ASSESSMENT, STRENGTHENING, AND REPAIR TECHNOLOGIES FOR BUILDINGS, INDUSTRIAL FACILITIES, AND LIFELINES

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I. Executive Summary

Experiences of catastrophic earthquakes such as San Francisco 1906, Kanto 1923, Northridge 1994, and Kobe 1995 show that great human and economic losses arise from unsatisfactory performance of the built environment: buildings, industrial facilities, and lifelines (public works and utilities). While earthquakes are inevitable hazards, they are not inevitable disasters. U.S. and Japanese experiences have shown that properly sited, designed and constructed structures can resist earthquake effects. This paper describes what the central governments of the United States and Japan, in cooperation with one another and with industry, academia and local governments, can do in supporting the further development, testing and application of assessment, strengthening, and repair technologies for buildings, industrial facilities, and lifeline systems. The scope includes new materials and systems, large scale testing and development of recommendations for design guidelines, standards and practices. The resulting knowledge and practice will support disaster mitigation, emergency assessments of vulnerability and damages, and post earthquake recovery investments.

II. Topic Description and Policy Issues

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This paper describes what the central governments of the United States and Japan, in cooperation with one another and with industry, academia and local governments, can do in supporting the further development, testing and application of assessment, strengthening, and repair technologies for buildings, industrial facilities, and lifeline systems. The scope includes new materials and systems, large scale testing and development of recommendations for design guidelines, standards and practices. The resulting knowledge and practice will support disaster mitigation, emergency assessments of vulnerability and damages, and post earthquake recovery investments.

The policy issues relevant to assessment, strengthening and repair technologies for buildings, industrial facilities and lifeline systems are:

1. Achievement of reduction of losses requires incentives to owners to reduce the vulnerability of their facilities. Incentives can range from profits for owners from investments in mitigation to regulations when the public will benefit from investments in mitigation.

2. Public and private investments are needed to produce cost-effective, performance-based planning, siting, design and construction practices for the seismic safety of new buildings, industrial facilities and lifeline systems.

3. Public and private investments are needed to produce cost-effective, performance-based assessment and strengthening practices for the seismic safety of existing buildings, industrial facilities and lifeline systems. Seismic safety is technically and economically more difficult for existing facilities than for new construction. Situation-specific decisions are required whether to strengthen, to replace, or to prepare for losses of functions, property or lives.

4. Mitigation requires that earth science provide quantified definition of the earthquake effects to be resisted.

5. Owners' and public policy makers' decisions to invest in mitigation require societal knowledge of the potential human and economic consequences of failures.

6. Engineering, human factors and societal research and testing programs are needed to improve abilities to predict: the physical performance of constructed facilities in the earthquake environment, the injuries and deaths that would result, and the direct and indirect economic consequences.

7. Large scale research and testing facilities are needed for engineering and human factors research. Japan has made major investments following the Kobe earthquake; U.S. investments are under consideration; remaining inadequacies in facilities should be addressed.

8. Marketplace incentives are needed to justify investments by industry in improved products and services for seismic safety. International standards and conformity assessment practices that recognize and accept improved seismic performance create the incentive of a world marketplace.

9. Earthquakes provide a unique opportunity for understanding: successful and unsuccessful physical performance of constructed facilities, events resulting in injuries and deaths, and direct and indirect economic effects. Because data are likely to be destroyed in secondary

losses, search and rescue, and response and recovery operations, advance planning and training are essential to data acquisition and effective learning from earthquakes.

10. Post-earthquake investigations are needed to understand technical and societal requirements for assessment, strengthening and repair practices.

11. Special emergency practices are needed for the assessment, strengthening and repair of the buildings, industrial facilities and lifelines required to support emergency response activities.

III. Background

Important lessons for seismic safety have been learned from research and post-earthquake investigations:

1. Recent earthquakes have shown mitigation measures to be effective [1,2][1]. Collapses have been rare in buildings designed and constructed in accord with modern standards. The costs of such construction are about one percent higher than they would have been without attention to seismic resistance. Retrofit for seismic resistance is more expensive, on the order of 10 percent of replacement cost for buildings, but has been shown to be effective in avoiding collapses. In the U.S. cost effective, nationally applicable, seismic standards are available for new buildings, and soon to be available for existing buildings.

