a large capital investment in the United States. A variety of factors, however, including experience on joint research projects, suggest that a cooperative Japanese-American research/test program using the Japanese facilities will not meet the mission-oriented earthquake engineering needs of the United States. The Japanese use different construction and design techniques than are used in the United States. Because of the remoteness of Japanese facilities, their use is constrained by the cost and time associated with carrying out American experiments and tests. Also, in the view of many there are significant language communication problems that perhaps can be minimized. Finally, there are serious problems in gaining access to the Japanese test facilities--particularly their large shaking table, because the Japanese already have the table heavily scheduled for several years into the future.

Recommendation

The present Japanese-American cooperative program in earthquake engineering research should be maintained, and every effort should be made to enhance information exchange and suitable joint experiments between the United States and Japan. No program should be undertaken, however, that seeks to substitute the use of Japanese facilities for a large-scale, mission-oriented experimental/test facility in the United States.

Operational Funding and Program Management

Conclusion

A national experimental/test facility capable of providing data on the behavior of full- or nearly full-scale structures subjected to earthquake forces will make its maximum contribution if it is managed and funded as a part of a mission-oriented program aimed at earthquake mitigation. The facility needs to be constructed and managed in a manner that will provide data on those buildings and structures whose failure will result in the highest costs. Maximum benefit would result from the location of responsibility for the facility in a mission-oriented agency. That agency needs to ensure that the experimental/test program is designed to make the maximum contribution to earthquake mitigation. The experimental/test program carried out on the facility needs to be centrally designed and managed and therefore should involve more than simply the sum of a set of individual investigator-initiated research projects. The program needs to be aimed at delivering information that is directly and immediately usable by the design and construction industries.

The federal agency responsible for the national test facility must ensure that the organization that constructs and operates the facility is competent, stable, and ongoing. The facility itself will need a full-time staff of professionals capable of running a complex experimental/test facility. In designing and operating the facility, the management organization should search out and make use of the most talented and competent earthquake researchers and practitioners in the United States.

Recommendation

The national earthquake experimental/test facility should be the responsibility of a mission-oriented federal agency. That federal agency should have as one of its important goals ensuring that the national facility makes the maximum contribution to earthquake hazard mitigation. The agency will have to make policy decisions based on the results of various studies, conceptual designs, evaluations of needs and costs, etc., that will be inherent in the early stages of the development of the facility. In making such policy decisions, the agency should fully utilize appropriate advisory commmittees representing the concerned technical community. The organization responsible for the construction and operation of the facility must be competent and stable, with a staff fully capable of maximizing its technical usefulness. Operational funding for the facility should come from a single agency and should be sufficient to ensure that the facility is fully used. Every effort should be made to ensure that the broad community of earthquake engineering researchers and practitioners is involved both in the design and construction of the facility and in the design and operation of the experimental program.

1

INTRODUCTION

Growing public awareness of potential consequences of major earthquakes has led to increasing federal attention being focused on these natural disasters. Concern with earthquake hazards led the Congress, in 1977, to pass the Earthquake Hazards Reduction Act (Public Law 95-124). Triggered in part by that legislation and by the associated increase in federal funding for work on earthquakes, a number of studies have sought to compile what is known about earthquakes and their effects on structures, all with the purpose of identifying priority needs.

These studies start with the recogniton that approximately 70 million Americans located in 39 states face the risk of moderate to high-level earthquakes (Federal Emergency Management Agency, 1983, p. 1). Based on available information, the Federal Emergency Management Agency (FEMA) suggests that "earthquakes are probably the greatest natural hazard the United States must face in terms of potential loss of life and property and impact on the nation as a whole" (Federal Emergency Management Agency, 1983, p. 1). Something of the scale of potential economic and social consequences arising from a major earthquake is suggested by FEMA's findings that the "potential loss from a single major event could reach $50 billion" (Federal Emergency Management Agency, 1983, p. 1). The potential loss of life has been estimated to be as high as 23,000 people (Federal Emergency Management Agency, 1980, p. 4).

NATIONAL PROGRAM

The congressionally mandated program for mitigating the costs of earthquakes (Public Law 95-124) has three distinct foci. The first is a research and development program aimed at understanding the causes and the behavior of earthquakes. The goal of this research program would, in the ideal sense, include the prediction of where and when earthquakes will occur as well as their severity and character. Better scientific understanding of the causes, timing, and character of earthquakes would, of course, contribute significantly to being able to mitigate the costs to life and property.

Second, Congress mandated a focus on increased public understanding of earthquakes and on the identification of appropriate responses to earthquakes. As an element of this program, work is under way that would, for example, facilitate the evacuation of populations given the knowledge of an imminent earthquake threat.

Third, Congress mandated a focus on the design and construction of structures aimed at minimizing the losses from earthquakes.

Federal funding for fiscal year 1983 for the above three programs was $63 million. These funds were organizationally divided as follows: approximately $34.5 million, or 55 percent, went to the United States Geological Survey, the lead agency in carrying out the research aimed at understanding and predicting earthquakes. The Federal Emergency Management Agency received approximately $3 million, or about 5 percent, to plan, coordinate, and improve seismic codes and increase public understanding and planning for responses to earthquakes. The National Bureau of Standards received approximately $0.5 million, or less than 1 percent, to conduct research and to develop standards for use in designing and constructing structures that are earthquake-resistant. The National Science Foundation received approximately $25 million, with roughly $9 million, or about 14 percent, devoted to seismology and $16 million, or about 25 percent, to engineering. Within the engineering component, some $8 to $10 million is specifically allocated to structures, i.e., roughly 14 percent of the total.

