This paper presents the revised Seismic Design Specifications of Highway Bridges, Japan Road Association (JRA), in 2002 [1]. The revised specifications are based on the Performance-based Design Code Concept and the improved knowledges on the seismic design methods for highway bridges are also included. According to the Performance-based Design Code Concept, the design requirements are clearly specified and the existing detailed design methods including the analytical methods and the allowable limits are specified as verification methods and the examples of acceptable solutions. The designers can modify or select other verification methods and/or acceptable solutions with appropriate verifications. It is expected that new ideas on the materials and structures will be employed much easier than before. In this paper, the revised major points in the 2002 JRA Seismic Design Specifications are briefly described including the performance-based design code concept, seismic performance levels, the seismic design force, and the ductility evaluation methods for foundations and superstructures.

KEY WORDS: Seismic Design  
JRA Design Specifications  
Performance-based design Code  
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 Great 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 Earthquake of January 17, 1995, caused destructive damage to highway bridges. Collapse and nearly collapse of superstructures occurred at 9 sites, and other

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destructive damage occurred at 16 sites [2, 3]. The earthquake revealed that there are a number of critical issues to be revised in the seismic design and seismic strengthening of bridges. Based on the lessons learned from the Hyogo-ken-Nanbu Earthquake, the design specifications for highway bridges were significantly revised in 1996 [3, 4, 5]. 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.

In the Japan Road Association (JRA), the "Bridge Committee" (Chairman: Dr. Syo-ichi SAEKI, Director of Public Works Research Center) has worked on the revision of the design specifications of highway bridges. The target point of the revision was to be based on the performance-based design code 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. The new Design Specifications of Highway Bridges was issued by the Ministry of Land, Infrastructure and Transport on December 27, 2001. The JRA has released it with the commentary in March 2002. This paper summarizes the new Design Specifications of Highway Bridges, Part V: Seismic Design, issued in March 2002.

2. MAJOR REVISION OF JRA SEISMIC DESIGN SPECIFICATIONS

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

The major revisions of the Part V: Seismic Design are as follows:
(1) Based on the performance-based design code concept, principle requirements on the seismic performance of highway bridges, determination concept of design earthquake ground motion and principle to verify the seismic performance are clearly specified.
(2) Two earthquake level design concept is 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 is employed as the same as 1996 JAR Specifications. The ground motions are named as Level 1 Earthquake and Level 2 Earthquake, respectively.
(3) Verification methods of seismic performance are rearranged as "Static Analysis" and "Dynamic Analysis." The selection of two design methods is clearly shown. The applicability of the dynamic analysis is much widened and the detailed verification method for the dynamic analysis is specified.
(4) The evaluation method of dynamic earth pressure for the Level 2 Earthquake design is introduced. This is the based on the modified Mononobe-Okabe earth pressure theory. The evaluation method of the dynamic water pressure for the Level 2 Earthquake design is also introduced.
(5) The verification method of the seismic performance of abutment foundations on the liquefiable ground is newly introduced.
(6) The evaluation method of the force-displacement relation models for steel columns with/without infilled concrete is improved.
(7) The verification method of the seismic performance for steel and concrete superstructures are newly introduced.
(8) The evaluation methods of the strength for bearing supports are improved.
(9) References on the back data of the design methods and related information are added at the back of the specifications.

3. PERFORMANCE-BASED DESIGN SPECIFICATIONS

The JRA Design Specifications has been 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 are employed 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, 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 that 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 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.

4. BASIC PRINCIPLES OF SEISMIC DESIGN

Table 1 shows the performance matrix including the design earthquake ground motion and the Seismic Performance Level (SPL) provided in the revised JRA Seismic Design Specifications in 2002. There is no revision on this basic principle from the 1996 Version.

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).

The Level 1 Earthquake provides the ground motions induced by the moderate earthquakes and the ground motion considered in the elastic design method in the past for a long time 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 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. The recurrence period of the Type-II ground motion may be longer than that of the Type-I ground motion, although the estimation is very difficult.

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 must 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 at 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.

