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IMPROVING SEISMIC DESIGN OF HIGHWAY BRIDGES IN WESTERN CHINA

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ABSTRACT

The Chinese Government launched a twenty-year major road investment program, estimated at more than $50 billion, to improve the transportation infrastructure system in the western provinces of China in 1999. To assist the Chinese Government in addressing many technical challenges arising from this massive construction undertaking, the Canadian International Development Agency (CIDA), in collaboration with the Ministry of Communications (MOC) of China, has implemented a five-year Technical Assistance (TA) program entitled China Western Roads Development Project. It covers a broad range of technical areas. Improving seismic design of highway bridges (referred to as WBS 212) is one of the six TA assignments under the project output category of Improved Road Design. In the last three years, several TA missions on WBS 212 have been carried out by the author and significant progress has been made as per the project implementation plan. This paper provides an overview of the WBS 212 TA assignment including review of the current seismic design practice, an interim report on the TA activities and a brief summary of the first pilot project completed.

Introduction

The CIDA China Western Roads Development Project begins in 2003 and is expected to be completed in 2008. The main objective of this project is to provide technical assistance and training to Chinese senior officials at the provincial and central government levels. The project has three main categories of output:

- Improved access to poverty areas;
- Improved road design; and,
- Improved road maintenance.

Work Breakdown Structure (WBS) 212 - Seismic Design is one of the six TA assignments under the Improved Road Design and is being carried out by ND LEA Inc. (Canadian Executing Agency) and MOC/Yunnan Provincial Department of Communications (Chinese Executing Agency). As per the Project Implementation Plan (PIP) for the China Western Roads Development Project, the TA activities under WBS 212 include:

- Reviewing the current practice in seismic design of highway bridges in the western provinces;
- Identifying any shortcomings in the current knowledge of seismic analysis, evaluation and design of bridges;

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- Providing technical advices on new seismic design practice; and,
- Assisting in the development of seismic design and retrofit procedures.

This paper provides (a) a brief review of the current seismic design practice for highway bridges in the western China; (b) an interim report on the TA assignment on seismic design; and (c) a summary of the first pilot project completed on the seismic assessment and retrofitting of an existing six-span highway bridge.

Review of the Current Seismic Design Practice in Western China

In western China, the two most active seismic regions are located along Eurasian seismic belts: (1) the southwest region including Tibet, Yunnan and Sichuan; (2) the northwest region covering Qinghai, Ningxia and Xinjiang. The majority of earthquakes in western China are relatively shallow and the depth is typically within 50 – 60 kilometers. The largest earthquakes ever recorded in the regions were the 8.6 magnitude Chayu earthquake in Tibet in 1950 and the 8.5 magnitude Haiyuan earthquake in Ningxia in 1920.

Currently, there are several Chinese national seismic design codes dealing with a wide range of different disciplines of engineering, such as residential buildings, industrial structures, highways, railways, dams and nuclear power plants, etc. The leading code is the Chinese Building Code and the 2001 edition of this code requires consideration of three levels of performance: (1) no damage for a small earthquake of 65% probability of exceedance in 50 years; (2) repairable damage for a moderate earthquake of 10% in 50 years; and (3) no collapse for a large earthquake of 1 – 2% in 50 years. The design earthquakes are defined by the ground motion parameters of acceleration and characteristic period which are presented in the zonal maps. However, the seismic design code for highway bridges has not been updated since 1989 and the Ministry of Communications of China is currently in the process of revising the 1989 code. Until the new code is published, the 1989 edition is still the governing code for the highway bridge design in China including all western provinces.

Design Horizontal Peak Ground Acceleration

The 1989 bridge seismic design code is largely influenced by the seismic design method and recommendations proposed in ATC-6 (1981) and its design principle is based upon the elastic response spectrum method. It requires consideration of a single level of design earthquake having 10 - 13% probability of exceedance in 50 years. The design horizontal peak ground acceleration (PGA) is given in the code in terms of three levels of Basic Seismic Intensity (BSI), as shown in Table 1.

Table 1. Design horizontal peak ground acceleration for three levels of basic seismic intensity.

Basic seismic intensity	7	8	9
Horizontal PGA in g	0.1	0.2	0.4

The Basic Seismic Intensity is derived by assessing macro-seismic damage levels expected in a region and the 1977 zonal maps of BSI are the basis for the seismic design of highway bridges.

