# SITE-SPECIFIC DESIGN EARTHQUAKE GROUND MOTION AND SEISMIC DESIGN TECHNOLOGY IN NEXT GENERATION

by

Shigeki UNJOH[1)], Takaaki KUSAKABE[2)], Sho-ichi NAKATANI[3)], Takeshi OHSHITA[4)], Yasuhiko WAKIZAKA[5)], Kei-ichi TAMURA[6)] and Jiro FUKUI[7)]

## ABSTRACT

This paper briefly describes the outcome of the earthquake engineering R&D in the 5-years R&D program for developing the road technology and the implementations conducted by the Road Bureau of the Ministry of Land, Infrastructure and Transport (MLIT), National Institute for Land and Infrastructure Management (NILIM), MLIT, and the Public Works Research Institute (PWRI). The 5-years program was initiated in November 1998 and concluded in the end of March 2003. The comprehensive R&D issues for the road technology including road environment, safety and security of roads, efficiency of road traffic, and accountability of public works were raised. In total, 13 projects were given high priority and had been conducted in the program.

The earthquake engineering R&D, titled as "Site-Specific Design Ground Motion and Seismic Design Technology in Next Generation," was selected as one of the 13 projects. R&D on the evaluation technology of site-specific active fault and the fault-induced earthquake ground motion, and the rational seismic design technology to assure the safety and economical efficiency had been conducted.

**KEYWORDS**: 5-year R&D Program
Road Technology
Earthquake Engineering R&D
Road Structures
Fault-induced Ground Motion
Rational Seismic Design

## 1. 5-YEARS R&D PROGRAM FOR ROAD TECHNOLOGY

For the purpose to create and improve a better social environment in 21st century, the road construction and improvement projects have been expected to play an important role in stimulation of the economy. The Road Bureau of the Ministry of Land, Infrastructure and Transport (MLIT), National Institute for Land and Infrastructure Management (NILIM), MLIT, and the Public Works Research Institute (PWRI) developed the 5 years program for road technology initiated in

———————————————————————

1) Leader, Earthquake Engineering Team, Earthquake Disaster Prevention Research Group, Public Works Research Institute (PWRI), Tsukuba-shi, Ibaraki-ken, 305-8516 Japan

2) Head, Earthquake Disaster Prevention Division, Research Center for Disaster Risk Management, National Institute for Land and Infrastructure Management (NILIM), Ministry of Land, Infrastructure and Transport (MLIT), Tsukuba-shi, Ibaraki-ken, 305-0804 Japan

3) Head, Bridge Division, Road Department, NILIM, MLIT

4) Leader, Construction Technology Team, Construction Technology Research Department, PWRI

5) Director, Daidogawa Dam Construction Office, Kinki Construction Bureau, MLIT (Former Leader, Geology Team, Material and Geotechnical Engineering Research Group, PWRI)

6) Leader, Ground Vibration Team, Earthquake Disaster Prevention Research Group, PWRI

7) Leader, Foundation Engineering Team, Structures Research Group, PWRI

November 1998 [1]. The comprehensive R&D issues on road technology including “Road Environment,” “Safety and Security of Roads,” “Efficiency of Road Traffic,” and “Accountability of Public Works” were pointed out.

Based on these concepts, the following 13 projects were given high priority to be conducted in 5 years.

(1) Improving the Road Environment

1) Technology for improving the roadside environment and the source of atmospheric, noise and vibration pollution

2) Technology for preserving and rehabilitating the natural environment

(2) Improving the Safety and Security of Roads and Living

1) Development of the AHS (Advanced Cruse Assist Highway System) which aims to prevent accidents through the provision of driver information and driving assistance

2) Evaluation of earthquake ground motion taking into account the regional characteristics, and development of the earthquake resistance engineering for next generation

3) Risk management technology for bedrocks and landslides

(3) Improving the Efficiency of Road Traffic

1) Technology for reinforcing bridges and pavements, and enlargement the diameter of tunnels to accommodate large vehicles

