Soil Dynamics and Earthquake Engineering 74 (2015) 56–68

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

journal homepage: www.elsevier.com/locate/soildyn

Modelling of shear keys in bridge structures under seismic loads

Kaiming Bi*, Hong Hao

Department of Civil Engineering, Curtin University, Kent Street, Bentley, WA, 6102, Australia

ARTICLE INFO

Article history:
Received 12 May 2014
Received in revised form
27 November 2014
Accepted 20 March 2015
Available online 11 April 2015

Keywords:
Shear key
3D model
Seismic response
Failure mode
Damage mechanism

ABSTRACT

Shear keys are used in the bridge abutments and piers to provide transverse restraints for bridge superstructures. Owing to the relatively small dimensions compared to the main bridge components (girders, piers, abutments, piles), shear keys are normally regarded as secondary component of a bridge structure, and their influences on bridge seismic responses are normally neglected. In reality, shear keys are designed to restrain the lateral displacements of bridge girders, which will affect the transverse response of the bridge deck, thus influence the overall structural responses. To study the influences of shear keys on bridge responses to seismic ground excitations, this paper performs numerical simulations of the seismic responses of a two-span simply-supported bridge model without or with shear keys in the abutments and the central pier. A detailed 3D finite element (FE) model is developed by using the explicit FE code LS-DYNA. The bridge components including bridge girders, piers, abutments, bearings, shear keys and reinforcement bars are included in the model. The non-linear material behaviour including the strain rate effects of concrete and steel rebar are considered. The seismic responses of bridge structures without and with shear keys subjected to bi-axial spatially varying horizontal ground motions are calculated and compared. The failure mode and damage mechanism of shear keys are discussed in detail. Numerical results show that shear keys restrain transverse movements of bridge decks, which influence the torsional–lateral responses of the decks under bi-axial spatially varying ground excitations; neglecting shear keys in bridge response analysis may lead to inaccurate predictions of seismic responses of bridge structures.

1. Introduction

Shear keys are normally used in the bridge abutments and piers to restrain the excessive transverse displacements of bridge superstructures during service load and moderate earthquakes. However, during the maximum considered earthquake, shear keys are expected to break off before damages occur in bridge abutments or piers. In other words, shear keys are designed as sacrificial elements and expected to perform as structural fuse to protect the bridge abutments or piers from damage during major earthquakes. Depending on the strength of shear key and the pounding force between shear key and corresponding bridge girder, serious, moderate or minor shear key damages were observed in many previous major earthquakes. Fig. 1(a) shows that shear keys were totally sheared off and large transverse displacements occurred at bridge girders due to loss of restraints [1]; an obvious diagonal crack developed at the stem wall of abutment is shown in Fig. 1(b) [2]; and Fig. 1(c) shows that flexural failure was initiated at the shear key-stem wall interface [3].

Seismic induced pounding responses of bridge structures have been extensively studied by many researchers. However, these studies mainly focused on the pounding between main components of bridge structures, i.e. between bridge girders or between bridge girder and adjacent abutment e.g. [4–6]. Hao et al. [7] gave a state-of-the-art review on previous studies. It should be noted that most of previous studies modelled the bridge girder as a lumped mass or beam-column elements and the pounding by a contact element. These simplified models can be easily implemented in the FEM programs. However, because these are 1 dimensional (1D) models, they can only simulate point-to-point pounding with the pre-defined pounding locations. In a real bridge structure under seismic loading, pounding could take place along the entire surfaces of the adjacent segments. Moreover, torsional responses of adjacent girders induced by spatially varying transverse ground motions can result in eccentric poundings that occur at corners of adjacent decks. In fact most poundings observed in previous earthquakes were associated with eccentric poundings, i.e., pounding occurred at corners of adjacent bridge structures. To realistically capture the surface-to-surface and eccentric poundings, a detailed 3D finite element (FE) model is needed. More recently, Bi et al. [8]

* Correspondence to: Room 414, Building 204, Curtin University, Kent Street, Bentley, WA 6102, Australia. Tel.: +61 8 9266 5139.
E-mail address: kaiming.bi@curtin.edu.au (K. Bi).

http://dx.doi.org/10.1016/j.soildyn.2015.03.013
0267-7261/

Fig. 1. Typical shear key damages: (a) totally shear off [1]; (b) diagonal shear failure [2]; and (c) flexural failure [3].

