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EFFECT OF SKEW ON THE SEISMIC RESPONSE OF RC BOX-GIRDER BRIDGES

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ABSTRACT

Seismic vulnerability of highway bridges remains an important problem and has received increased attention as a consequence of unprecedented damage observed during major earthquakes. A significant number of research studies examined the performance of skew highway bridges under service and seismic loads. It is noted that results of these studies are particularly sensitive to modeling assumptions in view of the interacting parameters which include: (1) skew angle, (2) superstructure flexibility, (3) boundary conditions, (4) in-span hinges (if any), (5) width-to-span ratios, and (6) mass and stiffness eccentricity. To investigate basic seismic response characteristics of two-span skewed post-tensioned box-girder bridges, three dimensional enhanced beam stick models of bridges with skew angles varying from 0 to 60 degree are developed. Relative accuracy of simplified beam-stick models are verified against counterpart finite element models. Both SAP2000 and DRAIN3DX programs were employed in the study. Effect of various parameters on the overall seismic performance was examined such as: effect of skew angle, levels of ground motions, soil conditions, support (foundation) conditions, end conditions (with and without abutment shear-keys), and aspect ratio.

Introduction

Design codes and guidelines for static and dynamic analyses of regular bridges are well-established and understood. However, there remains significant uncertainty with regard to the response characteristics of skew highway bridges as it is reflected by the lack of detailed procedures in the current guidelines. As evidenced by past seismic events (e.g. 1994 Northridge – Gavin Canyon Undercrossing and 1971 San Fernando – Foothill Boulevard Undercrossing), skew highway bridges are particularly vulnerable to severe damage due to earthquakes. Even though a number of studies have been conducted over the last three decades, research findings have not been sufficiently comprehensive to address the response characteristics of skew highway bridges under static and dynamic loading. Therefore, a large number of highway bridges are still at risk with consequential threat to loss of function, life safety, and economy following a major earthquake.

It is generally agreed that bridges with skew angles greater than 20 degrees exhibit complex response characteristics under seismic loads. Several studies have investigated the effect of skew angle on the response of highway bridges. Saiidi and Orie (1991) noted the skew effects and suggested that simplified models and methods of analysis would result in sufficiently accurate

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predictions of seismic response for bridges with skew angles less than 15 degrees. On the other hand, Maleki (2002) concluded that slab-on-girder bridges with skew angles up to 30 degrees and spans up to 20 m have comparable response characteristics to straight bridges, and therefore, simplified modeling techniques such as rigid deck modeling were justified in many cases. Bjornsson et al. (1997) conducted an extensive parametric study of two-span skew bridges modeled with rigid deck assumption. In this study, maximum relative abutment displacement was found to be influenced strongly by the impact between the deck and the abutments. Critical skew angle was introduced as a function of span length and width that maximizes the rotational impulse due to impact and it was found to be between 45 and 60 degrees.

In comparing results across various analytical studies, one must consider the underlying assumptions implemented in the analytical treatment of the skew highway bridges. These may pertain to material modeling, inelastic (hysteretic) response characteristics of components, boundary conditions, soil-structure interaction, component geometry (i.e. idealized beam-stick versus full finite element), superstructure (i.e. rigid versus flexible), seismic mass (i.e. distributed versus lumped), etc. For instance, Meng and Lui (2000) suggested that the effects of modeling boundary conditions properly may outweigh the effects of skew angle on the overall dynamic response characteristics of a bridge. In fact, differences in assumptions may lead to inconsistent results as seen in the analysis of the Foothill Boulevard Undercrossing, which sustained severe damage during the 1971 San Fernando earthquake. A study conducted by Wakefield et al. (1991) concluded that the failure was controlled by rigid-body motion, which agreed with a previous study conducted by Maragakis (1984). On the other hand, a study conducted by Ghobarah and Tso (1974) explained that highway bridges are sensitive to damage due to earthquake. Ghobarah and Tso (1974) assumed the deck was fixed at the abutments, while Wakefield et al. (1991) assumed free translation of the deck at the abutments. Meng et al. (2001) concluded that response of skew bridges depend on deck aspect ratio, stiffness eccentricity ratio, skew angle, natural frequency, and frequency ratio. Meng and Lui (2002) introduced and validated an accurate dual beam stick modeling technique for skew bridges. The present study utilizes this approach and introduces further improvements.