2) Development of distribution systems that strengthen inter-urban and intra-city transportation linkages

3) Technology for realizing the TDM (Traffic Demand Management) policy

4) Environmentally friendly technology for setting countermeasures against extremely snowy and cold road conditions by utilizing unused energy

(4) Improving the Accountability of Public Works

1) Management technology for increasing the life span of pavements and bridges, and minimizing the LCC (Life Cycle Cost)

2) Efficient road planning and design technology that takes into account regional features

3) Technology for construction of new transportation link that promotes regional cooperation and consolidation

## 2. EARTHQUAKE ENGINNRING R&D

The earthquake engineering related R&D was one of the 13 projects with high priority. The title of the research is "Site-specific Earthquake Ground Motion and Seismic Design Technology in Next Generation." Project team was established from the seven teams and divisions in total from the NILIM including the Earthquake Disaster Prevention Division and the Bridge Division, and the PWRI including the Construction Technology Team, the Geology Team, the Earthquake Engineering Team, the Ground Vibration Team and the Foundation Engineering Team.

### 2.1 Background and Objective of R&D

Japan is one of the most earthquake prone countries in the world and has a history of numerous devastating earthquakes. During the Hyogo-ken-nanbu Earthquake in 1995, over 6,000 people died, and the damage of houses was about 513,000 in which about 249,000 were near collapse. The social and economic loss due to damage caused by the earthquake was immeasurable. Loss of the GDP was estimated as Reduced Ratio of 0.1～0.45. Direct damage to roads, ports, railways were estimated as 2,200 billion Yen. Collapse of highway was caused on 27 routes and the close of highways was caused at 36 points.

Main causes of serious damage was the strong earthquake ground motion with a wide natural period range caused by the inland active fault just under the urban area, and the serious damage to structures were caused mainly at the structures with smaller ductility capacity.

Based on the past experience of earthquake disasters, road networks that are reliable and less impacted by disasters is necessary to be constructed. In the recommendations submitted by the Construction Technology Development Council (1997), and the Comprehensive National Land Development Plan titled, "Ground Design for the National Land Development in the 21st Century (1998)," "improving safety throughout Japan" and "ensuring safety and security" were placed as two most important technology for revising the seismic design standards. Development of evaluation method of active faults and prediction method of earthquake ground motions were required. They are the basis for ensuring the safety of infrastructures in the event of earthquakes.

On the other hand, from the perspective of reducing the construction cost and promoting the efficient investment of social infrastructures, technology for securing both earthquake safety and economical efficiency is required.

The fundamental target of the earthquake engineering R&D was that no serious effect on the people lives against large inland earthquakes and large inter-plate type earthquakes. Since the roads have important functions as emergency routes and to support social and economical activities, higher performance for road networks are required. Therefore, it was needed to develop the earthquake engineering for next generation to achieve the higher level of the seismic performance and to reduce the construction cost under the difficult economic and financial conditions.

### 2.2 Earthquake Engineering R&D

To improve the earthquake safety and the reliability of road networks and society, and to promote the efficient development of social infrastructures with reasonably reduced costs, the following research was conducted. The target of the R&D was to develop the technology and to reflect the outcomes to the practical implementations including the development and revise of design codes/guidelines/manuals.

(1) Development of Evaluation Method of Design Earthquake Ground Motion considering the Effect of Active Faults

1) Risk Evaluation Technology and Hazard Mapping Technology of Anticipated Earthquake Effect considering Historical Earthquake Record and Active Fault Information

2) Evaluation Technology of Active Faults and the Structures of Deep Soil Layers, and Prediction Method of Site-Specific Near-Field Earthquake Ground Motions for the Seismic Design

(2) Development of Rational Seismic Design Methods for Infrastructures

1) Rational Seismic Design Methods and Seismic Retrofit Methods for Highway Bridges
   - a) Development of Performance-based Seismic Design Concept for Highway Bridges
   - b) Improvement of Evaluation/Verification Methods of Seismic Performance of Highway Bridges
   - c) Development of Rational Seismic Retrofit Methods of Highway Bridges

2) Seismic Design Methods for Underground Structures and Soil Structures based on the Deformation Evaluation

## 3. OUTCOMES OF EARTHQUAKE ENGINEERING R&D

The wide ranged outcomes had been produced from the project. The main outcomes are introduced in the following.

