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Seismic analysis of highway skew bridges with nonlinear soil–pile interaction

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ABSTRACT

Performance of highway bridges during an intense seismic event is an issue of utmost importance. Of particular interest is the response of skewed highway bridges, where the skew angle and other related factors make the problem more complex. Although a number of studies had been carried out to address these issues in the past, most of them have neglected or over-simplified the soil–structure interaction effects, primarily relying upon the assumption that soil–structure interaction generally leads to a conservative estimation of seismic demands. The present study focuses on investigating the effect of skew angle on seismic response of a bridge-foundation system including nonlinear soil–pile interaction subjected to bi-directional ground motions. It has been observed that the rotational demand of the bridge deck is greatly affected by the skewness, indicating an increased vulnerability of skewed bridges due to rotational movement of the deck leading to deck unseating. It is also observed that the shear and moment demands of the piers increase significantly with increasing skew angle, as much as 54% and 37%, respectively. The maximum bending moment of the pile shaft is also found to increase upto 55%, indicating higher design requirements for the foundation components of the skew bridges compared to a similar normal bridge.

Introduction

Skewe bridges are increasingly used in the highway intersections and interchanges mainly to overcome the space constraint. A bridge can be designated as a skew bridge when the centerline of the bridge and the centerline of the abutment and/or pier cap are non-perpendicular to each other (Fig. 1). The skewed geometry of the bridge affects the static and dynamic load transfer mechanism of the system, and subsequently may lead to an altered force and displacement demand. Moreover, the skew bridges are strongly influenced by the abutments, as the center of the mass of the superstructure and the center of the stiffness for the abutment do not coincide, the inertial loading on the bridge tends to cause bridge rotation about its vertical axis, leading to an excessive transverse moment and unseating of the superstructure and pounding to the abutment walls. For example, during 1971 San Fernando earthquake, the Foothill Boulevard Undercrossing in California suffered a rotation in the horizontal plane resulting in a permanent offset of about 10 cm (4 inch) in the direction of increasing skewness at the abutment (Meng and Lui, 2000). Further, during 1994 Northridge earthquake, the abutments of the Pico-Lyons skewed bridge located near Newhall, California, had experienced a movement of about 51 mm (2 inch) in the transverse direction (Apirakvorapinit et al., 2012).

A number of research efforts have been made in the last few decades to understand the load transfer mechanism of

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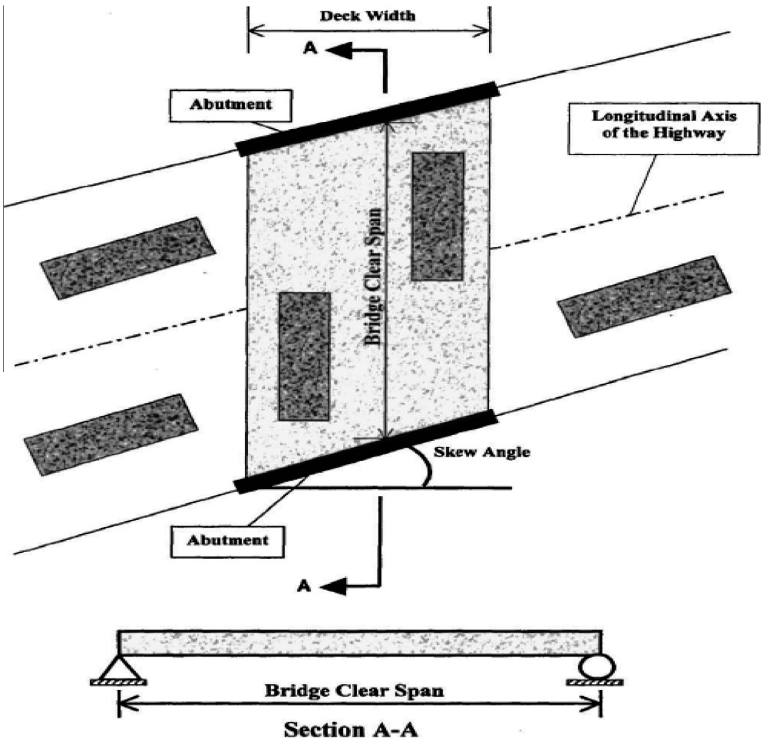

Fig. 1. Schematic description of a skew bridge (Menassa et al. 2007).

skewed bridges under static and dynamic loading conditions. Some of these studies have adopted numerical modeling, whereas others relied upon experiments on bridge component models, or field observations. Followed is a brief discussion on studies carried out to understand the behavior of skewed bridges.

Literature review

In a pioneering study, Ghobarah and Tso (1973) adopted a beam model to take into account the flexural and torsional modes of the deck of a skew bridge. Bakht (1988) critically reviewed the design practice of skew bridges through analyzing skewed slab-on-girder bridges and concluded that if the effect of skew angle is ignored, the maximum moment demand will be over-estimated, but the maximum longitudinal shear demand may be under-estimated leading to an un-conservative design. Meng and Lui (2000) focused on the superstructure flexibility, substructure boundary conditions, structural skewness and stiffness eccentricity in their model. Menassa et al. (2007) investigated the effect of the span length, slab width, and skew angle on the response of a simple-span reinforced concrete bridge using finite element method. It was observed that the AASHTO LRFD design specifications overestimated the maximum longitudinal bending moment, and this overestimation increases with increasing skew angle. Shamsabadi and Yan (2008) developed a global three-dimensional finite-element model for the seismically instrumented Painter Street Overpass incorporating nonlinear foundation–soil interaction. The results of the analyses showed that the modeling of the pile foundations at the bent contributed less to the overall bridge response as compared to the abutments. Huo and Zhang (2008) studied the skewness effect on live load reactions at the piers of continuous bridges. Kalantari and Amjadian (2010) proposed an approximate hand-method for dynamic analysis of a skew highway bridge with continuous rigid deck. Apirakvorapinit et al. (2012) conducted a series of pushover and dynamic analyses using a nonlinear finite element model of Pico-Lyons Bridge showing that at the end girders the percentage increase in stress due to skewness can be 50–60% for skew angle of 40°. In a recent study, Deepu et al. (2014) carried out a dynamic analysis of a number of 3D finite element models of various bridge configurations incorporating 0°, 15°, 30°, 45° and 60° skew angles using SAP 2000 software, with an assumption that the bridge piers are fixed at their bases. It was found that the skewed-bridge decks undergo significant rotations about the vertical axis during seismic ground events and are permanently displaced from the original location at the end of the shaking.

Provisions in the design codes

In the past, the skewed bridges were analyzed, designed, and constructed in the same way as straight bridges regardless of the magnitude of the skew angle. For example, AASHTO (2003) standard specifications used to provide distribution factors for the interior girders of simply supported bridges as a function of girder spacing. It did not specify the consideration of the effect of the skew angle and bridge continuity. In its more recent version,