Seismic Forces on Piers

The seismic force demands on bridge piers are obtained by the elastic response spectrum method and are governed by the following three key parameters:

(1) **Bridge Important Factor, C_i**: it varies from 0.6 for a regular bridge on a Class III highway to 1.7 for a important bridge on an expressway or a Class I highway.

(2) **Soil Amplification Factor, β_1**: it depends on the fundamental period of free-vibration of the structure and the soil type at the bridge site. There are four soil types prescribed by the 1989 code: ***soil type I*** – rock or dense gravels; ***soil type II*** – loose to medium dense gravels, medium dense sands and stiff clay with an allowable bearing strength not less than 250 kPa; ***soil type III*** – loose sands, medium to dense fine sands, medium stiff clay with an allowable bearing strength less than 250 kPa and backfill soil with an allowable bearing strength not less than 130 kPa; and ***soil type IV*** – soft clay, loose fine sands and backfill soil with an allowable bearing strength less not 130 kPa.

(3) **Overall Influence Factor, C_z**: it accounts for the effect of a response modification factor, R, and its value can be interpreted as the inverse of an R-value. It varies between 0.20 and 0.35 depending on pier heights and configurations.

The 1989 bridge seismic design code also requires consideration of the soil and foundation interaction and the effects of lateral shear stiffness of elastomeric bearings and dynamic friction forces over PTFE sliding bearings in the elastic response spectrum analysis.

Seismic Forces on Abutments

The seismic force demands on bridge abutments in the longitudinal direction are obtained by the static method and are determined by the following simplified Mononobe-Okabe equation:

$$E_{ea} = \frac{1}{2}\gamma H^2 K_A (1 + 3C_i C_z K_h tg\phi) \quad (1)$$

Where E_{ea} is the total active earth pressure loading in kN/m to be applied at 0.4 H from the base of abutments; γ is the soil density in kN/m^3; H is the abutment height in m; K_A is the static active earth pressure coefficient; K_h is the design PGA coefficient as per Table 1; ϕ is the internal friction angle of the soil; C_i is the bridge important factor; and $C_z = 0.35$ which accounts for inelastic response of the soil.

The 1989 bridge seismic design code also requires consideration of the effects of liquefiable soil and hydro-static pressure on the seismic earth pressure loading.

Seismic Resistances of Foundation Soils and Piles

The 1989 bridge seismic design code allows for some increase of bearing capacity of foundation soils and piles in the case of seismic design. Table 2 shows that ratios of allowable seismic bearing capacity vs allowable static bearing capacity for various soil types.

Table 2. Ratios of allowable seismic bearing capacity vs allowable static bearing capacity.

Soil type	I	II	III	IV
Ratios	1.5	1.3	1.1	1.0

For end-bearing piles, a 50% increase in bearing capacity is generally permitted. For friction piles, however, the increase in bearing capacity shall be determined as per Table 2 above for a given soil type.

Seismic Detailing

There are some minimum requirements of seismic detailing specified in the 1989 bridge seismic design code and they include:

- Providing minimum support length to prevent longitudinal unseating of the superstructure;
- Using shear keys or transverse restrainers to limit the transverse movement of the superstructure;
- Providing lateral tie beam for tall pier column frames;
- Strengthening connections between cap beam and columns and between footing and columns;
- Providing transverse reinforcement for confinement at the top and bottom regions of column;
- Prohibiting the use of rocker type expansion bearings;
- Providing diaphragms to improve lateral response of beam-type superstructure; and
- Selecting abutment structures having better seismic resistance such as U-shape or box-type abutments.

It should be noted that most of these requirements are given in general terms only and they are lack of specific design clauses. One of the noticeable deficiencies in the seismic detailing is the insufficient design requirement for column transverse reinforcement. Specifically, there is no explicit design requirement for transverse reinforcement for circular columns except for minimum vertical spacing and minimum bar size.

In many respects, the 1989 bridge seismic design code lags behind the current state of practice in earthquake engineering design. Its design philosophy is largely based on the outdated force design method. It is expected that the bridges designed to the 1989 code are likely vulnerable to collapse and major damage under the design earthquake. A program of seismic retrofitting is necessary to bring these bridges to the seismic performance level of the new seismic design standards which are expected to be adopted in the near future.