### 3.1 Risk Evaluation Technology and Hazard Mapping Technology

Currently used earthquake hazard map in Japan was developed based on the measured earthquake record data for about past 100 years and the historical earthquake information for about past a thousand and several hundreds years. These information is not enough to evaluate more accurate earthquake hazard considering the earthquakes induced from active faults with the return period of over a few thousands years. Also, large scale earthquakes known as repeatedly occurred at specific active faults and inter-plates were not considered in detail in the current hazard map and the effect of the earthquakes in the near-fault area was not accurately evaluated.

In the project, the hazard mapping technology was developed considering both the past earthquake occurrence information and the information on the large scale earthquakes known as repeatedly occurred at the specific active faults and the inter-plates which has been recently accumulated. The developed mapping method was verified using the JMA Intensity information from 1926. **Fig.1** shows a model hazard map computed for throughout the Japan. These results are expected to be contributed in the next revision of design codes for the rational seismic design considering the regional earthquake information.

### 3.2 Evaluation Technology of Active Faults and the Structures of Deep Soil Layers

To estimate the ground motion induced from specific active faults, it is necessary to evaluate the parameters including size, segmentation, directions, and so on, of each active fault. In the project, to accurately evaluate the place and size of active faults, the evaluation technology by reading the aerial photographs was studied. The relation between the active fault tracing and active fault landform, and the reliability and activity was studied. The results were compiled as an investigation manual for the evaluation of active faults.

Regarding the length of the active faults, the segmentation of active faults which moved at the same time was studied, and the pattern of the activity of fault segment according to the branch pattern was proposed.

To evaluate more accurate earthquake ground motion transmitted from the earthquake source, it is necessary to know the effect of deep soil layers which characteristics is surveyed by the soil search. The effects of the deep soil structures and the shallow soil layer over the stiff soil layer were analytically studied. The earthquake ground motion was found to be significantly affected by the bedrock depth and the form of the deep soil structure as well as the depth of stiff soil layer of shallow soil layer. These results were compiled as the attention points to be considered in the development of soil layer model.

### 3.3 Prediction Method of Site-Specific Earthquake Ground Motions

The evaluation technology of the earthquake ground motion induced from specific active faults using an empirical green function has been currently applied for the estimation of fault-specific earthquake ground motion. The method can estimate the ground motion of larger scale earthquake by superimposing the earthquake records of small earthquake according to the active fault modeling. The limitation of the method is that the appropriate earthquake records during small earthquakes is necessary at the point at which the earthquake ground motion is evaluated. Because of lack of the earthquake records, the accuracy and applicability of the method is limited.

To compensate the limitation of the above method, the method using a statistical green function is proposed. In this method, the earthquake records of small earthquakes are artificially produced based on the statistical analyses of a number of small earthquake records. The proposed method was compared with the strong motion observation data and the statistical attenuation equations, and the good correspondence was verified. **Fig. 2** shows the demonstration example to estimate the peak ground acceleration distribution caused by the 1923 Kanto Earthquake. The peak acceleration is varied site by site and the effect of the failure mechanisms of the faults is considered. This proposed method has been applied to evaluate the design earthquake ground motions of the several actual projects of long span bridges.

Other than the above outcomes, the evaluation method of surface fault displacement induced from active faults, and the application method of nonlinear acceleration design spectrum were also studied.

### 3.4 Performance-based Seismic Design Concept for Highway Bridges

The Japan Road Association (JRA) Design Specifications for Highway Bridges were revised based on the Performance-based design code concept for the purpose to respond the international harmonization of design codes and the flexible employment of new structures and new construction methods. The performance-based design code concept is that the necessary performance requirements and the verification policies are clearly specified. The JRA specifications employed the style to specify both the requirements and the acceptable solutions including the detailed performance verification methods which were based on the existing design specifications including the design methods and the design details. For example, the analysis method to evaluate the response against the loads was placed as one of the verification methods or acceptable solutions. Therefore, designer can propose the new ideas or select other design methods with the necessary verification.