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 importance; 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 should 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 should prevent critical failure (SPL: 3), while the Type-B bridges should 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 1  Seismic Performance Matrix: Design

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

Note) SPL: Seismic Performance Level

Table 2 Key Issues of Seismic Performance

<table>
<thead>
<tr>
<th>SPL</th>
<th>Safety</th>
<th>Functionability</th>
<th>Repairability</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPL 1 Prevent Damage</td>
<td>Safety against Unseating of Superstructure</td>
<td>Same Function as before Earthquake</td>
<td>No Need of Repair for Function Recovery</td>
</tr>
<tr>
<td>SPL 2 Limited Damage for Function Recovery</td>
<td>Safety against Unseating of Superstructure</td>
<td>Early Function recovery can be made</td>
<td>Function Recovery can be made by Temporary Repair</td>
</tr>
<tr>
<td>SPL 3 Prevent Critical Damage</td>
<td>Safety against Unseating of Superstructure</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
5. VERIFICATION METHODS OF SEISMIC PERFORMANCE

5.1 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 are to be developed at the expected portions and the capacity of plastic hinges has to be determined so that the damaged members can be repaired relatively easily and quickly without replacement of main members, 2) the plastic hinges are to be developed at the portions with appropriate energy absorption and with high repairability, 3) considering the structural conditions, the members with plastic hinges are to be combined appropriately and the limit states of members with plastic hinges are to 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.

5.2 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>
<thead>
<tr>
<th>Dynamic Characteristics</th>
<th>Bridges with Multi Plastic Hinges and without Verification of Applicability of Energy Constant Rule</th>
<th>Bridges with Limited Application of Static Analysis With Multi Mode Behavior</th>
<th>Bridges with Complicated Behavior</th>
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</thead>
<tbody>
<tr>
<td>SPL to be verified</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SPL 1</td>
<td>Static Verification</td>
<td>Dynamic Verification</td>
<td>Dynamic Verification</td>
</tr>
<tr>
<td>SPL 2/SPL 3</td>
<td></td>
<td></td>
<td></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) Bridges with Steel Columns</td>
<td>1) Cable-stayed Bridges, Suspension Bridges 2) Arch Bridges 3) Curved Bridges</td>
</tr>
</tbody>
</table>
Shows the 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.

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.

5.3 Major Revision Points of the Verification Methods of Seismic Performance

(1) Verification Methods of Abutment-Foundation on Liquefiable Ground against Level 2 Earthquake

In the 1996 design specifications, the performance of the abutment-foundations was not verified. This is because 1) the serious damages to abutment-foundations were not found in the past earthquakes when the soil liquefaction was not developed, 2) abutment-foundation is affected by the backfill soils during earthquakes and the effect of the inertia force of abutment itself is relatively small to the pier-foundations, 3) since abutments generally resist against back-fill earth pressure, the abutment-foundations tend to develop displacement to the direction of the earth pressure that is to the center of bridges, then it is generally low probability to have the unseating of superstructures.

On the other hand, recently, the dynamic earth pressure against Level 2 Earthquake based on the modified Mononobe-Okabe theory has been proposed and the behavior of the abutment-foundations can be evaluated during the Level 2 earthquakes. Based on investigations using the modified Mononobe-Okabe theory, it is shown that the abutment-foundations designed according to the Level 1 Earthquake generally satisfy the performance requirement during the Level 2 Earthquake. Therefore, based on these results, the performance of the abutment-foundations only on the liquefiable ground is to be verified in order to give the necessary strength to the foundations and to limit the excessive displacement even if the nonlinear behavior is expected in the abutment-foundations.

(2) Verification Methods of Strength and Ductility of Steel Column

In the 1996 design specifications, the concrete infilled steel columns was designed according to the static ductility design methods using the response evaluation based on the energy equal theory. The force-displacement relation was based on the experimental data of steel columns. On the other hand, steel columns without infilled concrete was designed based on the dynamic analysis because the applicability of the static response evaluation was not verified.

In the 2002 design specifications, new and more appropriate force-displacement relation models for steel columns with and without infilled concrete are proposed based on the experimental data of steel columns which has been made before
and after the last 1996 revision. Using these new models, the seismic performance is verified based on the dynamic analysis.

(3) Verification Methods of Strength and Ductility of Superstructure

Generally, the seismic design of superstructures is not critical except the portion around the bearing supports which are the connection between superstructure and substructures. However, the seismic design sometimes becomes critical to the design of rigid frame bridges and arch bridges in the longitudinal direction, and to the design of bridges with long spans relatively to the bridge width in the transverse direction.

The nonlinear behavior of superstructures against cyclic loading is investigated in the recent research. Therefore, the verification method of the limited nonlinear performance for the superstructures is newly specified with the energy absorption at the plastic hinges at the columns.

6. CONCLUDING REMARKS

This paper presented an outline of the revised JRA Seismic Design Specifications of Highway Bridges issued in 2002. Based on the lessons learned from the Hyogo-ken-Nanbu Earthquake in 1995, 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. Major point of the revision was the introduction of explicit two-level seismic design methods. In the 2002 revision, the target point of the revision is to be based on the performance-based design code 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.

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