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Seismic design of highway bridge foundations with the effects of liquefaction since the 1995 Kobe earthquake

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Abstract

The seismic design of highway bridges has been improved through the lessons learned from earthquake damage and advances in earthquake engineering. The Design Specifications for Highway Bridges, including a volume on seismic design, have been revised three times since the 1995 Kobe earthquake. This report presents the major changes and improvements in the seismic design techniques for highway bridge foundations with the effects of liquefaction and their background since the 1995 Kobe earthquake. Particular emphasis is placed on the liquefaction potential assessment, ductility design of pier and abutment foundations for liquefaction, and seismic design of pier foundations for liquefaction-induced ground flow.

Keywords: Seismic design; Highway bridge; Foundation; Liquefaction; Design Specifications for Highway Bridges

1. Introduction

The first seismic design requirements for highway bridges in Japan were included in the Details of Road Structures (Draft), which were issued by the Ministry of Internal Affairs in 1926, three years after the 1923 Kanto earthquake. Since then, the seismic design regulations for highway bridges have repeatedly been revised based on the lessons learned from damaging earthquakes, e.g., the 1964 Niigata earthquake, 1978 Miyagi-ken Oki earthquake, and 1983 Nihon-kai Chubu earthquake, along with the progress of earthquake engineering. The seismic performance of highway bridges was improved by this process, even though the Kobe (Hyogo-ken Nanbu) earthquake on January 17, 1995, caused the worst damage to various structures, including highway bridges, since the 1923 Kanto earthquake. Highway bridges suffered destructive damage, such as the collapse of piers and the unseating of superstructures. The 1995 Kobe earthquake induced extensive soil liquefaction over a wide area, including reclaimed land composed of coarse sand and gravel layers, which caused serious influence on the seismic safety of structures. After this earthquake, the Design Specifications for Highway Bridges were extensively revised in 1996 (Japan Road Association, 1996; Unjoh and Terayama, 1998). The Design Specifications for Highway Bridges have been revised twice more since that revision in 1996.

In the 1996 Design Specifications for Highway Bridges, intensive earthquake motion with a short distance from an inland fault such as that generated by the 1995 Kobe

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earthquake was designated as a design earthquake motion called the Type II Earthquake Motion. With this, the design earthquake motions in the Design Specifications for Highway Bridges were organized into two levels, i.e., Level 1 and 2 Earthquake Motions, with three different earthquake motions. Note that the Type I Earthquake Motion representing earthquake motion generated by a large interplate earthquake, which is one of the Level 2 Earthquake Motions, was already employed in the 1990 Design Specifications for Highway Bridges. Ductility design was widely applied to bridge piers, foundations, bearing supports, and unseating prevention systems in the 1996 edition of the Design Specifications. The liquefaction potential assessment method was reviewed and revised for the Level 2 Earthquake Motion. Moreover, the seismic design of pier foundations for liquefaction-induced ground flow was newly prescribed.

Later, the Design Specifications for Highway Bridges were revised in 2002 (Japan Road Association, 2002, 2003). In this revision, emphasis was placed on the introduction of a performance-based design concept. For this, the principal requirements for the seismic performance of highway bridges, the design earthquake motions, and the verification of the seismic performance were explicitly specified. The verification methods for the seismic performance were reorganized into static analysis and dynamic analysis methods, and the selection of these two methods was based on the structural properties of highway bridges. A method for evaluating the seismic active earth pressure for the Level 2 Earthquake Motion, which is based on the modified Mononobe-Okabe method, was introduced. This was further applied to newly prescribe a verifying method for the seismic performance of abutment foundations for liquefaction during the Level 2 Earthquake Motion.

Most recently, the Design Specifications for Highway Bridges were revised in 2012 (Japan Road Association, 2012), just one year after the Great East Japan earthquake of 2011. In this earthquake, highway bridges suffered destructive damage, such as the washing away of superstructures as a result of the massive tsunami. The performance of highway bridges to ground motion differed according to the design years. Highway bridges designed by older specifications such as those earlier than the 1980 Design Specifications suffered damage similar to that observed in previous earthquakes. In contrast, those designed by newer specifications such as the 1990 Design Specifications or later performed well under the strong motions developed by the earthquake, and this contributed to the prompt relief from the earthquake and emergency response. In the revision of 2012, stress was placed on the importance of maintenance from the design stage, and the provisions were enhanced. The Type I Earthquake Motion was reviewed according to the results of recent research on large interplate earthquakes such as the Tokai, Tohnankai, and Nankai earthquakes. The provisions for unseating prevention systems were revised. Design considerations related to the connection of a bridge abutment and the earth structure behind it were introduced.

This report presents the major changes and improvements in the seismic design techniques for highway bridge foundations and their background since the 1995 Kobe earthquake, in relation to liquefaction potential assessment, ductility design of pier and abutment foundations for liquefaction, and seismic design of pier foundations for liquefaction-induced ground flow. Note that particular emphasis is laid on describing innovative design practice, and an overall review of previous studies is beyond the scope of this report. The same terms and symbols used in the Design Specifications for Highway Bridges are employed in this report to make it easier to understand the design practice.

2. Liquefaction potential assessment

2.1. Soil layers to be assessed

The 1995 Kobe earthquake caused liquefaction even at coarse sand and gravel layers that had been regarded as invulnerable to liquefaction, and the design practice changed to include both sandy and gravelly layers in the soil layers that require liquefaction potential assessment. The 1996 Design Specifications for Highway Bridges designated that the liquefaction potential should be assessed if an alluvial saturated granular soil layer meets the following three conditions:

(1) saturated soil layer located within 20 m from the ground surface in which the groundwater level is less than or equal to 10 m deep;
(2) soil layer with the fine particle content ratio FC equal to 35% or less, or the plasticity index I_p equal to 15 or less and
(3) soil layer with the mean grain size D_{50} equal to 10 mm or less and the 10% grain size D_{10} equal to 1 mm or less.

2.2. Estimation of liquefaction potential

The liquefaction potential is estimated by the liquefaction resistance factor F_L, where a soil layer with F_L of 1.0 or less is judged to be liable to liquefy during an earthquake. The liquefaction resistance factor F_L is defined as

$$F_L = R/L \tag{1}$$

where F_L is the liquefaction resistance factor, R is the dynamic shear strength ratio, and L is the shear stress ratio during an earthquake.

The dynamic shear strength ratio R is practically modeled as

$$R = c_W R_L \tag{2}$$

where c_W is the corrective coefficient for earthquake motion characteristics, and R_L is the cyclic triaxial strength ratio. c_W originally represented a correction coefficient accounting for the difference between the random earthquake loading and the sinusoidal loading normally used in the triaxial test, and was improved to consider different cyclic characteristics of earthquake motions, as discussed in a later section.

The shear stress ratio during an earthquake L may be expressed by the following equation, which is essentially the