The most important issue of the performance-based design code concept is the clear specifications of the requirements, which the designers are not allowed to select other methods, and the acceptable solutions, which the designers can select other methods with the necessary verification. In the JRA Specifications, they were clearly specified including the detailed expressions. In future, the acceptable solutions will be increased and widened with the increase of the verification of new ideas on the materials, structures and constructions methods.

The code structure of the Part V: Seismic Design is as shown in **Fig. 3**. The static and dynamic verification methods of the seismic performance as well as the evaluation methods of the strength and ductility capacity of the bridge members are placed as the verification methods and the acceptable solutions, which can be modified by the designers with the necessary verifications.

In addition to the above outcomes, the following outcomes were produced.

1) Performance matrices considering Input-Output-Cost Curve
2) Selection method of seismic performance considering cost-benefit efficiency
3) Limit state concept for bridge structures
4) Analysis method of partial safety factors for seismic design of highway bridges based on reliability analysis
5) Testing methodology of reinforced concrete columns (**Photo 1**)
6) Improved ductility evaluation methods of reinforced concrete and steel columns and the ductility improvement technology
7) Design method of abutment based on ductility design concept
8) Improved evaluation method of soil resistance in foundation design considering the effect of liquefaction
9) Improved evaluation method of soil bearing capacity and a dynamic nonlinear modeling of foundations (**Photo 2**)

### 3.5 Rational Seismic Retrofit Methods of for Existing Foundations

There are existing infrastructures with weak resistant capacity against large scale earthquakes. Seismic retrofit works for such structures including bridges have been conducted after the 1995 Hyogo-ken-nanbu Earthquake. However, the seismic retrofit works are restricted and affected by the conditions of sites such as the limitation of construction space. The seismic retrofit methods under the restricted construction conditions had been developed. The micro pile retrofit method, as shown in **Fig.4**, is one of the effective retrofit methods for the foundations. Five types of micro pile retrofit methods were developed and the effectiveness was verified. The design and construction manual was complied and the test constructions were made at 9 sites. **Photo 3** shows one example of actual implementations.

### 3.6 Seismic Design Methods of Underground and Soil Structures based on the Deformation Evaluation

Underground structures including highway tunnels and common utility ducts have relatively safer seismic performance than structures on the ground like buildings and bridges. To evaluate the seismic performance of underground structures against the large scale earthquake, the analysis method of soil-structure interaction, evaluation method of shear deformation of structures, standard design earthquake ground motion which is to be used as input motion on the base of surface layer, and the design method against floating effects due to soil liquefaction (**Photo 4**) were proposed.

For the soil structures, the stability was currently evaluated by the equilibrium of forces applied to the structures. The method can evaluate the safe or not, but cannot evaluate the seismic performance in detail. Therefore, the deformation characteristics of soil structures subjected to large scale earthquakes and the evaluation method was proposed.

### 3.7 Practical Applications/Implementations of the Research Outcomes

From the research project, the following outcomes and practical applications have been made.

(1) Design Earthquake Ground Motion considering the Effect of Active Faults

1) Evaluation Methods of Site-specific Level 2 Design Earthquake Ground Motions, to be published by NILIM
2) Development Method of Earthquake Hazard Map, to be published by NILIM
3) Manual for Evaluation of Active Faults from Landform, Cooperative Research Report of PWRI, No.284, March 2003

(2) Rational Seismic Design Methods for Infrastructures

1) Specifications of Highway Bridges, Part V: Seismic Design, JRA, March 2002
2) Manual for Earthquake Countermeasure Methods (Pre-earthquake and Post-earthquake measures), JRA, April, 2002
3) Data Book for Seismic Retrofit and Repair of Seismic Damage of Highway Bridges considering the Lessons learned from 1995 Hyogo-ken-nanbu Earthquake, Cooperative Research Report of PWRI, No.272, March 2001
4) Manual for Design and Construction of Micro-pile Retrofit Methods for foundations, Cooperative Research Report of PWRI, No.282, September 2002
   (Micro Pile Retrofit methods have been implemented at 9 bridges.)