An Interim Report on the TA Activities of WBS 212

Due to the SARS outbreak in the winter of 2003 and the spring of 2004, the start of the Technical Assistance (TA) program under WBS 212 – Seismic Design was delayed to the fall of 2004. In the last two years, a total of four TA missions were carried out by the author. Through collaboration with the Chinese counterparts, a number of TA objectives has been accomplished. Below is a brief summary of key TA activities performed by the author during the last four TA missions to China.

Field Visits

To gain the first-hand knowledge of the current status of seismic performance of existing bridges in western China, several field visits were carried out in the Province of Yunnan. Bridges in this province cover a broad spectrum of highway bridges including concrete arch bridges, cast-in-place/precast concrete girder bridges, concrete segmental bridges, and cable-stayed bridges. All of these bridges are located in an area of high seismicity with peak ground accelerations varying from 0.15 to 0.3g for the 1-in-475 years design earthquake. They were constructed in different eras spanning from the late 60’s to late 90’s. The majority of the existing highway bridges are concrete girder bridges with typical span lengths between 15 m and 30 m. In general, the bridges built prior to 1990 did not incorporate any seismic design requirement whereas the bridges constructed after 1990 have minimum provisions for seismic design. It is expected that the majority of the existing bridges are vulnerable to major damages from a major earthquake event. Some of older bridges are not expected to survive the shaking force of an earthquake. The Provincial Government of Yunnan has already recognized this problem and had started a preliminary investigation on the seismic vulnerability of the existing bridge inventory. However, they do not have any policy or procedure for the seismic vulnerability analysis.

Technical Training

Several technical training sessions were delivered in Yunnan, Guizhou, Beijing and Chongqing. More than 200 Chinese engineers attended these technical training sessions. The training topics were suggested by the Chinese side and included the following:

- Canadian seismic design practice for highway bridges;
- British Columbia seismic retrofit criteria for highway bridges;
- British Columbia experience on seismic retrofit of highway bridges;
- General overview of seismic hazard and mitigation measures for highway bridges;
- Integral (jointless) highway bridges;
- Fundamentals of structural dynamics and earthquake response analysis; and
- Practical design procedures and examples.

Guidelines for Preliminary Screening and Seismic Rating of Existing Highway Bridges

Based on the seismic vulnerability rating methods recommended in the 1995 FHWA Seismic Retrofitting Manual for Highway Bridges, a draft copy of the guidelines for preliminary screening and seismic rating of the existing highway bridges has been proposed to the Yunnan Provincial Department of Communications. The proposed guidelines take into account the new seismic design criteria recommended in the 2005 draft copy of the new Chinese bridge seismic design code, local construction methods, local bridge systems, commonly observed seismic deficiencies, and anticipated peak ground accelerations. The main objective of the proposed guidelines is to provide a simple and easy-to-use seismic rating system which requires minimum calculations but relies on accurate bridge inventory data.

Pilot Projects

The first pilot project selected for the TA program was the seismic retrofit of an existing highway bridge. Details of this pilot project are presented in the subsequent section. There are two more pilot projects planned for the remaining duration of the TA program. The main focus of these two additional pilot projects will be on promoting integral/semi-integral bridge design concepts for new highway bridge constructions in western China. This will not only significantly improve the seismic performance of the highway bridge but will also greatly enhance their long-term durability.

Design and Construction of the First Pilot Project

The Shi Yang Jiang Bridge, shown in Figure 1, is a six-span, simply supported, concrete slab/precast concrete ‘T’ girder bridge carrying two lanes of traffic. The original bridge was built in 1972, having five equal spans of 21.6 m with a total bridge length of 108 m. In 1986, a major flood event destroyed its west abutment causing collapse of the end span and severe damage to the adjacent pier (Pier 4). The collapsed end-span (Span 5) at the Muo Jiang side and the damaged Pier 4 were re-constructed in 1987. To minimize future flood damage, the new west abutment was moved further back from the river channel and a new pier (Pier 5) and a new span (Span 6) were added. The total bridge length was increased to 122 m and the number of spans increased to 6.

The superstructure of Spans 1 to 5 consists of five lines of precast, reinforced concrete ‘T’ girders with a cast-in-place reinforced concrete topping, all simply supported on the piers and east abutment. The new Span 6 is a simply supported concrete slab haunched near its supports. The piers consisting of twin concrete columns are either supported on drilled large diameter concrete piles (Piers 1, 2, 3 & 5) or on a piled footing (Pier 4). The piled footing of Pier 4 has a group of five drilled concrete piles, two of which are from the original construction. The original east abutment and the new west abutment are both constructed as a gravity masonry wall structure using large stone blocks. The original design as well as the subsequent reconstruction work did not have adequate capacity for earthquake loadings. Consequently, the bridge has a high vulnerability of collapse during a moderate to large seismic event.