Although maximum protection of life and property will require development in each of these three areas of focus, this report is mainly concerned with the third (design and construction of structures). This report, therefore, focuses specifically on how to gain improved understanding of the behavior of structures subjected to earthquake forces and how to gain maximum use of that understanding in the construction, retrofit, damage assessment, and rehabilitation of structures. Even though significant progress has been made in recent years, it is the consensus of the engineering community that major gaps exist in our understanding of how best to engineer earthquake-resistant structures. Indeed, substantial doubt exists that many contemporary structures will adequately survive the major earthquakes of the future.

OVERVIEW OF NEEDS

The economic and human costs of major earthquakes are predominantly associated with the behavior of structures and the lifelines that supply and connect them. In both urban and suburban areas, the consequences of severed lifelines (e.g., gas and water lines), collapsing buildings, and associated fires can be devastating. The question is not whether but when the nation will experience an earthquake of catastrophic proportions.

The capital investment in structures in the United States is estimated to be $5.5 trillion (Wiggins, 1980, p. 2). Estimates of the annual national investment in new construction are in the range of $230 billion, with roughly half of that investment in seismic regions (Earthquake Engineering Research Institute, 1984, p. 7). The limits of knowledge with regard to engineering seismic-resistant structures are identified both specifically and by analogy in report after report. It is repeatedly noted that a number of buildings specifically designed to be seismic-resistant have failed in earthquakes of less than catastrophic proportions. Regularly used examples are the Olive View Hospital, which failed in 1971 in San Fernando Valley, California, and the Imperial County Services Building, which failed in 1979 in Imperial County, California. In these instances, the earthquakes were substantially smaller in intensity than those anticipated in the future (Earthquake Engineering Research Institute, 1984, p. 1). Alternatively, it is repeatedly noted that a number of buildings designed with no specific concern for seismic resistance (for example, the Ferry Terminal in San Francisco) have performed remarkably well in earthquakes.

It is important to understand why only limited understanding exists concerning the engineering requirements of seismic-resistant buildings. The most pervasive limitation is the inherent difficulty in making proof tests of structures (Earthquake Engineering Research Institute, 1984, p. 3). Unlike electrical and mechanical equipment, for which it is sometimes required that proof tests of prototypes be made before quantity production proceeds, the expense and size of buildings and other structures and the fact that they are not quantity-produced preclude such proof testing. Designers of structures must therefore rely on experience, component testing, tests of small-scale structures, and computer models of structures to predict their performance under various loads. In the absence of compelling new information and understanding, engineers must continue to rely on design and construction practices that have worked in the past, usually making incremental adjustments as new information becomes available or new experience develops.

Many practitioners argue that, if better understanding existed concerning the designs, types of materials, and construction techniques that would be most effective in resisting seismic shocks, it would be possible to reduce construction costs while at the same time reducing the threat to both life and property from earthquakes (Earthquake Engineering Research Institute, 1984, p. 6).

The central question addressed by this committee concerns the setting of priorities for governmental expenditures on experimental/test facilities for earthquake engineering. In the context of the Earthquake Hazards Reduction Act, the committee formulated its basic charge as follows: Given the desire to achieve the most rapid and the most cost-effective way to mitigate the threat to life and property from earthquakes, what priorities should be assigned to alternative experimental and analytical approaches to earthquake engineering research?

Successful design and construction of structures that are seismic-resistant require three things: (1) an understanding of the design and construction principles that will most efficiently contribute to structural safety, (2) the development of a cadre of engineers and construction experts capable of implementing and using this new understanding and information, and (3) the translation of this information into construction design specifications and practices (including building codes) that lead to more seismic-resistant structures at a cost commensurate with the risk.

Understanding of optimal design and construction techniques for seismically engineered buildings can be obtained from a variety of sources. One source is the analysis and evaluation of damage sustained by structures shaken by earthquakes. A second source is computer models that simulate the effect of a range of earthquake forces on different kinds of structures. A third source is tests on small-scale models of structures and on either full- or small-scale components. The fourth source is tests of full-scale or nearly full-scale structures.

Clearly, all of the above alternatives have contributions to make to the goal of seismic-resistant design and construction. Before priorities can be established, it is necessary to look in more detail at information needs and at the ways and costs of satisfying those needs. Establishing priorities requires assessing approaches that will (1) deliver the most reliable and useful information, (2) contribute most to the development of the necessary expert engineering cadre, and (3) provide those data and sources of data that are most likely to lead to rapid implementation of improved understanding in building standards, practices, and codes.

2

EARTHQUAKE ENGINEERING DEFICIENCIES AND NEEDS

Improved understanding of the design and construction of earthquake-resistant structures should contribute to safer structures in three contexts: (1) new structures, (2) retrofit, and (3) rehabilitation. Given an estimated annual capital investment in new structures in seismic regions of $115 billion, implementation of improved design and construction techniques will have a large impact immediately as well as a very large cumulative impact. Because of limited understanding, designers tend to compensate by being conservative. That is, they attempt to provide additional strength to compensate for those areas where understanding is thought to be incomplete. Given that the time span between catastrophic earthquakes is years, the nation has no experience with the behavior of most contemporary building systems subjected to these forces. Therefore, attempts on the part of practitioners to be conservative may prove either under-reactive or overreactive. Only testing in an actual earthquake or in a full- or nearly full-scale simulator (e.g., shaking table) will provide data adequate to assess the issue.

