Journal of Japan Association for Earthquake Engineering, Vol.4, No.3 (Special Issue), 2004

SEISMIC DESIGN OF HIGHWAY BRIDGES

Kazuhiko KAWASHIMA[1]and Shigeki UNJOH[2]

[1] Member of JAEE, Professor, Department of Civil Engineering, Tokyo Institute of Technology, Tokyo, Japan, kawashima@cv.titech.an jp
2Member of JAEE, Leader of Earthquake Engineering Team, Eartquake Disaster Prevention Research Group, Public Works Research Institute, Tsukuba, Japan, unjoh@pwri.go.jp

ABSTRACT: The Hyogo-ken-Nanbu (Kobe) Earthquake of January 17, 1995, caused destructive damage to the highway bridges. Based on the lessons learned from the Kobe Earthquake, the seismic design specifications for highway bridges were significantly revised in 1996. The intensive earthquake motion with a short distance from the inland-type earthquakes with Magnitude 7 class as the Kobe Earthquake has been considered in the seismic design. This paper summarizes the seismic design specifications for highway bridges after the 1995 Kobe Earthquake.

Key Words : Highway Bridges, Seismic Design, Kobe Earthquake, Design Spesifications

INTRODUCTION

Seismic design methods for highway bridges in Japan has been developed and improved based on the lessons learned from the various past bitter experiences after the Kanto Earthquake (M7.9) in 1923. By introducing the various provisions for preventing serious damage such as the design method against soil liquefaction, design detailing including the unseating prevention devices, a number of highway bridges which suffered complete collapse of superstructures was only a few in the recent past earthquakes.

However, the Hyogo-ken-Nanbu (Kobe) Earthquake of January 17, 1995, caused destructive damage to highway bridges. Collapse and nearly collapse of superstructures occurred at 9 sites, and other destructive damage occurred at 16 sites (Ministry of Construction 1995, Kawashima 1995). The earthquake revealed that there were a number of critical issues to be revised in the seismic design and seismic strengthening of bridges.

Just after the earthquake, the "Committee for Investigation on the Damage of Highway Bridges Caused by the Hyogo-ken-Nanbu Earthquake" was established in the Ministry of Construction to survey the damage and to clarify the factors which affected the damage. The committee has released the intermediate investigation report in March, 1995 and final one in December, 1995 (Ministry of Construction 1995). Besides the investigation of damage of highway bridges, the Committee approved the "Guide Specifications for Reconstruction and Repair of Highway Bridges which suffered Damage due to the Hyogo-ken-Nanbe Earthquake" on February 27, 1995, and the Ministry of Construction noticed on the same day that the reconstruction and repair of highway bridges which suffered damage during the Hyogo-ken-Nanbu Earthquake should be made according to the Guide Specifications. Then, the Ministry of Construction noticed on May 25, 1995 that the Guide Specifications should be tentatively used in all sections of Japan as emergency measures for seismic design of new highway bridges and seismic strengthening of existing highway bridges until the Design Specifications of Highway Bridges were revised.

Based on the lessons learned from the Hyogo-ken-Nanbu Earthquake through the various investigations, the seismic design specifications for highway bridges were significantly revised in 1996 (Japan Road Association 1996, Kawashima et al. 1996). The intensive earthquake motion with a short distance from the inland earthquakes with Magnitude 7 class as the Hyogo-ken-Nanbu Earthquake has been considered in the design.

After that, the revision works of the design specifications of highway bridges have been continuosly made. The target point of the revision was to be based on the performance-based design concept and to enhance the durability of bridge structures for a long-term use, as well as the inclusion of the improved knowledges on the bridge design and construction methods after the 1996 specifications. The 2002 design specifications of highway bridges were issued by the Ministry of Land, Infrastructure and Transport on December 27, 2001 (Japan Road Association 2002, Unjoh et al. 2002).

LESSONS LEARNED FROM THE HYOGO-KEN-NANBU EARTHQUAKE

The Hyogo-ken-Nanbu earthquake was the first earthquake which hit an urban area in Japan since the 1948 Fukui Earthquake. Although the magnitude of the earthquake was moderate (M7.2), the ground motion was much larger than that considered in the design specifications. It occurred very close to the Kobe City with shallow focal depth.