## 7. CONCLUDING REMARKS

This paper briefly presented the outcome of the earthquake engineering R&D in the 5-years R&D program for developing the road technology and the implementations conducted by the Road Bureau of MLIT, NILIM, and PWRI.

The outcomes of the project have already been reflected to some of the seismic design codes/manuals as well as the practical applications. It is expected that the outcomes will be contributed in the wide area of applications and that the improvement and development will be continuously conducted to achieve the construction of safer, more durable and more cost-effective infrastructures against earthquakes in the future.

## ACKNOWLEDGMENTS

The outcomes of the earthquake engineering R&D were evaluated by the "Evaluation Committee for Earthquake Engineering R&D (Chairman: Prof. Kazuhiko Kawashima, Tokyo Institute of Technology; Members: Prof. Koichi Maekawa, University of Tokyo, and Mr. Tomoyasu Hamada, Kajima Corporation)" and will be reviewed by the "Committee for New R&D for Road Technology (Chairman: Prof. Hideo Nakamura, Professor Emeritus of University of Tokyo)." The authors would like to express our appreciation to Chairmen and all members of the evaluation committee.

The Earthquake Engineering R&D project had been conducted and worked with the following several committees and groups. The Authors greatly thank all the members of committees and groups for their contribution to the projects.

1) Research Committee on the development of Evaluation Methods of Level 2 Earthquake Ground Motion (Chairman: Prof. Tatsuo OHMACHI, Tokyo Institute of Technology)
2) Japan Road Association, Bridge Committee (Chairman: Dr. Shoichi Saeki, PWRC), Subcommittees on the Seismic Design for Highway Bridges and the Foundation Design
3) Cooperative Research on Development of Evaluation Methods of the Place and Size of Active Fault (PWRI and 13 Private Companies)
4) Cooperative Research Project on Investigation, Repair and Seismic Retrofit of Highway Bridges (PWRI, JH, MEX, HE)
5) Cooperative Research Project on Retrofit of Foundation using Micro-Piles (PWRI, ACTEC, 12 Private Companies)

## REFERENCES

1) Road Bureau of the Ministry of Land, Infrastructure and Transport, National Institute for Land and Infrastructure Management, and Public Works Research Institute: New Five-year Program for Road Technology in Japan, November, 1998
2) Japan Road Association: Design Specifications of Highway Bridges, Part I Common Part, Part II Steel Bridges, Part III Concrete Bridges, Part IV Foundations, and Part V Seismic Design, 2002
3) Ministry of Construction: Report on the Damage of Highway Bridges by the Hyogo-ken-nanbu Earthquake, Committee for Investigation on the Damage of Highway Bridges Caused by the Hyogo-ken-nanbu Earthquake, 1995
4) Kazuhiko Kawashima, et. al.: 1996 Design Specifications for Highway Bridges, 29th UJNR Joint Panel Meeting, May 1996
5) Shigeki Unjoh, et. al.: 2002 Design Specifications for Highway Bridges, 34th UJNR Joint Panel Meeting, May 2002