In the case of new structures, improved understanding offers the possibility of more earthquake-resistant and more cost-effective designs. These possible benefits would accrue to all new construction occurring after improved earthquake engineering was implemented.

Increased understanding also offers the possibility of cost-effective retrofitting of existing structures, i.e., the enhancement of the seismic resistance of structures. Cost-effective retrofit activities would offer protection for the massive investment in existing structures while also acting to reduce injury and loss of life.

Finally, a central problem is the accurate assessment of earthquake-damaged structures. Given present understanding, damage assessment is a highly uncertain art. Where assessment is uncertain, the common decision is to leave the damaged (and possibly dangerous) building unrepaired and in use. Better understanding of damage characteristics offers two possible advantages: first, improved confidence in the assessment of the structural integrity of earthquake-damaged buildings and, second, the possibility of cost-effective rehabilitation.

In all three of the above instances (new structures, retrofit, and rehabilitation), it is important to recognize that there exists a spectrum of objectives based on the function of the structure. For example, dams, nuclear plants, and certain other critical facilities are normally designed with the goal of withstanding major earthquakes without sustaining any significant damage. For most other buildings and structures, the normal design-construction goals are as follows: (1) All structures should be able to resist minor earthquakes without damage. (2) Most structures should be able to resist moderate earthquakes without significant damage to the structural frame, but with the expectation that there would be some nonstructural damage. (3) Most structures should be able to resist major earthquakes, of the highest severity anticipated for the site of the specific structure, without collapse, but with structural damage as well as nonstructural damage (Structural Engineers Association of California, 1980, p. 1-c). Achieving these very practical goals requires a sophisticated understanding of the behavior of real structures during major earthquakes--a level of understanding not presently available.

At least 170 distinct but relatively common types of buildings exist or are being built in the United States (Earthquake Engineering Research Institute, 1984, p. 7). In addtion to those is a wide range of other structures, such as dams, bridges, and electric power plants. Each of these distinct structural types has the potential to behave differently when subjected to earthquake forces. In addition, although the structures may be similar, both design practices and the quality of construction can significantly influence the seismic resistance of the structure.

Data on and conceptual understanding of structures designed to be seismic-resistant are presently uneven and in some areas strikingly limited. The reasons for this limited understanding are associated largely with the fact that proof testing has been accomplished solely by the life experience of as-built buildings and structures, a haphazard approach dependent on the whims of nature.

GENERIC DATA

Significant improvement in the earthquake resistance of buildings requires additional information and understanding in three primary areas: (1) improved knowledge of the forces generated by strong ground shaking, (2) empirical data on the behavior of structural components and whole structures, and on the interaction of structures and nonstructural elements, when subjected to strong ground motions, and (3) development and verification of mathematical models that can be used to calculate the response of structures to seismic forces from damage initiation to collapse.

The primary source of information and understanding of earthquakes is strong ground motion seismology. While substantial progress has been made in recent years in the understanding of strong ground motion seismology, the current predictive capability of seismologists on the expected ground motion at a specific site is probably lower than that of earthquake engineers in predicting the failure modes of a given building from a specific ground motion. Since the improved accuracy of failure prediction must be matched by an improved accuracy of ground motion prediction to reduce earthquake hazards, there is a need for intensified work in strong ground motion seismology in parallel with the proposed intensified earthquake engineering program (Committee on Earthquake Engineering Research, 1982, pp. 3-4).

Research on and understanding of earthquake engineering need not, however, await future discoveries in strong ground motion seismology. The key and critical need at this time is to gain a better understanding of how presently known earthquake forces affect real structures.

The most advanced understanding of structures is associated with the linear behavior of structural components subjected to earthquake forces. Similarly, significant progress has been made in using computer models to estimate the effects of a variety of forces on the linear behavior of whole structures. In fact, computer models are now used routinely by architectural and engineering firms for analysis of linear behavior. Even in this area, however, understanding is by no means complete, and confidence varies substantially over the range of different types of structures, since accurate linear models of actual structures are difficult to develop. Nonetheless, the engineering community does not see the analysis of linear behavior as a major limitation in the design of adequately safe structures.

By comparison, understanding is significantly more limited with regard to the behavior of structures in the nonlinear regime. This is the regime experienced by structures as they move from damage initiation to collapse. Computer modeling of structural behavior in the nonlinear regime is now at an early stage of development. With the availability of supercomputers, the problem is not the lack of computing power but rather the lack of reliable data on (1) the properties of common construction materials (e.g., reinforced concrete) subjected to dynamic loads and at deformations appropriate to the damage and failure process, (2) the behavior of components, (3) the behavior of known component interactions, and (4) kinds of interactions that may occur in the nonlinear regime but have not yet been identified. Under earthquake conditions, structures may sustain progressive damage or may display unanticipated strengths by mechanisms that are not understood; predicting when progressive damage leads to failure is beyond the state of the art of present computer modeling.