Benchmark Bridge

The geometry and properties of a so-called benchmark bridge was established based on data collected from twelve reinforced-concrete box-girder bridges located in California. The average properties were best represented by one of the twelve bridges which was selected for further analytical investigation. Hence, the benchmark bridge is a two-span concrete box-girder bridge with a span length of 40.85 m. In addition, the selected bridge has the largest skew angle of 52 degrees with an aspect ratio of approximately 0.3. The aspect ratio is defined as the ratio of the width (including the overhang) to the span length of the bridge. Fig. 1 shows the cross section of the benchmark bridge. Subsequently, the benchmark bridge model was altered to develop models with various skew angles and aspect ratios (Figs. 2 and 3).

Modeling of Bridges

In order to facilitate a comprehensive analytical study, improved three-dimensional (3D) beam-stick models of the bridges were developed (Fig. 4). Significant effort was necessary to arrive at consistent inelastic modeling assumptions for various structural details. Attention was given to ensure that the models were general enough to capture the global response characteristics and at the same time detailed enough to allow accurate estimation of component level seismic response, both in elastic and inelastic ranges.

In light of these objectives, both 3D finite element (FE) and improved 3D beam-stick (BS) models of selected bridge geometries were developed. SAP2000 (CSI, 2005) was used to develop detailed nonlinear 3D FE as well as improved BS models, whereas DRAIN3DX (Prakash et al., 1994) was employed to develop the improved BS models only. In all of the models, the superstructure was assumed to be linear elastic and all of the nonlinearity was assumed to take place in the substructure elements including, bents, shear keys, and in terms of abutment-soil interaction. In order to assess and ensure the accuracy of the simplified models, FE and BS models of the same bridge geometries were subjected to the same excitation and results were compared in terms of both global and component level response (Abdel-Mohti, 2009). Improved 3D BS models were deemed sufficiently accurate and efficient compared to their 3D FE counterparts (Fig. 5). Table 1 along with Figs. 1,2, and 3 summarize the properties of superstructure, bent cap beam, and bent columns for bridges with different aspect ratios considered in this study.

Parametric Study

Nonlinear models of the benchmark bridge was further refined and updated following a detailed parametric study. The primary purpose was to arrive at proper modeling techniques and assumptions to represent nonlinear response characteristics of bent columns, abutment-soil interaction, and shear keys to enable accurate and reliable system response prediction and assessment. Various modeling alternatives in both SAP2000 and DRAIN3DX were investigated and calibrated using some of the available experimental data. Also, a preliminary comparative nonlinear time history analysis was conducted to ensure the accuracy of beam stick models. For the modeling of nonlinear column behavior, various fiber distribution alternatives were considered. The various fiber distributions include testing twelve concrete wedges, for each of the inner and outer core, and adding concrete fibers surrounding the reinforcement. Fibers surrounding reinforcement means to add fibers very close to the reinforcement and the concrete cover to capture the initial failure. The fiber distribution that has the concrete fibers surrounding the reinforcement was recommended and used in the remaining of this study. Also, it was recommended that the column should be divided into number of fibers which satisfy the condition that the fiber section length is at least 10% of the column height. In addition, it is recommended for the realistic system response prediction, the abutment-soil interaction is included in the bridge response studies. In SAP2000 models, nonlinear abutment-soil response is modeled using a combination of multi-linear and nonlinear link elements. Megally, et al. (2002) studied experimentally cyclic pushover response of both internal and external shear-keys. Capacity determination of external shear-keys in this study has been adopted and nonlinear external shear-key response is modeled using a combination of series of link elements to simulate the entire hysteretic response using SAP2000.