Damage was developed at highway bridges on Routes 2, 43, 171 and 176 of the National Highway, Route 3 (Kobe Line) and Route 5 (Bay Shore Line) of the Hanshin Expressway, the Meishin and Chugoku Expressway. Damage was surveyed for all bridges on National Highways, Hanshin Expressways and Expressways in the area where destructive damage occurred. Total number of surveyed piers reached 3,396 (Ministry of Construction 1995). Most of piers (bridges) which suffered damage were designed according to the 1964 Design Specifications or older Design Specifications. In the 1964 Design Specifications or older Specifications, the requirement for lateral force coefficient of 0.1-0.3 was provided.

Based on these comprehensive damage investigations, the lessons learned from the Kobe Earthqauke were summarized as follows (Ministry of Construction 1995):

(1) Earthquake Ground Motion

Based on the strong motion observation records and the results of seismic response analyses of the ground, the effect of the horizontal earthquake motion by the earthquake on the structures was the largest in any earthquake ground motions previously experienced, not only in Japan but throughout the world, since the beginning of the strong motion observations made it possible to accurately measure the earthquake ground motion after the 1964 Niigata Earthquake. The level of the earthquake ground motion significantly exceeded the design seismic force accounted for in the practical design for highway bridges ever used. The vertical earthquake ground motion was also extremely large.

(2) Reinforced Concrete (RC) Bridge Piers

Those RC bridge piers designed prior to the 1980 design specifications, in which the design method for the termination of longitudinal reinforcement at mid-height section of the column was revised, suffered severe damage caused by the bending damage progressing to the shear failure. Severe damage was also found at some bridge pier bases. An analysis of the relation between the damage to RC bridge pier and the design standards applied indicates that about 15% of all bridge piers on the Route 3 (Kobe Line) of the Hanshin Expressway, which was constructed in accordance with the design specifications for highway bridges of 1964 and 1971, suffered severe damage including complete collapse, cracking, buckling, or fracture of reinforcement, while this level of damage was not found at RC bridge piers on the Route 5 (Bay Shore Line) of the Hanshin Expressway, which was constructed in accordance with design specifications for highway bridges issued in 1980 or later.

(3) Steel Bridge Piers
There were steel bridge piers at which local buckling at the webs and flanges of rectangular steel columns was caused by the horizontal seismic force. Then the split of the corner welds occurred and the decks were subsided by the loss of the vertical strength of columns.
(4) Superstructures
Most of damage to superstructures were found around the bearing supports caused by the damage to bearing supports. Damage was also found at the fixing points of unseating prevention devices.
(5) Unseating Prevention Devices
Some unseating prevention devices to connect adjacent girders failed to prevent the collapse of the bridges because of the local failure of the device itself or the girder to which the device was attached.
(6) Bearing Supports
Many damages such as fracture of set bolts, damage of bearing itself, dislodgement of roller and fracture of anchor bolts, were found at the steel bearings. Damage to rubber bearings was relatively lighter than that to steel bearings.
(7) Ground and Foundations
Liquefaction and lateral spreading caused by liquefaction were observed even in the gravel ground and other ground consisting of large grain material where the liquefaction assessments were not required in the practical design. Structural damage such as settlement, fracture of reinforcement, spalling-off of concrete, or other damage, which could affect bridge stability during an earthquake, were not found at foundations. But the residual displacement as a result of lateral spreading caused by liquefaction in the reclaimed land area was found at the foundations located near shorelines. Even in these cases, the damage to foundations was limited to the bending crack and there is no collapse primarily caused by the lateral spreading. Caisson foundations, diaphragm wall foundations, and other foundations with high stiffness were found to have little residual displacement, even those subjected to the same degree of larteral spreading.