Over the years, the bridge deck and precast concrete girders have deteriorated and shown extensive cracking due to a large volume of overloaded vehicles. Since 2004, use of the bridge has been reduced to one lane of traffic. The Yunnan Highway Bureau has determined that a major rehabilitation should be carried out as soon as possible. However, the original plan did not include any seismic retrofitting. Given the economic benefits, combined seismic and non-seismic rehabilitation was recommended and accepted by the Yunnan Highway Bureau.

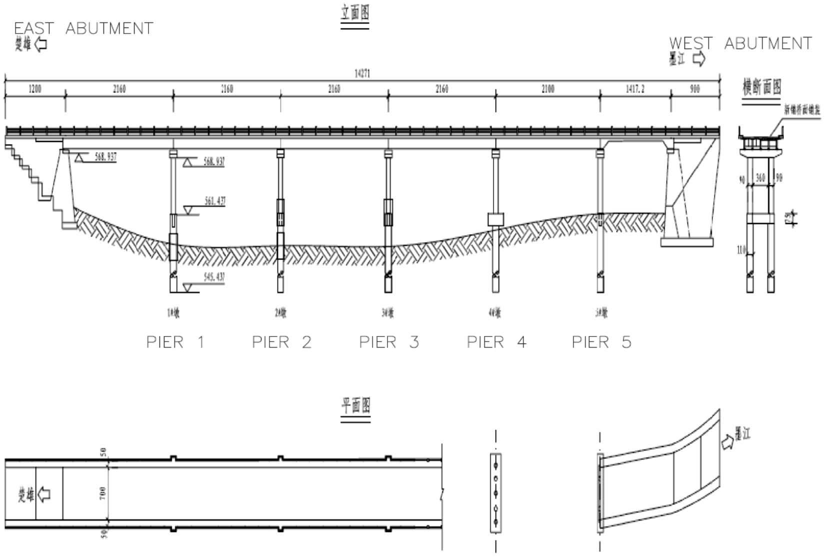


Figure 1. General arrangement of Shi Yang Jiang Bridge.

Assessment of Existing Structure

Design Earthquake and Seismic Resistance Design Criteria

The Shi Yang Jiang Bridge is located on a Class II highway linking two prefectures of Yuxi and Chuxiong. The bridge site is in the basic seismic intensity zone 7, with a peak horizontal ground acceleration of 0.1 g for the 1-in-475-year design earthquake. In accordance with the 2005 draft copy of the new bridge seismic design code, the Shi Yang Jiang Bridge is classified as a Class B Structure and should be upgraded to the basic seismic intensity zone 8.

Sub-Soil Condition and Preliminary Geotechnical Assessment

In a 1987 Rehabilitation Design Report for the Shi Yang Jiang Bridge, the sub-soil condition at the bridge site was described as follows:

- The river bed up to a depth of 4.6 m is generally a mix of sand and gravels;
- Below the sand and gravels, there is a layer of fine sand up to 4.3m thick; and
- Below the fine sand, there is approximately 4.0m thick weathered sandstone, followed by bed rock.

The sub-soil condition is rated as Class III as per the 2005 draft copy of the new code. A preliminary geotechnical assessment indicated that the bridge foundation soils are relatively competent and have a low risk of liquefaction. Consequently, no further geotechnical investigation and assessment was carried out except for evaluation of the existing pile capacity.

Seismic Assessment Methodology

The seismic assessment methodology used for the present study can be summarized by the following procedures:

(1) Determine the design response spectrum based upon the site-specific peak horizontal ground acceleration and site soil conditions;

(2) Carry out an elastic multi-modal spectral analysis of the bridge structure using effective member stiffness and taking into account the effects of soil-structural interaction to obtain the displacement demands for all piers;
(3) Perform 'push-over' analysis of the entire bridge system to obtain the displacement capacities of individual piers or the entire bridge system; and,
(4) From the 'push-over' analysis and considering the over-strength effects, the force demands are checked against the force resistance of the members.