A wide range of parameters and their effects on the seismic response of bridges with various skew angles were investigated. As the accuracy of the improved BS models was established (Figure 5), subsequent investigation was conducted using DRAIN3DX. The effect of the following on the seismic performance of the skew bridges were investigated: 1) skew angle (0 – 60), 2) ground motion intensity (0.3g – 0.6g), 3) soil type (B and D), 4) abutment support conditions including abutment-soil interaction and shear keys. It is noted that all of the models included spring elements to model abutment-soil interaction and shear key hysteretic response explicitly, unless otherwise noted, 6) bridge aspect ratio (0.3, 0.54, 1.1), and 7) foundation boundary conditions (fixed, pinned).

Selection of Ground Motions

The benchmark bridge (52° skew) was designed according to a site specific response spectra for soil type D with moment magnitude, M_W of 6.5 and peak ground acceleration (PGA) of 0.3g. Two soil types (D and B), two PGA levels (0.3g and 0.6g), and six ground motions for each of the PGA levels were selected. The acceleration time histories were obtained from PEER Strong Motion Database (http://peer.berkeley.edu/ smcat) for epicenteral distances of up to 30 kilometers. The stronger component of each ground motion is applied in the transverse direction of the bridge models while the weaker component is applied in the longitudinal direction. It is noted that no significant effect of orientation of excitation with respect to the skew angle is expected (Schroeder, 2006). The ground motions selected for soil type D are El Centro 1940, El Centro 1979, Loma Prieta 1989, Northridge 1994, Superstition Hills 1987, and Kocaeli Turkey 1999; and El Centro (Bond Corner) 1979, Duzce Turkey 1999, El Centro (Array #5) 1979, Loma Prieta 1989, Northridge (NewHall) 1994, and Northridge (Sylmar) 1994. Similarly, the ground motions selected for soil type B are Castaic 1971, Duzce Turkey 1999, Lake Hughes 1971, Loma Prieta 1989, Morgan Hill 1984, and Tabas Iran 1978; and Coalinga 1983, Duzce Turkey 1999, Kobe 1995, Loma Prieta 1989, Northridge (Castaic) 1994, and Northridge (Katherine) 1994, respectively.

Seismic Response of Skew Bridges

Larger response quantities (deformations, forces, etc.) were observed with larger levels of ground motions, larger aspect ratios, and increasing skew angles in general. Nonetheless, bent columns as well as shear keys remained linear-elastic as shown in Fig. 6 with negligible abutment-soil interaction during the design level of excitations (0.3g). Note that, the plot of abutment-soil interaction is not shown here. This study suggests that failure of shear keys is followed by elevated transverse displacements and increased demand on columns (Figs. 7 and 8). It was also noted that the relative effectiveness of shear keys in controlling the seismic response of bridges diminish as the skew angle becomes larger. For Mzz (Fig. 7), some discrepancy was observed in terms of trend for bridges with and without shear keys. Response of bridges with shear keys increases with skew while response of those without shear keys decreases with skew showing larger response. This observation confirms that the effectiveness of shear keys reduces as skew angles increases. Skewed bridges that were modeled without the shear keys experienced larger gap openings at the acute corner that became smaller toward the obtuse corner (Fig. 9). The observation was valid for all skew angles and for all aspect ratios as well. The gap opening was significantly smaller in bridges modeled with the shear key elements. The absence (or failure) of shear keys leads to elevated abutment-soil structure interactions (Fig. 9). Gap opening in the abutment support length is larger and increases with skew. Introducing larger aspect ratios slightly increased displacement in the longitudinal and significantly increased displacement in the transverse direction of the bridge deck (Fig. 8). The bent forces on columns increased which led to the increased demand on columns. However, complex response behavior was observed in bridges with larger aspect ratios. On the other hand, gap opening and closing at the abutments become more pronounced and the demand on shear keys increased, and larger in-plane deck rotations with skew was evident. Uneven distribution of abutment forces may take place which can lead to progressive failure, and complex global system behavior. It is noted that only a very short summary and brief highlights of analytical observations are presented in this paper due to space limitation.