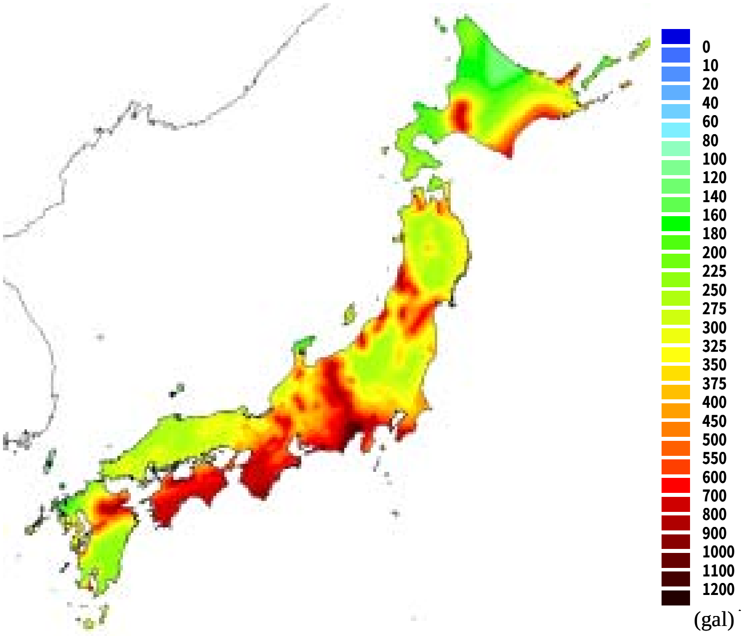



**Fig.1** A Computed Model Map of Earthquake Hazard (Maximum Ground Acceleration with 5% exceeding probability in 100 years from January 1, 2001)