The elastic multi-modal spectral analysis and non-linear 'push-over' analyses of the bridge were carried out using the SAP2000 computer program (2003). The non-linear moment-curvature analysis of the pier columns was based on an in-house computer program CCFyber2004 (2004) developed by the Chongqing Communications Research & Design Institute. The results obtained from CCFyber2004 were verified using a similar computer program UCFyber (1999).

The existing bridge superstructure has three expansion joints placed at each end of the bridge and over Pier 4. For a regular bridge like the Shi Yang Jiang Bridge, the seismic analysis can be performed by modelling individual frames separately. Each frame would then represent a set of the structural members between two adjacent expansion joints. For the present study, however, a stick-model of the entire bridge structure was used to perform the elastic spectral analysis and 'push-over' analysis for both longitudinal and transverse motions.

The shear assessment of the pier columns was based on the capacity design principles and the shear capacity of pier columns follows the Caltrans seismic design criteria (2001). The shear keys at Piers 4 and 5 were evaluated by considering three possible failure modes: (a) shear friction; (b) flexural; and (c) strut-and-tie.

Development of Seismic Retrofit Strategy

After carefully evaluating the pros and cons of all feasible solutions, the project team adopted an innovative retrofit strategy which will not only effectively address the seismic deficiencies, but also significantly improve the load carrying capacity and serviceability of the bridge.

The first innovation is to change the bridge deck articulation such that the re-constructed deck slab is continuous from Span 1 to Span 5. Among many other benefits, the strategy of constructing a continuous deck will

- eliminate maintenance-intensive deck joints;
- redistribute live load bending moments, thereby reducing positive bending moment demand on the existing 'T' girders;
- tie simply supported beams together in longitudinal direction, thereby eliminating the necessity of installation of seismic restrainers;
- reduce vehicle-induced vibration; and,
- provide a better riding surface for the traveling public.

The second innovation is attributed to the concept of semi-integral abutments and incorporation of approach slabs. This concept has been used for new bridge construction in North America since the 1990's. However, its application in a retrofit environment is relatively new. For the Shi Yang Jiang Bridge seismic retrofit, the use of semi-integral abutments will result in the following benefits:

- It will eliminate a deck joint between the deck slab and abutment ballast wall;
- It will engage the passive earth pressure resistance of the backfill material, thereby transmitting the bridge inertial forces directly into the soil and reducing seismic demands on the bridge substructures;
- It will provide additional support length without modifying the seat width of abutments; and
- It will improve the distribution of live load forces.

Similarly, the use of approach slabs at the bridge ends will result in the following benefits:

- It will act as a tie-back system to the bridge superstructure under seismic loading;
- It will prevent the adverse effect of the abutment backfill settlement; and,
- It will reduce lateral earth pressures and the live load surcharge loading on the abutment.

The third innovation relates to the constructability of the proposed retrofit strategy. As part of the overall objectives for the pilot project, it was recognized that any recommended retrofit measures should be designed to suit the local construction capability and should use the locally available materials. To this end, the project team went to the bridge site and held an on-site meeting with the field engineers of the Yunnan Highway Bureau who was responsible for the construction phase of the pilot project. The valuable input was received on constructability issues, and consequently, the final recommended retrofit measures are all conventional and can be readily constructed by using local equipment and materials.

Substructure Retrofit Design and Construction

The substructure retrofit design and construction included (a) concrete jacketing of the column base and its connection to a drilled concrete pile for Piers 2 and 3; (b) modification of the existing abutments to a semi-integral configuration; and (c) incorporation of approach slabs at the bridge ends. The details of concrete jacking are illustrated in Fig. 2 (a) and the completed columns at Pier 2 are shown in Fig. 2(b). A typical design for the semi-integral abutment and approach slab is presented in Fig. 3.