   These standards are intended and successful for prevention of collapse in severe earthquakes. It is widely recognized that performance based standards are needed to provide for reduction of property loss and for continuity of function when such performance is desired by the owner.

   Nationally applicable seismic standards are available for highway bridges and nuclear power facilities, but not for other types of lifelines.

2. Siting considerations are important for seismic safety. Substantial amplifications of bedrock motions occur on sites with soft soils. Pounding damage can be inflicted by too close neighboring structures. Seismically safe structures can be damaged by debris falling from adjacent weak structures, or ignited by fires in adjacent structures. Poorly consolidated, saturated soils can liquefy from earthquake shaking and cause failures of

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[1] Numerals in brackets denote entries in Section 6. Key References

the structures they support or of those they flow into. Tsunamis or dam failures also can flood or displace structures.

3. The dynamic characteristics of the earthquake ground shaking and of the structure are important. Energy is transmitted most effectively to the structure when the frequencies of ground shaking and the natural frequencies of the structure are similar. For instance, tall, and therefore low frequency, buildings are susceptible to the low frequency pulse encountered near the earthquake fault and quite insensitive to the high frequency vibrations of rock sites at greater distances from the fault.

4. Ductility, the ability of a structure to absorb energy and to redistribute forces through local inelastic deformation, effectively reduces earthquake-induced forces in a structure. It often is more economical to provide ductility than to increase strength. The unexpected brittle behavior of welded steel frame structures, revealed in the Northridge and Kobe earthquakes, is a critical issue because these systems have been designed as if they were very ductile. If brittle they will be vulnerable to failure even in moderate ground shaking.

5. Base isolation, allowing the supporting ground to move independently of the structure, is effective in reducing earthquake-induced forces and thereby reducing property damage and facilitating continuity of functionality.

6. Earthquake ground shaking sets structures into motion. If things should stay connected they must be well connected; for instance, many failures have occurred from poorly anchored buildings and bridges being shaken off of their supports.

7. Structural irregularities weaken seismic resistance. For instance, split-level houses usually suffer more damage than neighboring two story houses.

8. Structural safety assessments are needed urgently following an earthquake to determine what facilities can be used to support emergency activities, what repairs are needed to return to normal living and working conditions, and what facilities are so severely damaged and unsafe that removal is more cost effective than repair.

Innovations based on research provide great potential for reducing earthquake losses and reducing the costs of seismic safety [3].

1. Knowledge of earthquake hazards, the response of structures, the human and economic consequences of successful and unsuccessful structural performance, and the costs of mitigation will reveal to owners of buildings, industrial facilities and lifelines the incentives to mitigate losses. This knowledge also will provide to pubic policy makers the bases for incentives or regulations to achieve mitigation that is vital to the public but not directly cost-effective for owners.

2. Performance standards speak directly to the qualities desired by owners: continuity of function, avoidance of damage to structure or contents, and safety of occupants or neighbors from injuries or death. Traditionally, our seismic building regulations have been intended to prevent injuries and deaths by preventing structural collapse in severe earthquakes, but not to avoid damages or maintain continuity of function. Avoidance of damages and continuity of function can be provided to owners willing to invest in such higher levels of performance. Performance standards and corresponding conformance assessment practices will guide owners in defining cost effective investments in performance better than that required for public safety.

3. Innovative high performance materials and systems have great potential for cost-effective mitigation. Soil stabilization can prevent ground failures. High performance steel, concrete, masonry, timber and composites can increase the resistance of new structures and provide cost-effective strengthening for existing structures. Base isolation and energy absorbing devices can reduce structural response. Active control systems that change structural characteristics or counteract earthquake motions also can reduce structural response. Improved materials and designs for non-structural systems (elevators, windows, lighting fixtures, etc.) can reduce property losses and casualties associated with their failures.

4. Innovative assessment techniques will support quality assurance in new construction, assessment for mitigation of existing facilities, and emergency assessments of structural safety. Advanced non-destructive evaluation methods will determine the presence and characteristics of hidden structural elements and detect flaws. Advanced analytical methods, with non-destructive evaluation techniques, will predict structures' response to future earthquakes and other loadings.

IV. Proposals for Actions and Collaborations

The United States and Japan individually, and cooperatively through the U.S.-Japan Earthquake Disaster Mitigation Partnership, should:

1. Prepare practices and train practitioners for: 1) emergency assessments of the safety of facilities needed during the earthquake emergency period, 2) emergency actions for strengthening and repair, and 3) systematic assessment of damaged facilities and cost-effective decisions for repair or demolition and reconstruction following the emergency period.