Knowing how damage to real world structures is initiated, and how it develops through the course of an earthquake until the point of collapse, would provide a data base that would result in a major step forward in improving the design and construction of seismic-resistant structures. Experts regularly identify the need for improved understanding in three areas: (1) how damage propagation occurs in certain types of structural components (e.g., concrete and masonry), (2) the behavior of those points in structures at which components are joined, and (3) the relationship between the structure and nonstructural elements. Better information in these three categories would be directly usable by designers and builders and is essential to the validation of computer models.

STRUCTURE TYPES

The preceding section suggests some of the generic kinds of information, understanding, and predictive capabilities needed to move the design and construction of seismic-resistant buildings forward in a significant way. Concern over limited understanding in the generic areas varies greatly from one type of structure to another. In general, there are higher levels of confidence in the earthquake resistance capabilities of steel structures and of low-rise wooden structures. Alternatively, a consistent and serious concern is identified with the earthquake resistance of conventional concrete and masonry structures. Because of their lower cost, large numbers of masonry and concrete structures have been built all over the United States, and any attempt to act rapidly to protect life and property from earthquakes needs to assign concrete and masonry structures a higher priority.

UTILIZATION

Any acceleration of the nation's efforts to enhance the earthquake resistance of structures must give special attention to the linkage between understanding and use. Clearly, without additional understanding little progress will be made; however, increased understanding does not always result in rapid utilization.

In short, any research/test program should have as a major concern the need to be able to make the most convincing possible case to the design and construction industry and to the governmental officials responsible for modification and enforcement of codes.

The construction industry in the United States is highly fragmented. Similarly, the regulation of that industry is fragmented. Design professionals are licensed separately in each state, building codes vary from one governmental jurisdiction to another, and the ability of many jurisdictions to enforce building codes adequately is limited. Given the fragmented character of both the industry and its regulation, concern needs to be focused on collecting data and developing understanding that is convincing to a broad spectrum of people who will make use of new earthquake engineering knowledge. Certainly, any improvement in the understanding of seismic-resistant buildings that requires significant changes in the way construction is now done is likely to face broad inertia-based resistance.

Earthquake engineering research/test efforts that provide real world examples of why change would be beneficial will be attractive with regard to implementation. By general agreement, the most convincing evidence that can be provided to this industry is evidence of the behavior of full-scale structures subjected to a broad range of earthquake forces.

PERSONNEL NEEDS

A final and fundamental need is for an adequate cadre of professionals who are capable of assimilating and using new information in the design and construction of earthquake-resistant structures and in the preparation and enforcement of new codes incorporating this information. This cadre must be derived from those parts of engineering schools that do research and teaching in the area of earthquake engineering.

It must be kept in mind that the need for a high degree of expertise goes beyond simply the design and construction of new structures. It includes also the capacity to retrofit existing buildings, to assess damage to buildings that have been subjected to earthquakes, and to design and carry out the rehabilitation of damaged structures. The need for a sophisticated cadre of professionals with earthquake engineering competence, then, must be a central concern of any government-supported earthquake engineering activity. Certainly, with new understanding and the use of complex and more sophisticated test facilities and computer models, the field will be more attractive to superior professionals.

3

SOURCES OF UNDERSTANDING

In an ideal world, earthquake engineering researchers would have experimental/test facilities that could (1) subject full-scale structures of all types to earthquakelike forces in a true-to-life environment, (2) deliver forces of any intensity desired by the researchers, (3) be able to collect a wide range of data, (4) function with a high degree of reliability, and (5) do all of the preceding at relatively low cost. In fact, none of the known methods for generating and collecting data on the behavior of structures subjected to earthquake forces can meet all of the desired standards.

The following discussion investigates the strengths, weaknesses, and interrelationships of four different sources of information and understanding: (1) analysis of the behavior of structures during, and the assessment of structural damage after, an earthquake, (2) computer modeling and analysis, (3) small-scale laboratory experiments on components and structures, and (4) full- or nearly full-scale experiments on components and structures.

REAL WORLD DATA

In the abstract, the best source of data and information for improved earthquake engineering of existing structures would be that derived from heavily instrumented structures that experience natural earthquakes. According to a report by the Earthquake Engineering Research Institute (1984, p. 12), "Instrumented buildings for natural earthquakes are valuable sources of test data for earthquake engineering because they can be used for proof tests of the ultimate capacity of real full-scale buildings. At present, approximately 400 buildings in the United States are instrumented with strong-motion accelerographs. About 75 are instrumented for the purpose of obtaining building response data for structural response studies, with the rest instrumented to help evaluate possible overstressing and damage."

The best real world test would be one in which seismologists collected comprehensive information on strong ground motions and engineers collected information on behavior, response, and damage propagation for many kinds of structures, all through a wide range of earthquake intensities. The advantages of this method of gaining data include the ability to investigate "soil-structure interaction, complete building response (including nonstructural as well as structural components), and response over a wide amplitude range, even to damaging levels if a severe earthquake occurs" (Earthquake Engineering Research Institute, 1984, p. 12). Data derived from real world events provide not only improved understanding for earthquake engineering researchers but credibility for those who will use or enforce the results of research.