developed a detailed 3D FE model of a two-span simply-supported bridge and validated the accuracy of using LS-DYNA to simulate surface-to-surface and eccentric poundings. Bi and Hao [9] then further extended this method by involving the non-linear material properties of concrete and steel rebars in the model and examined the influences of pounding-induced local damage on bridge responses under spatially varying earthquake loadings. In the latter studies, only the poundings between adjacent bridge spans/decks are considered. Although shear key damages due to deck pounding have been observed in many previous earthquakes, none of these studies considered the shear keys and their influences on overall bridge responses. This paper extends the previous studies [8,9] on detailed modelling of pounding damages between adjacent bridge spans to bi-axial spatially varying horizontal ground motions by including shear keys in the model. The poundings between shear keys and bridge decks are modelled and examined in detail. Since pounding between deck and shear key prevents excessive transverse movements of the deck and absorbs a large amount of energy, it may significantly affect the overall bridge structural responses. Therefore the influence of including shear keys in the analysis of bridge responses is also investigated and discussed in the present paper.

Limited research is available in the literature on the seismic performance of bridge shear keys. Bozorgzadeh et al. [10,11] carried out experimental studies to assess the shear strength and failure mode of exterior shear keys in bridge abutments under transverse forces. Two kinds of failure mechanism, i.e. sliding shear failure and diagonal shear failure, were identified for exterior shear keys. Silva et al. performed experimental and analytical investigations to evaluate the seismic performance of sacrificial interior [13] and exterior [14] shear keys. Rational models of the force and deformation capacity of shear keys as well as their postpeak performance under cyclic loads were proposed based on the experimental data. Maleki investigated the seismic performance of ordinary [15] and skewed [16] bridges with retainers placed on each side of elastomeric bearings. Design recommendations were proposed for bridges with such retainers. Goel and Chopra [17] examined the role of shear keys at bridge abutments on the seismic behaviour of ordinary bridges crossing fault-rupture zones. Three different shear key conditions, i.e. nonlinear, linear and no shear keys, were examined. Numerical results show that seismic demands for a bridge with nonlinear shear keys can generally be bounded by the demands of a bridge with elastic shear keys and a bridge with no shear keys.

It can be seen that previous studies on the shear key mainly focused on its shear strength. The investigation of the influence of shear keys on the whole bridge responses, i.e., restraining the transverse deck movement which may influence the overall bridge responses because of the restrained torsional responses of the deck, were relatively less. Moreover, all these studies [15–17] used the simplified spring-dashpot elements to model the pounding between shear key and bridge girder/bearing, indicating only point-to-point pounding by assuming uniform contact between deck and shear key was considered. In reality, spatially varying earthquake ground motions always induce torsional responses on even a perfectly symmetric bridge deck, which usually cause eccentric pounding between bridge deck and shear key, as observed in many earthquakes, e.g. Fig. 1(c). Thus it is important to develop a detailed 3D model that can simulate the surface-to-surface and eccentric poundings for more realistic predictions of interactions between bridge superstructures and shear keys.

In this study a two-span simply-supported bridge located at a canyon site is selected as an example to investigate the seismic induced poundings between bridge decks and shear keys and their influences on the overall bridge responses. This work is an extension of the authors' previous work [9]. The primary differences between the current study and the previous work include: (1) detailed 3D models of shear keys are included in the numerical simulation; (2) poundings between shear keys and bridge girders are examined in detail; (3) the influence of shear keys on overall bridge responses are discussed; and (4) the failure mode and damage mechanism of shear keys due to pounding with bridge decks are examined.

Many previous studies (e.g. [18,19]) revealed that soil–structure interaction (SSI) can further alter the bridge responses under earthquake loadings. Not to further complicate the problem, SSI is, however, not considered in the present study since the primary aim of this study is to investigate the influence of shear keys on the seismic induced pounding responses of bridge structures. It is believed that the general observations made in this study regarding the influence of shear keys on the seismic responses of bridge structures will not be changed although SSI is not considered. In fact, this is not an uncommon practice in studying the pounding responses of engineering structures subjected to earthquake loadings, e.g. Refs. [4,5,20–23] among many others did not consider the influence of SSI.

2. Finite element model

2.1. Bridge details

Fig. 2 shows the elevation view of a two-span simply-supported bridge located at a canyon site. The length of each box girder as shown in Fig. 3(a) is 30 m. To allow for contraction and expansion of bridge girders from creep, shrinkage, temperature fluctuation and traffic without generating constraint forces in the structure, a 60 mm gap is introduced between the abutment and the bridge girder and between the adjacent girders. The cross section at the central pier is shown in Fig. 3(b). The pier foundation is a strip footing with the dimension of $6 \times 4 \times 1.8\ m^3$. The height of the two-square-column central pier is 9 m, and the length and width are 1.2 m respectively. Fig. 3(c) shows the cross