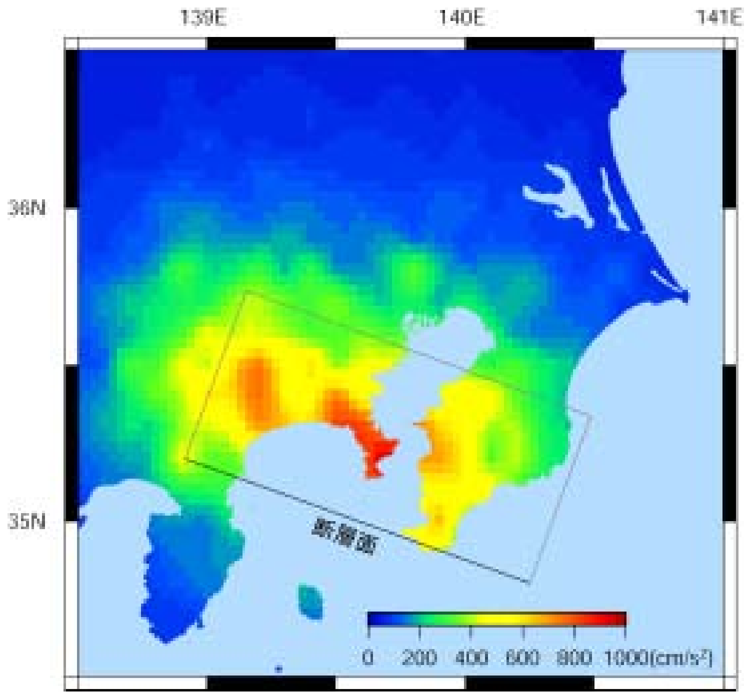



**Fig.2** Evaluation of Peak Ground Acceleration on Stiff Bed Soil Layer caused by the 1923 Kanto Earthquake

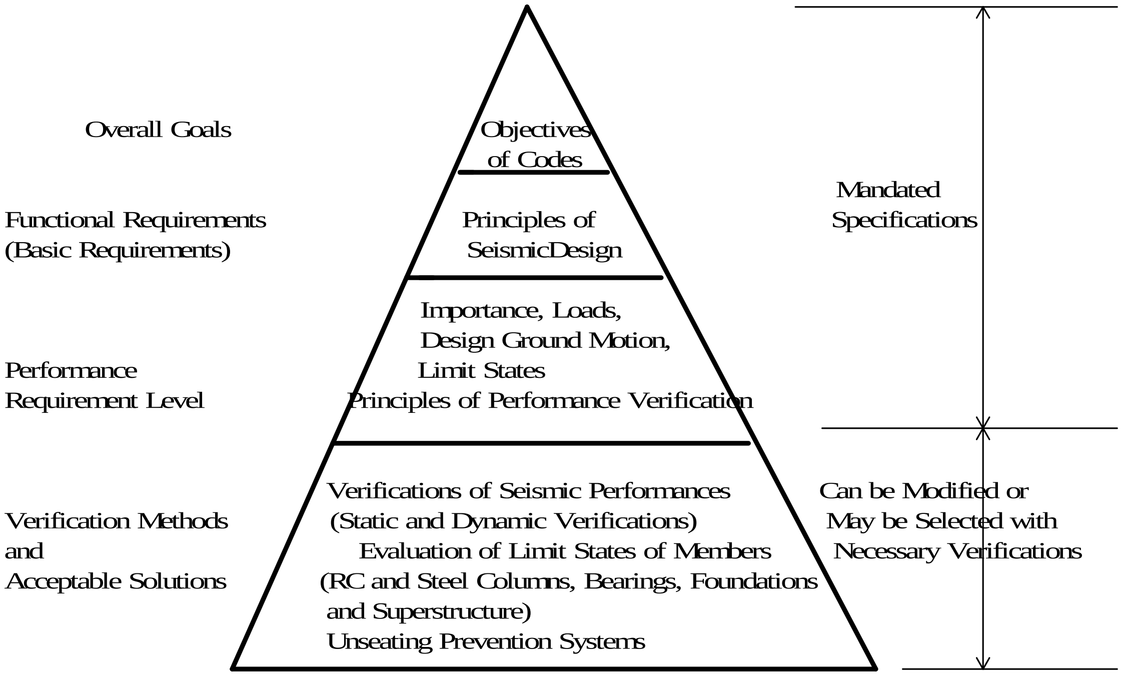
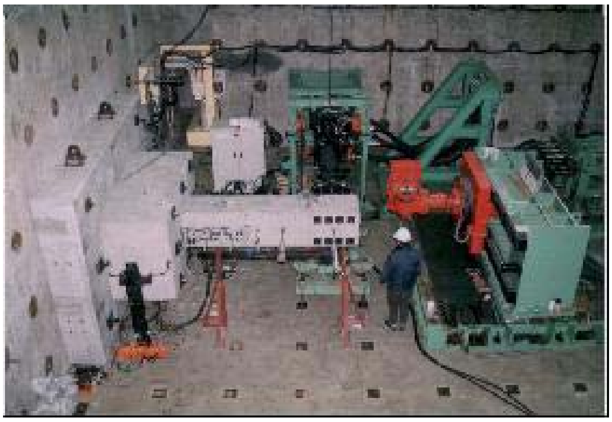