Concluding Remarks

Behavior of skew highway bridges is complex and modeling assumptions affect the analytically predicted seismic performance. Moreover, modeling of the abutment is critical for realistic response assessment. It was demonstrated that improved beam stick models may be used to conduct accurately nonlinear time history analyses of skew bridges. One very important aspect of nonlinear analysis is the need to identify and model accurately the inelastic response characteristics of individual components. For this reason, nonlinear response due to abutment-soil interaction, shear key and bent columns were incorporated explicitly. In general, larger deformations and forces were observed with increasing skew angles. The critical effect of shear keys on the seismic response of skew bridges with respect to abutment support length, bent column forces, and deck displacements has been demonstrated. Further research is necessary to develop practical design guidelines to account for the complex skew response and interactions thereof.

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Table 1. Section Properties of Bridges with Aspect Ratio of 0.3, 0.54, and 1.1

Aspect Ratio	Deck (beam-stick)	Bent Cap	Columns
0.3	A_s = 2.05E4 cm^2 $I_{sy(middle)}$ = 6.63E7 cm^4 $I_{sy(edge)}$ = 9.52E7 cm^4 I_{sz} = 9.93E8 cm^4 (typ.) $J_{s(edge)}$ = 3.94E7 cm^4 n = 3	A_s = 3.07E4 cm^2 I_{ex} = 4.37E7 cm^4 I_{ez} = 4.47E7 cm^4	A_s = 1.16E4 cm^2 I_e = 7.14E6 cm^4
0.54	A_s = 3.79E4 cm^2 $I_{sy(middle)}$ = 1.59E8 cm^4 $I_{sy(edge)}$ = 1.68E8 cm^4 I_{sz} = 1.00E9 cm^4 (typ.) $J_{s(edge)}$ = 1.99E8 cm^4 n = 3	A_s = 3.07E4 cm^2 I_{ex} = 4.37E7 cm^4 I_{ez} = 4.47E7 cm^4	A_s = 1.16E4 cm^2 I_e = 7.14E6 cm^4
1.1	A_{se} = 4.64E4 cm^2 A_{sm} = 7.14E4 cm^2 $I_{sy(middle)}$ = 2.87E8 cm^4 $I_{sy(edge)}$ = 3.08E8 cm^4 I_{sz} = 7.92E8 cm^4 (typ.) $J_{s(edge)}$ = 7.78E8 cm^4 n = 4	A_s = 3.07E4 cm^2 I_{ex} = 4.37E7 cm^4 I_{ez} = 4.47E7 cm^4	A_s = 1.16E4 cm^2 I_e = 7.14E6 cm^4