The fundamental deficiency of a program relying on real world events for data is the infrequent occurrence of strong motion earthquakes. The odds are very low that a program could be designed with a reasonable probability that the right buildings would be instrumented. Put a different way, given the limited capability to predict not only when but where earthquakes will occur, the probabilities of acquiring the needed data in anything like the foreseeable future are too low. Furthermore, even if a major instrumentation program were begun, there is a question of the reliability of the instruments over long periods of time. The typical goal with regard to earthquake instruments is that they must be reliable over decades with little maintenance (Earthquake Engineering Research Institute, 1984, p. 12). That is an exceptionally demanding performance requirement, and present instruments, measured against that requirement, do not leave the engineering community with a high level of confidence. Finally, instrumenting existing structures limits the data to present structural systems and allows little opportunity for testing new or improved systems.

COMPUTER MODELS AND ANALYSIS

Present computer models can, with reasonable confidence, analyze and estimate the effects of ground motion on the linear behavior of simple structures. The understanding of how to develop these models in conjunction with the massive increase in capacity of supercomputers suggests that this will be an area of great and growing importance to the design and construction of seismic-resistant structures.

The next major breakthrough in the area of computer modeling will likely involve the capacity to develop reliable models of the nonlinear behavior of real structures subjected to earthquake forces. With the development of supercomputers, the computing capacity necessary to handle these complex models may now exist. Such models will have litle value, however, without the collection of a body of reliable data that will be the input to the new models and the basis for their validation. Reliable data will require experiments and tests of full- or nearly full-scale structures. In addition, it is believed that tests of full- or nearly full-scale structures will lead to the identification of relationships and interactions that have not previously been identified.

An interesting illustration of the limitations of computer models when developed without extensive experimental validation arose in the recent U.S.-Japan cooperative earthquake research program. In that program, a seven-story full-scale building was tested in a simulated earthquake environment and the experimental results were compared with the predictions of computer models. The building was constructed from reinforced concrete, and many features of typical buildings, such as interior walls, were included.

The seismic environment was simulated by applying lateral loads at the sides of the building from a reaction wall. These lateral loads were programmed to replicate the loads that would be sustained in the building during lateral motions of the ground, including the effects of the building's inertia. For this reason, the technique is called a pseudo-dynamic test. Because of the way the loads were applied, lateral loading in only one direction, rather than the combination of lateral, rocking, twisting, and vertical loads that characterize earthquakes, was simulated. However, this hampered the validation of computer models only insofar as it prevented their simulating these modes.

The computer models represented a two-dimensional cross section of the building. This is conventional in both normal engineering design and in research for this type of load. The prediction of this model, however, was only 62 percent of that obtained from the test.

A careful examination of the experimental results then revealed that the laterally loaded frame interacts strongly with the transverse beams after the initiation of cracking and yielding in the wall. This frame-beam interaction contributes substantially to the strength of the building, and in fact when simple representations of this interaction were added to the computer model, the strength of the building was predicted within 10 percent (Yoshimura and Kurose, in press).

The development of computer modeling capability is an essential ingredient in improved earthquake engineering.

Computer models deserve particular emphasis because, under the best of circumstances, test and experimental data will be available only for a limited number of different structural systems. The computer potentially offers the ability to develop validated models that can then be applied to a wider range of different structures. Simply stated, it is computer models that will allow the earthquake engineering community to generalize and rapidly to advance the quality of earthquake-resistant design and construction across the broad range of structural systems. In sum, then, computers are a vehicle for rapid improvement in the conceptual understanding of earthquake-resistant structures and the rapid application of that understanding to a wide range of individual and unique structures. Computer models, however, cannot be substituted for experimental data; on the contrary, they depend on such data.

SMALL-SCALE EXPERIMENTS

Small-scale experiments and associated research carried out at various institutions and organizations are contributing significantly to progress in earthquake engineering. The Earthquake Engineering Research Institute has identified 13 universities that have test and experimental facilities (Earthquake Engineering Research Institute, 1984, pp. 13-14). The dominant pattern in academic institutions is to have three interrelated activites occurring: (1) tests or experiments across a spectrum from specific structural components through small-scale structures, (2) development of computer models that use the test facilities for verification, and (3) the training of professionals, at both the undergraduate and graduate level. The university-based research/teaching activities are one of the important sources of increased understanding of seismic-resistant structures.

Another source is private sector and governmental organizations that have earthquake test facilities that are used to support ongoing research programs. Most private sector and governmental facilities, however, are used primarily for testing components to meet their own or their clients' needs. As a general rule, private sector and governmental facilities are used to verify the adequacy of specific kinds of equipment and components needed to support the design and construction activities associated with specific structures. While university researchers use data from nonuniversity tests to support their research, the linkage between university researchers and small-scale private and governmental facilities is limited.

Small-scale test and experimental facilities are an important requirement for a vigorous and vital program aimed at enhancing the quality of earthquake engineering. These experimental facilities are now the major sources of data for the design of more reliable computer models, and they are the principal vehicles for validating those models. They are also central elements in the educational process and are essential to the development of a more sophisticated cadre of earthquake engineering professionals. The enhancement of small-scale experimental facilities and the support of research and tests carried out on those facilities are essential to the improvement of the nation's earthquake engineering capability. Simply stated, small-scale experiments are a critical ingredient if there is to be a creative research/educational activity. In the last analysis, this creativity is the foundation for improved earthquake engineering.