1996 SEISMIC DESIGN SPECIFICATIONS

Revised Points

Although the damage concentrated on the bridges designed with the older Design Specifications, it was thought that essential revision was required even in the recent Design Specifications to prevent damage against destructive earthquakes such as the Hyogo-ken-Nanbu earthquake. The main revised points were (Japan Road Association 1996):
(1) For inland direct strike type earthquakes, the seismic ground motion of the 1995 Hyogo-ken-Nanbu Earthquake, which had the largest seismic ground motion to date in terms of its influence on structures, was to be taken into account and it was specified as a new design seismic force in addition to the conventional design seismic force.
(2) While the conventional seismic design based on the seismic coefficient method was still adopted, seismic design was revised to include the consideration of the ductility design method, for structural members greatly affected by earthquakes such as bridge piers, foundations, bearing supports and unseating prevention systems.
(3) To accurately predict the behavior of a bridge during an earthquake including the nonlinear effects of structural members, dynamic analysis was necessary. Input earthquake motions for dynamic analysis were therefore specified, and the specifications concerning analytical models, analytical methods and safety checks by dynamic analysis were revised.
(4) The soil layers to be examined to evaluate liquefaction potential, the seismic forces used to evaluate liquefaction potential, liquefaction resistance, and the seismic design treatment of liquefaction were reviewed and newly specified as a seismic design method for cases where liquefaction was probable.
(5) Seismic design treatment of lateral spreading caused by liquefaction which might affect a bridge was newly specified.
(6) For seismic isolation design not specified hitherto, a seismic isolation design method considering the

distribution of seismic force from superstrucutre to substructures and the increase of damping capacity was newly specified.
(7) For reinforced concrete piers, the stress-strain relation of concrete considering the confining effect of ties and hoops was introduced, and the method of calculating the horizontal force-displacement relation was revised. Furthermore, a method of evaluating the shear strength considering scale effects, detailed arrangement of reinforcement to improve the ductility capacity, and a design method for reinforced concrete rigid frame piers based on the ductility design method were newly specified.
(8) Methods of calculating the horizontal capacity and ductility of concrete-filled steel piers, and seismic design details for hollow steel piers were newly specified.
(9) Methods of checking the horizontal capacity and ductility of various types of foundations including the effects of nonlinearity were specified, and a seismic design method for foundations based on the ductility design method was newly specified.
(10) For bearing supports, for which no clear design method had been specified, design seismic force and design methods for various types of bearing supports and structural design methods fixed to bearing supports were newly specified.
(11) For reliably preventing a superstrucutre from falling down, the functions of the unseating prevention structure are clarified, and an unseating prevention system was newly specified. Design load and design methods were also specified.

Basic Principle of Seismic Design

The bridges are categorized into two groups depending on their importance; standard bridges (Type-A bridges) and important bridges (Type-B bridges). Seismic performance level depends on the importance of bridges. For moderate ground motions induced in the earthquakes with high probability to occur, both A and B bridges should behave in an elastic manner without essential structural damage. For extreme ground motions induced in the earthquakes with low probability to occur, the Type-A bridges should prevent critical failure, while the Type-B bridges should perform with limited damage .

In the Ductility Design Method, two types of ground motions must be considered. The first is the ground motions which could be induced in the interplate-type earthquakes with magnitude of about 8. The ground motion at Tokyo in the 1923 Kanto Earthquake is a typical target of this type of ground motion. The second is the ground motion developed in earthquakes with magnitude of about 7-7.2 at very short distance. Obviously the ground motions at Kobe in the Hyogo-ken nanbu earthquake is a typical target of this type of ground motion. The first and the second ground motions are called as Type-I and Type-II ground motions, respectively. The recurrence time of the Type-II ground motion may be longer than that of the Type-I ground motion.

Bridges are designed by both the Seismic Coefficient Method and the Ductility Design Method. In the Seismic Coefficient Method, a lateral force coefficient ranging from 0.2 to 0.3 has been used based on the allowable stress design approach. No change was introduced since the 1990 Specifications in the Seismic Coefficient Method.

2002 SEISMIC DESIGN SPECIFICATIONS

Revised Points

The major revision point was to be based on the performance-based design concept. According to the performance-based design concept, the code structure, in which both the design requirements and the existing detailed design methods were clearly separated and specified, was employed. And the improved knowledges on the seismic design methods were also included.

The major revisions of the Part V: Seismic Design are as follows:
(1) Based on the performance-based design concept, principle requirements on the seismic performance of highway bridges, determination concept of design earthquake ground motion and principle to verify the seismic performance were clearly specified.