2. Prepare practices and train practitioners for systematic post-earthquake investigations that will: 1) document and explain satisfactory and unsatisfactory performance of constructed facilities, 2) identify and understand extraordinary performance, and 3) assess the direct and indirect human and economic consequences of failures and successful performance of constructed facilities.

3. Support the development of programs to quantitatively document earthquake ground shaking and the response of structures in future damaging earthquakes in densely urbanized areas of both countries as the basis for improvements in earthquake resistant design and retrofit practices.
4. Assess national and international needs for large scale research and testing facilities and define the national and international, public and private, programs required to create and operate these facilities and make them available appropriately for public and proprietary studies.
5. Plan, promote, and conduct the national and international research and testing programs needed to understand the seismic performance of buildings, industrial and lifeline systems.
6. Improve practices for the assessment of the seismic vulnerability of buildings, industrial and lifeline systems and their strengthening and/or repair.
7. Improve practices for the planning, siting, design and construction of seismically safe new buildings, industrial and lifeline systems.
8. Develop incentives for owners to invest in seismically safe new facilities, the assessment and strengthening or replacement of hazardous existing facilities, and the assessment and repair of damaged facilities.
9. Support the development and recognition of international standards for the seismic safety of buildings, industrial and lifeline systems, and the development and international recognition of conformity assessment practices to promote private sector investment in the development and marketing of improved products and services for seismic safety.
10. Involve state and local governments, professional and trade associations, industry, and academia appropriately in these collaborative activities.

Needs are extensive and resources are limited. Our nations and our collaborators will have to establish priorities for addressing these proposals.

V. Cooperative Mechanisms

Existing, effective collaboration mechanisms under the U.S.-Japan Program in Natural Resources (UJNR) provide an excellent framework for addressing these policy recommendations. The UJNR Panels active in the area are:

- Earthquake Research (ER)
- Fire Research and Safety (FRS)

- Wind and Seismic Effects (WSE)

Significant additional cooperative mechanisms result from the Earthquake Disaster Mitigation Partnership of the U.S.-Japan Common Agenda for Cooperation in a Global Perspective, and the Workshops on Natural Disaster Reduction and the Highway Science and Technology Program of the Japan-United States Science and Technology Agreement.
Assessment and strengthening technologies for buildings, industrial facilities and lifeline systems can be addressed by collaborative efforts of ER and WSE in the characterization of the earthquake hazard, and by WSE for vulnerability and strengthening. Enhanced involvement of private sector and academic experts is critical to the success of these collaborations.

Mechanisms and public policies to implement assessment and correction of dangerous structures can be addressed by WSE with enhanced involvement of federal, state, local and private officials representing owners and managers and of academic experts in public policies.

Advanced technologies and practices for the emergency use of damaged structures can be addressed by WSE and FRS with enhanced involvement of experts with operational roles in industry, federal, state, and local governments and of fire services.

Private and public, regional and urban, planning and land use practices and incentives for reducing vulnerability to secondary damages and fires following earthquakes can be addressed by WSE and FRS with involvement by public agencies, industry associations and academic experts concerned with land use and planning.

Collaborations in post-earthquake investigation and loss estimation will involve all three panels, again with augmentation to improve representation of industry and academia.

VI. Related Issues

Success in the above endeavors is dependent upon programs related to other themes of this Symposium:

1. Characterization of seismic hazards such as near source ground motions.
2. Loss estimation methodologies including direct and indirect human and economic losses.
3. Practices for urban planning and renewal conducive to earthquake hazards mitigation.
4. Advanced search and rescue and fire fighting techniques.
5. Programs for emergency response, search and rescue, recovery and reconstruction.

VII. Key References

1. Todd, Diana et al; *1994 Northridge Earthquake Performance of Structures, Lifelines and Fire Protection Systems*; Special Publication 862, National Institute of Standards and Technology, May 1994.

2. Chung, Riley M., Editor; *The January 17, 1995 Hyogoken-Nanbu (Kobe) Earthquake Performance of Structures, Lifelines and Fire Protection Systems*; Special Publication 901, July 1996.

3. National Earthquake Strategy Working Group; *Strategy for National Earthquake Loss Reduction*; National Science and Technology Council, April 1996.