Although small-scale experimental test facilities carry a high priority in any earthquake engineering research program, they have fundamental limitations. The most important limitation is the difficulty associated with fabricating small-scale models of most structures. Even when fabrication problems are largely overcome, small-scale models may still give distorted data. The result is that data from structures tested at small scale often cannot be confidently extrapolated to full scale. The confidence level is particularly low for data from masonry and concrete structures tested at small scale. Given the wide agreement on the scaling problem, neither the data nor the computer models built on data from small-scale structures are convincing to those who design structures or write and enforce building codes. Small-scale test facilities, then, are important, but they are not capable of allowing the nation to move confidently toward its earthquake engineering goals.

It should be noted that even existing small-scale test facilities have serious limitations in two important respects. First, many of the university facilities are old or suffering from aging and have limited capabilities. Many were built 10 to 20 years ago, and their data acquisition equipment is no longer supported by its manufacturers. Furthermore, limited funding has resulted in inadequate maintenance and upgrading. In general, these facilities need to be enhanced by state-of-the-art data acquisition and control equipment. Given the limitations of present earthquake engineering knowledge, there is a compelling need for the nation to ensure that the necessary enhancement of university facilities occurs.

Second, there is a need to support larger numbers of experimental activities making use of bigger specimens. A part of this second need might efficiently be addressed by a program that allows university researchers to take advantage of some of the underused experimental facilities in the private sector and at governmental laboratories or test facilities. Like some of the small-scale test facilities located at universities, many of the private sector and governmental facilities are underused. It is possible, then, that the government's earthquake engineering research program could move more efficiently and rapidly if a program were formulated that made nonuniversity facilities more readily available to university-based researchers.

FULL-SCALE EXPERIMENTS

The most rapid contribution to the development of more seismic-resistant structures will come from tests and experiments carried out on full-scale or nearly full-scale structures. Full-scale tests offer the most dependable and rapid source of data. Data and information from full- or nearly full-scale testing are essential to building and validating reliable computer models. Such tests provide a basis for learning how to reliably assess damage. Finally, understanding based on such tests is clearly the most credible basis for making changes in the way buildings are codified, designed, built, retrofitted, and rehabilitated. Simply stated, data from full-scale tests are of great value to those who build new structures and to those who must retrofit or rehabilitate existing structures.

Data from full-scale tests of structures offer an opportunity, over a relatively short period of time, to make a major and significant step forward in the nation's pursuit of more seismic-resistant structures. A major program to acquire these kinds of data and information is a compelling need.

Developing such a program will require making a number of choices among the kinds of experimental/test facilities that can be used to acquire data. Not the least of these choices concerns the determination of the size of full-scale structures to be tested. For example, the Earthquake Engineering Research Institute has used a three- to four-story structure as typical in its determination of an appropriate capacity for a test facility. It should be borne in mind, however, that various structural systems are of interest, and that these possess certain characteristics leading to different interpretations of the meaning of "full scale." For example, a masonry or concrete block building would likely be very well represented by a two- or three-story test structure, while a reinforced concrete or steel-framed building of greater complexity might well require a substantially larger test structure to represent "full scale". This has great importance in the final determination of the design capacity of a large test facility, not only with respect to technical objectives but also with respect to cost effectiveness.

The major proposals for full-scale experimental options can be divided into four categories: (1) in situ testing of existing buildings, (2) buried high-explosive excitation experiments, (3) reaction wall tests, and (4) shaking table earthquake simulation.

In Situ Tests of Existing Prototypical Structures

Prototype testing of existing structures is a traditional form of earthquake engineering experimentation. Normally, such tests have used three principal types of excitation: (1) harmonic excitation by eccentric mass vibrators, reciprocating mass vibrators, or gas pulsers; (2) ambient excitation by wind forces or buried explosives; and (3) impulse loading, including both pull-back and sudden release and controlled impulses, that can be generated by the programmed deceleration of a large mass (Earthquake Engineering Research Institute, 1984, p. 10). These tests offer the advantage of providing information on all of the elements of a full-scale structure as well as on limited aspects of the soil-structure relationships. Such experiments are bounded by the fact that, for the most part, the produced forces lead only to linear response in the structure. The structures are not subjected to the kinds of forces that earthquakes with large ground motion generate.

In addition, such prototype tests of existing structures are severely limited by the availability of existing structures. Unless a structure is slated for demolition, it cannot be tested to collapse. Prototype tests, then, are limited by the inability to plan an orderly, long-term research program and by limits on the kinds of forces that can be applied to structures.

Buried High-Explosive Tests

An alternative to the in situ testing of existing buildings would be the establishment of a facility where structures are built and subjected to buried high-explosive excitation experiments. As is the case with in situ tests on prototype structures, there is doubt within the professional community that explosives can be made to simulate earthquakelike forces, particularly over an adequately long time period. It should be emphasized, however, that some members of the professional community believe high explosives can be made to simulate earthquakelike ground motions with an accuracy sufficient to meet the needs of researchers. If the reliability of this approach is to be convincingly established, a significant effort will have to be made to resolve the present differences of opinion that exist within the technical community.

As previously noted, the most desirable kind of earthquake simulation would allow the testing of buildings from initiation of damage to collapse. The difficulties in achieving this range of tests with high explosives are substantial; some believe they are insurmountable. If these difficulties can be overcome, high-explosive tests might be cost effective.