(2) Two earthquake level design concept was used and the design earthquake ground motion with high probability to occur and the design earthquake ground motion with high intensity and low probability to occur was employed as the same as 1996 JRA Specifications. The ground motions were named as Level 1 Earthquake and Level 2 Earthquake, respectively.
(3) Verification methods of seismic performance were rearranged as "Static Analysis" and "Dynamic Analysis." The selection of two design methods was clearly shown. The applicability of the dynamic analysis was much widened and the detailed verification method for the dynamic analysis was specified.
(4) The evaluation method of dynamic earth pressure for the Level 2 Earthquake design was introduced. This was the based on the modified Mononobe-Okabe earth pressure theory. The evaluation method of the dynamic water pressure for the Level 2 Earthquake design was also introduced.
(5) The verification method of the seismic performance of abutment foundations on the liquefiable ground was newly introduced. The evaluation method of the force-displacement relation models for steel columns with/without infilled concrete was improved.
(6) The verification method of the seismic performance for steel and concrete superstructures were newly introduced.
(7) The evaluation methods of the strength for bearing supports were improved.
(8) References on the back data of the design methods and related information were added at the end of the specifications.

Performance-based Design Specifications

The Design Specifications has been revised based on the Performance-based design 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 employs the style to specify both the requirements and the acceptable solutions including the detailed performance verification methods which are 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 is placed as one of the verification methods or acceptable solutions. Therefore, designers can propose the new ideas or select other design methods with the necessary verification.

The most important issue of the performance-based design 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 are 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 Deign is as shown in Fig. 1. The static and dynamic verification methods of the seismic performance as well as the evaluation methods of the strength and ductilitycapacity 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.