**Fig. 3** Code Structure of JRA Design Specifications, Part V: Seismic Design

**Fig.4** Micro Pile Retrofit Methods



(b) Scaled Size Testing

(a) Real Size Testing

**Photo 1** Large Scale Testing for Verification of Seismic Performance of Reinforced Concrete Columns

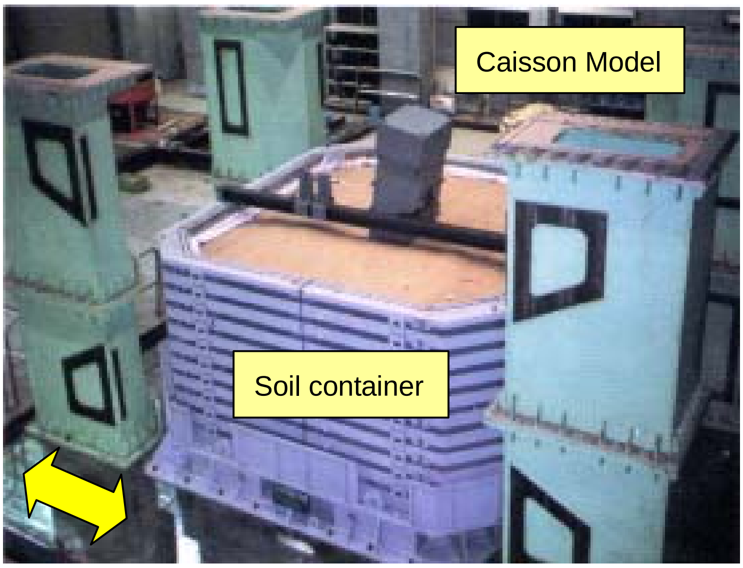



**Photo 2** Shake Table Test of Caisson Foundations to investigate Dynamic Behavior of Foundations

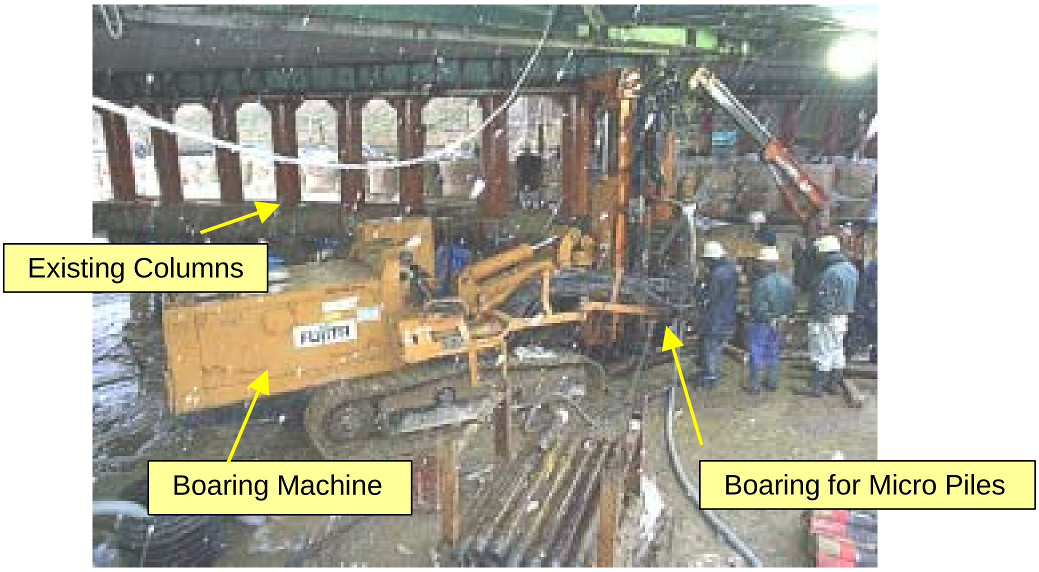
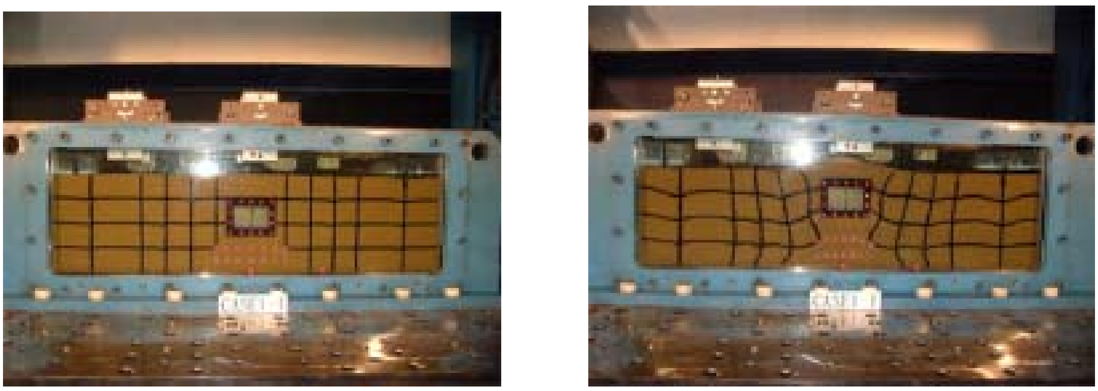



**Photo 3** Practical Implementation of Micro Pile Retrofit Methods



(a) Before Shaking (b) After Shaking

**Photo 4** Centrifuge Tests on Floating Effect of Underground Structures in Liquefiable Soil Layers