Reaction Wall Tests

Reaction walls have been used extensively to test the behavior of components and subassemblies. These walls use hydraulically driven actuators to apply forces to structures. Reaction wall experiments are widely believed to be extremely valuable sources of information for enhanced understanding of seismic-resistant structures. In general, reaction walls are limited by the fact that they apply essentially static forces to structures, whereas earthquakes apply dynamic inertial forces to structures. There is within the expert community, however, nearly universal agreement that reaction walls, because they are a low-cost way of testing full-scale structures, offer an attractive way to collect useful data and information. A large reaction wall is likely to be an essential adjunct to a large shaking table, particularly in determining the linear properties of structures to be tested dynamically. It should also be noted that reaction walls can simulate the application of other types of loadings, such as wind loads.

Large Shaking Table

There are a number of shaking tables in the United States capable of testing small-scale models of structures, but none is capable of full- or nearly full-scale experiments. Of all of the facilities for testing full- or nearly full-scale structures, the shaking table offers two distinct advantages. First, it offers the potential to simulate earthquake shaking in a controlled environment. Second, it offers the capability of simulating earthquake shaking across a range of intensities, from the point where damage is initiated through any number of stages to structural collapse. These two advantages are powerful attractions. They offer the maximum opportunity for understanding structural behavior and for learning how to design and construct earthquake-resistant structures and retrofit and rehabilitate existing structures.

Large shaking tables have limitations in that they provide no information on soil-structure interaction and are expensive, complex facilities. But they present the opportunity for a major step forward because they can simulate real world earthquake conditions for full- or nearly full-scale structures. The construction of a shaking table capable of testing full-scale multistory structures would allow the field of earthquake engineering to cross a critical threshold in the pursuit of more seismic-resistant structures.

Perhaps the central reservation associated with a large shaking table concerns its cost effectiveness. Estimates of the cost of a large shaking table range anywhere from $125 to $500 million. These estimates appear to be derived in part from the costs of building the large shaking table at Tadotsu, Japan. Reliable cost figures for building a shaking table in the United States of a size equal to or larger than the one at Tadotsu do not exist.

Even if the cost is acceptable, there is widespread uncertainty about the existing technical capability in the United States to construct a reliable shaking table. An informed decision on both the cost and reliability of a large shaking table requires the development of a much more reliable set of engineering data. These data can come only from an initial conceptual design effort.

Before that design effort can be effectively undertaken, it will be necessary to establish the performance characteristics of the table. For example, some experts suggest that if the primary objective of a large-scale U.S. shaking table is the testing of building structures, the load capacity of the table may not need to be as great as that of the Japanese table. This is because the Tadotsu table is designed to test liquid-filled vessels such as those used in nuclear power plants. Such vessels are extremely heavy. The needs of the United States in this area have to be defined. The average weight of conventional buildings is of the order of 100 pounds per square foot of floor area for each floor. Therefore, an average five-story building could be tested on a table designed to handle a load of only 500 pounds per square foot. Even if doubled, this would be substantially less than the requirements built into the Japanese table.

Similarly, questions can be raised concerning the complexity needed in an American table designed to test building structures. Shaking tables designed to move back and forth in only one horizontal direction are said to have one degree of freedom. Tables designed to move in two directions in the horizontal plane are said to have two degrees of freedom. Adding a vertical component of motion adds a third degree of freedom. The ability to twist about three coordinate axes adds three additional degrees of freedom.

While the Tadotsu table is reported to have horizontal and vertical degrees of freedom, some experts have speculated that the needed testing of most buildings might be adequately accomplished with a table having only two horizontal degrees of freedom. This is a controversial issue that needs to be resolved. The addition of a third or more degrees of freedom adds very substantially to a table's complexity and therefore to its cost. As complexity increases, so does uncertainty about existing capabilities in the United States to build such a table. Various sources--the Earthquake Engineering Research Institute, for example--seem to suggest that two horizontal and one vertical degrees of freedom be provided in any table built in the United States (Earthquake Engineering Research Institute, 1984, p. 29). Certainly any engineering assessment of a shaking table needs to look carefully into the range of capability most cost effective in improving the seismic resistance of the nation's structures.

The seemingly compelling advantages of a large-scale shaking table give particular emphasis to the need to carry out a quantitative assessment of the relative advantages and disadvantages of various table sizes, table loading capacities, and degrees of freedom needed to effectively test structures. The goal is to identify the combination of characteristics that will provide the greatest return relative to expenditures. Such an investigation would require completing a set of conceptual designs of tables in conjunction with analyses of the benefits derived from each. In this way a meaningful evaluation of the importance and costs of each of these parameters can be made.

Shaking tables are powerfully attractive because they can simulate, under controlled conditions, real world earthquake forces. Shaking tables capable of testing full- or nearly full-scale structures offer the opportunity to cross a major threshold in the design of earthquake-resistant structures. The precise characteristics required of a large table remain unclear.

USE OF JAPANESE TEST FACILITIES

The Japanese presently have both a large shaking table and large reaction walls. One option for gaining data on the behavior of full-scale structures subjected to earthquake forces would be to use these Japanese facilities. The attractiveness of this option flows from two aspects. First, use of the large Japanese facilities would relieve the United States from making the high capital investments necessary to build a large shaking table/reaction wall facility. Second, use of the Japanese facilities under the aegis of a cooperative program offers the opportunity for both Japanese and U.S. researchers to benefit from each other's insights. It also provides for the broader goal of Japanese-American cooperation.