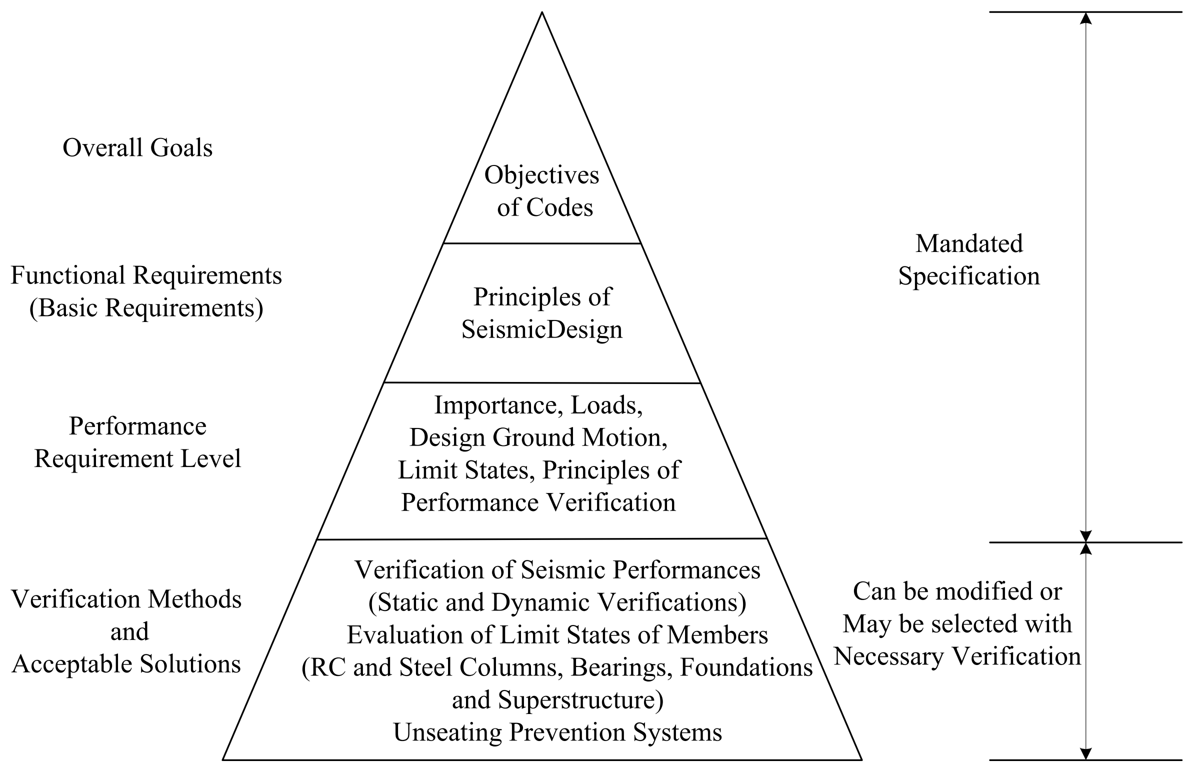


Fig. 1 Code structure of JRA Design Specifications, Part V: Seismic Design

Basic Principles of Seismic Design

Table l shows the performance matrix including the design earthquake ground motion and the Seismic Performance Level (SPL) provided in the revised Seismic Design Specifications in 2002. There is no revision on this basic principle from the 1996 Specifications. The two level ground motion as the moderate ground motions induced in the earthquakes with high probability to occur (Level 1 Earthquake) and the intensive ground motions induced in the earthquakes with low probability to occur (Level 2 Earthquake).

Table 1 Seismic peformance matrix

<table>
<tr><th colspan="2">Type of Design Ground Motions</th><th>Standard Bridges (Type-A)</th><th>Important Bridges (Type-B)</th></tr>
<tr><td colspan="2">Level 1 Earthquake: Ground Motions with High Probability to Occur</td><td colspan="2">SPL 1: Prevent Damage</td></tr>
<tr><td rowspan="2">Level 2 Earthquake: Ground Motions with Low Probability to Occur</td><td>Interplate Earthquakes (Type- I)</td><td rowspan="2">SPL 3: Prevent Critical Damage</td><td rowspan="2">SPL 2: Limited Damage for Function Recovery</td></tr>
<tr><td>Inland Earthquakes (Type- II)</td></tr>
</table>

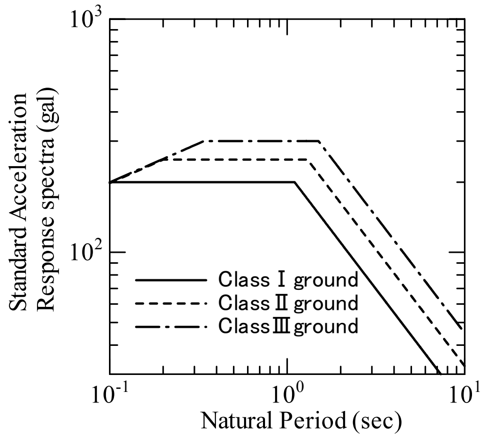
Note) SPL: Seismic Performance Level

The Level 1 Earthquake provides the ground motions induced by the moderate earthquakes and the ground motion considered in the conventional elastic design method is employed. For the Level 2

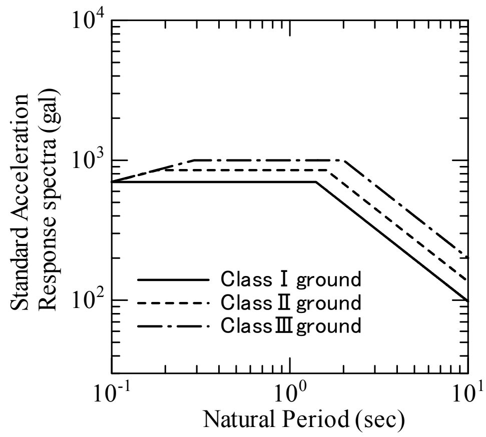
Earthquake, two types of ground motions are considered. The first is the ground motions which is induced in the interplate-type earthquakes with the magnitude of around 8. The ground motion at Tokyo in the 1923 Kanto Earthquake is a typical target of this type of ground motion. The second is the ground motion developed in earthquakes with magnitude of around 7 at a very short distance. The ground motion at Kobe during the Hyogo-ken-Nanbu Earthquake is a typical target of this type of ground motion. The first and the second ground motions are named as Type-I and Type-II ground motions, respectively.

Fig. 2 shows the acceleration response spectrums of the design ground motions.