Superstructure Retrofit Design and Construction

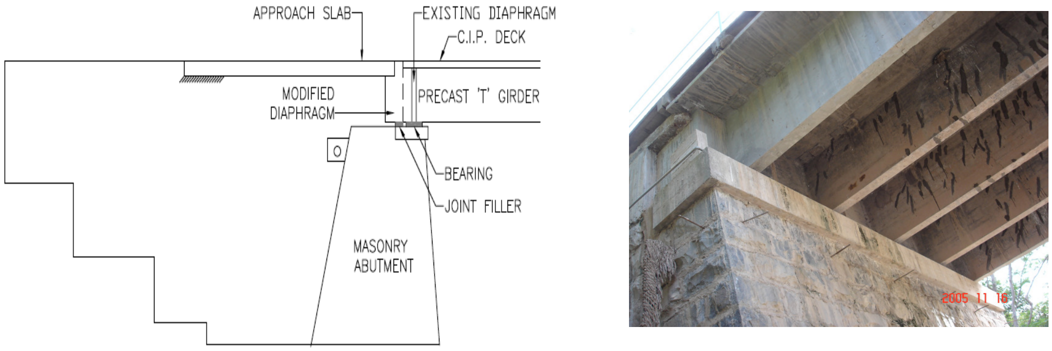
The superstructure retrofit design and construction involved the following tasks:

- Replacing the existing deck with a continuous deck from Span 1 to Span 5;
- Strengthening the existing pier diaphragms for Piers 1 to 4;
- Constructing new transverse shear keys on all piers and abutments;
- Installing new longitudinal restrainers between Span 5 and Span 6; and,
- Providing concrete encasement of vulnerable expansion rocker bearings.

The details of longitudinal restrainers are illustrated in Fig. 4 and a typical concrete encasement of a rocker bearing is depicted in Fig. 5.

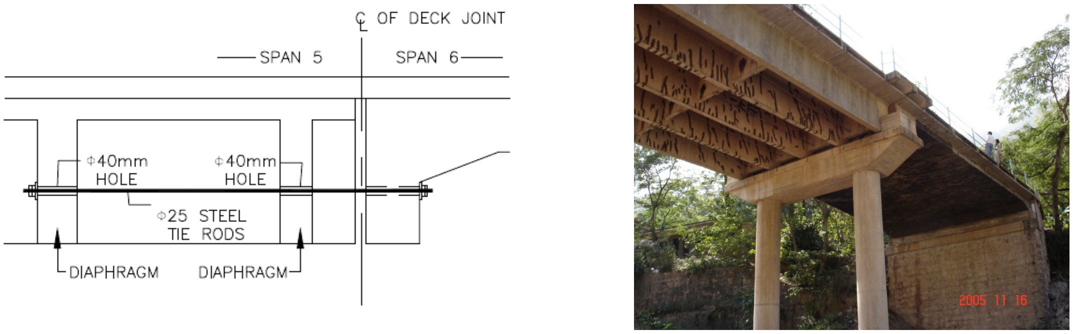
(a) (b)

Figure 2. Pier column concrete jacketing: (a) reinforcement detail; (b) completed columns.



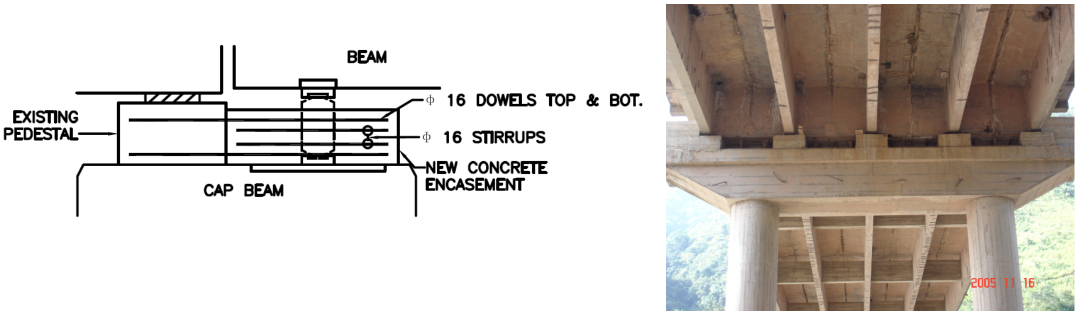
(a) (b)

Figure 3. Details of semi-integral abutment and approach slab: (a) illustration; (b) completed abutment.



(a) (b)

Figure 4. Longitudinal restrainer installed between Span 5 and Span 6: (a) illustration; (b) completed restrainers.



(a) (b)

Figure 5. Concrete encasement of existing rocker bearings: (a) illustration; (b) completed encasement.

Conclusions

The current seismic design practice for highway bridges in western China requires significant improvement in order to catch up with the current advances in earthquake engineering. The new Chinese seismic design code for highway bridges is expected to be issued by MOC for implementation in the near future. In the interim, effort should be made in the dissemination of best practices in seismic design. This is one of the main objectives of the TA assignment of WBS 212.

Acknowledgements

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