Many factors, however, suggest that use of the Japanese facilities is a less than satisfactory approach to the development of increased earthquake engineering capability in the United

States. A significant drawback is the distance to those facilities. That distance makes the cost to American investigators, in both time and money, exceptionally high. Furthermore, it inherently limits the number of American investigators that can be involved, particularly among graduate students and practitioners that would benefit from participation in such experiments.

There are other concerns as well. The Japanese, for example, use different design and construction techniques than are used in the United States. These differences are buried in cultural and economic considerations. It is unlikely that tests on structures built to Japanese standards would deliver reliable data for use in the United States. Furthermore, the Japanese have their large shaking table fully committed for seven years. There would be major negotiations and perhaps high costs involved for U.S. investigators to carry out any significant experimental program in the near future. Finally, there are inherent language communication problems that are viewed by many as constraints but perhaps can be minimized.

Continuation of joint research at Japanese facilities is desirable and useful and should be emphasized as a part of the investigator-initiated research program. Reliance on Japanese facilities is, however, not a practical vehicle for a mission-oriented program aimed at rapid, cost-effective earthquake mitigation.

DEVELOPING A NATIONAL FACILITY

The preceding paragraphs have identified alternative ways of gaining data and understanding on the behavior of full- or nearly full-scale structures subjected to earthquake forces. Given present information, a large national facility consisting of a shaking table and a reaction wall would appear to offer the data needed most in the most reliable form in a time frame consistent with the national need.

Before any final decision can be made on the development of a large-scale earthquake engineering test facility, a detailed engineering design effort and comparison will be necessary. Such an effort must start with the goal of maximizing data on the behavior of full- or nearly full-scale structures subjected to earthquake forces. The effort must assess available options in a detailed engineering study. If the detailed study supports the presently perceived advantages of the shaking table, then a rapid design and fabrication process should be undertaken.

Step one must be the development of a detailed design for the facility. This should include the following: (1) The concept design of the equipment should be established to realistically assess its performance and cost parameters. (2) The scenario of operations should be developed to bring into focus the harsh realities of anticipated research, proposed test schedules for a period of at least three or four years, anticipated results, and the formulation of tactics for the implementation of results. (3) Site selection should be carried out to the extent necessary to establish land costs, and several possible areas for the establishment of the facility should be chosen.

MANAGEMENT CONSIDERATIONS

This chapter has identified a number of needs associated with earthquake engineering, such as (1) an enhancement of the existing university-based earthquake engineering research/test program, (2) the development of a large national earthquake engineering test facility capable of testing full- or nearly full-scale multistory structures, and (3) vigorous support of computer modeling.

Any successful earthquake engineering program requires three components: (1) the physical facilities needed to gain the experimental data that would enhance the nation's earthquake engineering capabilities, (2) a plan designed to ensure that those facilities achieve maximum use and make the maximum contribution to the specific goals of the earthquake hazards mitigation program, and (3) the funding and development of of an organization capable of using the facilities to implement the plan. Success, then, is intimately tied to the character and pattern of funding, the organizational-managerial arrangements at the federal agency level, and the linkage of the funding agency, the research community, the organization that builds and operates the large facility, and the designers and builders who will use the new information.

Several points need to be emphasized. The reason for expanding support for earthquake engineering experimental/test facilities is to achieve the most rapid possible improvement in earthquake-resistant structures. To achieve this goal, the nation needs a mission-oriented program. An effective mission-oriented program requires that major effort be devoted to identifying priority national needs and developing a strategy that will move the nation in a rapid, cost-effective way toward the satisfaction of those needs. Finally, a mission-oriented program will require substantial funding increases over those presently devoted to the Earthquake Hazards Reduction Program authorized by the Earthquake Hazards Reduction Act of 1977.

The present earthquake engineering program in the United States is predominantly a research program. This investigator-initiated program is making significant contributions to improved earthquake engineering and needs to be sustained and accelerated. Any efforts to move toward a more mission-oriented program that would have the result of reducing support for the research program would be unwise in the extreme.

It must be emphasized, however, that the present research program does not provide the framework for a mission-oriented effort. In a research program, the maximum benefit is derived from funding for investigator-initiated studies. This approach to research funding has a long and positive history of underwriting creativity and innovation. Programs aimed at meeting explicit social needs, however, require application of different types of criteria.

Specifically, the need for a national facility capable of testing full- or nearly full-scale multistory structures, with the goal of delivering reliable, credible data in a rapid, cost-effective way, requires central planning and management. For success to be achieved, several postures seem obvious. First, the majority of the funding required for the construction and operation of a full-scale test facility should be specifically authorized by the Congress. The Congress should assign responsibility for carrying out the mission to a designated, mission-oriented agency. Experience suggests that, where funding for the use of large facilities must come from individual investigator-initiated research grants and contracts, substantially less than optimal use of test facilities occurs.

Second, the responsible agency must ensure that the national facility is constructed and operated by a stable, reputable organization. The operating organization will need a committed staff of competent professionals. That staff must have both the capability to construct large-scale structures and the necessary diversity to manage a complex facility.

Third, broad access to the facility by talented and competent researchers and practitioners needs to be ensured. This access should begin with the design of the national facility and carry through to the implementation of the experimental/test program. Establishing and maintaining the complex set of linkages with an earthquake engineering community consisting of researchers and practitioners are basic needs and major tasks. But success in achieving those linkages will have a very high payoff for the nation.

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