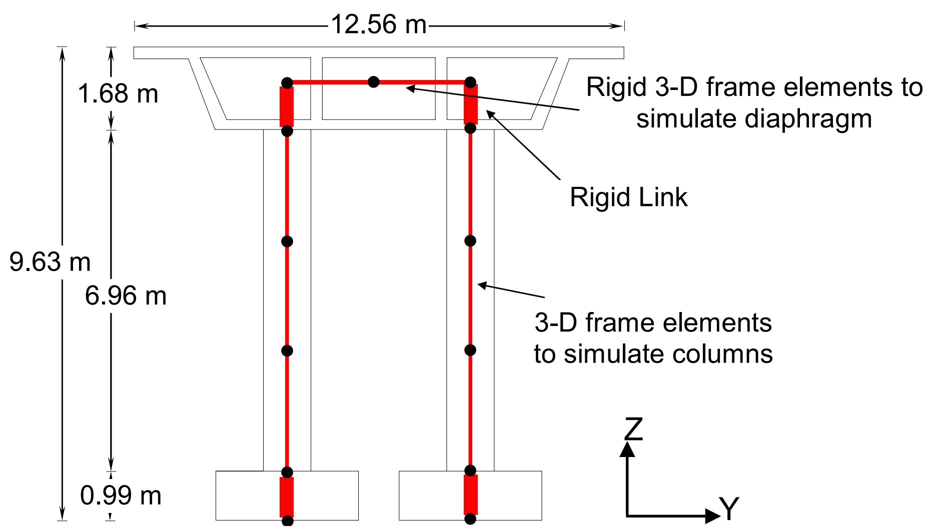

Figure 1. Bent Elevation of Benchmark Bridge with Aspect Ratio of 0.3

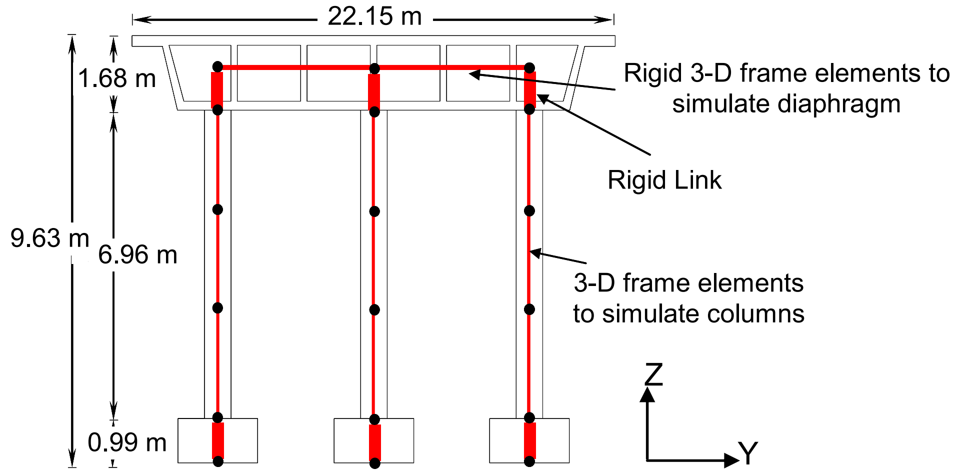

Figure 2. Bent Elevation of Bridge with Aspect Ratio of 0.54

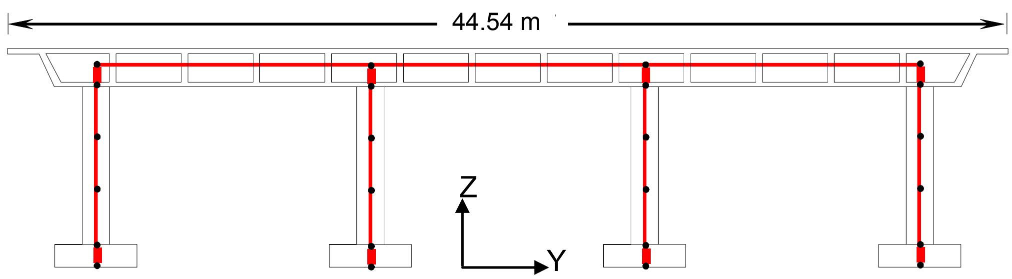