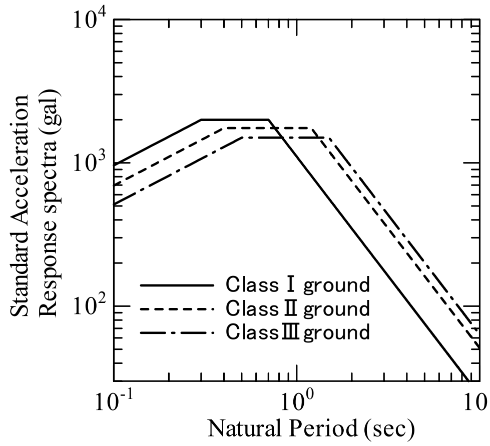
In the 2002 revision, the design ground motions are named as Level 1 Earthquake and Level 2 Earthquake. One more important revision on the design earthquake ground motion is that the site-specific design ground motions shall be considered if the ground motion can be appropriately estimated based on the information on the earthquake including past history and the location and detailed condition of the active faults, ground conditions including the condition from the faults to the construction sites. To determine the site-specific design ground motion, it is required to have the necessary and accurate informations on the earthquake ground motions and ground conditions as well as the verified evaluation methodology of the fault-induced ground motions. However, the area to get such detailed informations in Japan is very limited so far. Therefore, the continuous investigation and research on this issue as well as the reflection on the practical design of highway bridges is expected.



(a) Level 1 earthquake



(b)Level 2 earthquake (type I)



(c)Level 2 earthquake (type II)

Fig. 2 Design accerelartion spectrum

Ground Motion and Seismic Performance Level

The seismic design of bridges is according to the performance matrix as shown in Table 1. The bridges are categorized into two groups depending on their importances; standard bridges (Type-A bridges) and important bridges (Type-B bridges). Seismic Performance Level (SPL) depends on the importance of bridges. For the moderate ground motions induced in the earthquakes with high probability to occur, both A and B bridges shall behave in an elastic manner without essential structural damage (Seismic Performance Level (SPL): 1). For the extreme ground motions induced in the earthquakes with low probability to occur, the Type-A bridges shall prevent critical failure (SPL: 3), while the Type-B bridges shall perform with limited damage (SPL: 2) .

The SPLs 1 to 3 are based on the viewpoints of "Safety," "Functionability," "Repairability" during and after the earthquakes. Table 2 shows the basic concept of these three viewpoints of the SPL.

Table 2 Key issues of seismic performance

SPL	Safety	Functionability	Repairabilty	
			Short Term	Long Term
SPL 1 Prevent Damage	Safety against Unseating of Superstructure	Same Function as before Earthquake	No Need of Repair for Function Recovery	Simple Repair
SPL 2 Limited Damage for Function Recovery	Safety against Unseating of Superstructure	Early Function Rercovery can be made	Function Recovery can be made by Temporary Repair	Relatively Easy Permanent Repair Work can be made
SPL 3 Prevent Critical Damage	Safety against Unseating of Superstructure	—	—	—

Verification Methods of Seismic Performance

Seismic Performance Level and Limit States

As mentioned in the above, the seismic performance is specified clearly. It is necessary to determine and select the limit states of highway bridges corresponding to these seismic performance levels to attain the necessary performance in the design procedure of highway bridges.

In the 2002 revision, the determination principles of the limit state to attain the necessary seismic performance are clearly specified. For example, the basic principles to determine the limit state for SPL 2 is: 1) the plastic hinges shall be developed at the expected portions and the capacity of plastic hinges shall be determined so that the damaged members can be repaired relatively easily and quickly without replacement of main members, 2) the plastic hinges shall be developed at the portions with appropriate energy absorption and with high repairability, 3) considering the structural conditions, the members with plastic hinges shall be combined appropriately and the limit states of members with plastic hinges shall be determined appropriately. Based on the basic concept, the combinations of members with plastic hinges and the limit states of members for ordinary bridge structures are shown in the commentary.

Verification Methods of Seismic Performance

It is the fundamental policy of the verification of seismic performance that the response of the bridge structures against design earthquake ground motions does not exceed the determined limit states.

Table 3 shows the applicable verification methods of seismic performance used. In the seismic design of highway bridges, it is important to increase the strength and the ductility capacity to appropriately resist the intensive earthquakes. The verification methods are based on the static analysis and dynamic analysis. In the 1996 design specifications, the lateral force coefficient methods with elastic design, ductility design methods and dynamic analysis were specified and these design methods had to be selected based on the structural conditions of bridges. The basic concept is the same as 1996 one but the verification methods are rearranged to the verification methods based on static and dynamic analyses.

Table 3 Applicable verification methods of seismic performance depending on earthquake response characteristics of bridge structure

<table>
<tr><td rowspan="2">Dynamic Characteristics

SPL to be verified</td><td rowspan="2">Bridges with Simple Behavior</td><td rowspan="2">Bridges with Multi Plastic Hinges and without Verification of Applicability of Energy Constant Rule</td><td colspan="2">Bridges with Limited Application of Static Analysis</td></tr>
<tr><td>With Multi Mode Response</td><td>Bridges with Complicated Behavior</td></tr>
<tr><td>SPL 1</td><td rowspan="2">Static Verification</td><td>Static Verification</td><td rowspan="2">Dynamic Verification</td><td rowspan="2">Dynamic Verifiatin</td></tr>
<tr><td>SPL 2/SPL 3</td><td>Dynamic Verification</td></tr>
<tr><td>Example of Bridges</td><td>Other Bridges</td><td>1)Bridges with Rubber Bearings to distribute Inertia Force of Superstructures
2)Seismically Isolated Bridges
3)Rigid Frame Bridges
4)Beidges with Steel Columns</td><td>1)Bridges with Long Natural Period
2)Bridge with High Piers</td><td>1)Cable-stayed Bridges, Suspension Bridges
2)Arch Bridges
3)Curved Bridges</td></tr>
</table>

The static verification methods including the lateral force design method and the ductility design method are applied for the bridges with simple behavior with predominant single mode during the earthquakes. The dynamic verification method is applied for the bridges with complicated behavior, in such case the applicability of the static verification methods is restricted. In the 1996 design specifications, for the bridges with complicated behavior both the static and dynamic analyses had to be applied and satisfied. In the 2002 one, the applicability of the dynamic analysis is widened and the dynamic verification method is expected to be used mainly with appropriate design consideration.

CONCLUDING REMARKS

This paper presented the Seismic Design Specifications of Highway Bridges after the 1995 Hyogo-ken-Nanbu Earthquake. Based on the lessons learned from the 1995 Hyogo-ken-Nanbu Earthquake, the "Part V: Seismic Design" of the "JRA Design Specifications of Highway Bridges" was totally revised in 1996, and the design procedure moved from the traditional Seismic Coefficient Method to the Ductility Design Method.

In the 2002 revision, the target point of the revision is to be based on the performance-based design concept and to enhance the durability of bridge structures for a long-term use, as well as the inclusion of the improved knowledgs on the bridge design and construction methods. It is expected to have the circumstances to employ the new ideas on the materials, structures and constructions methods to construct safer, more durable and more cost-effective bridges in the future.

ACKNOWLEDGMENTS

Drafting of the revised version of the "Part V Seismic Design" of the "1996 and 2002 JRA Design Specifications of Highway Bridges" was conducted at the "Sub-committee for Seismic Design of Highway Bridges" and was approved by the "Bridge Committee," Japan Road Association. The authors served as members of bridge committee, and as former and present chairmen of the sub-committee, respectively. The authors thank all members of the Bridge Committee and the Sub-Committee.

REFERENCES

Japan Road Association (1996). "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" (in Japanese, Part. V :English version is available)

Japan Road Association (2002). "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" (in Japanese, Part. V : English version is available)

Kawashima, K. (1995). "Impact of Hanshin/Awaji Earthquake on Seismic Design and Seismic Strengthening of Highway Bridges," *Report No. TIT/EERG 95-2, Tokyo Institute of Technology* (in English)

Kawashima, K. et. al. (1996). "1996 Design Specifications for Highway Bridges," *Proceedings of the 29th Joint Meeting of US-Japan Panel on Wind and Seismic Effects, UJNR,* Technical Memodandum of PWRI, No.3524, 275-299 (in English),

Ministry of Construction (1995). "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* (in English)

Unjoh, S. et al. (2002). "2002 Design Specifications for Highway Bridges," *Proceedings of the 34th Joint Meeting of US-Japan Panel on Wind and Seismic Effects, UJNR*, NSIT Special Publication 987, 231-240 (in English)

(Submitted: April 27, 2004)
(Accepted: July 2, 2004)
Copyright JAEE