Figure 3. Bent Elevation of Bridge with Aspect Ratio of 1.1

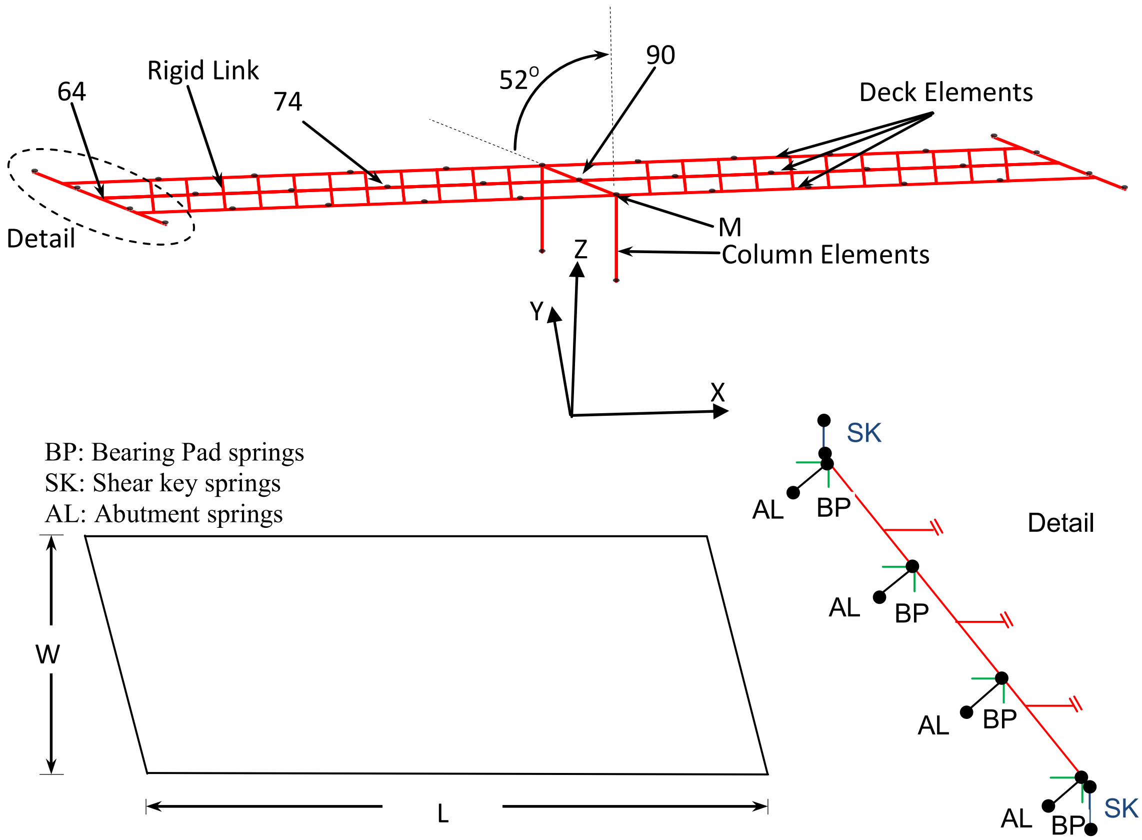

Figure 4. Modified Refined Beam-Stick Model

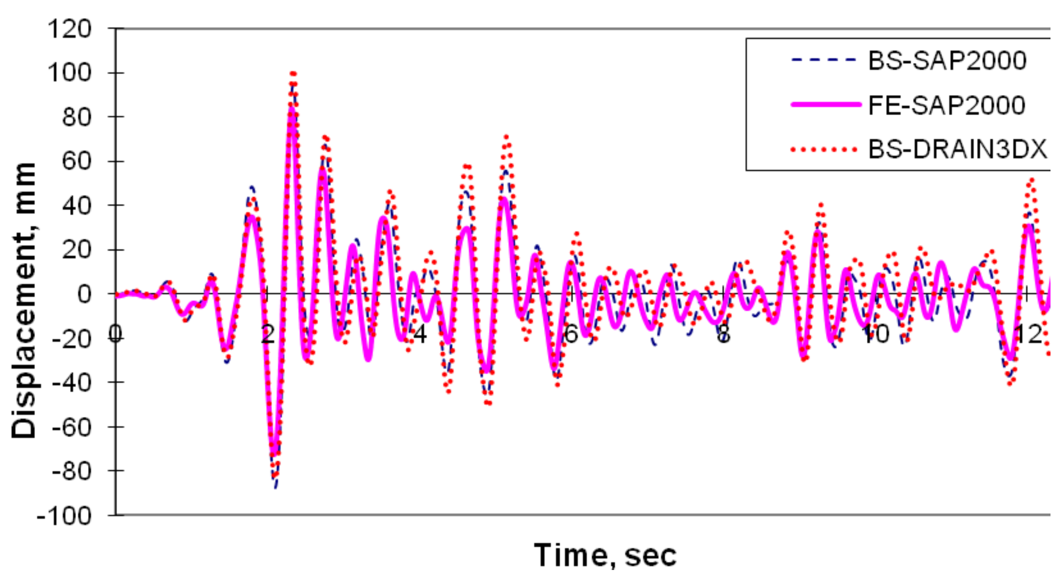

Figure 5. Comparison of Displacement-Time History Response

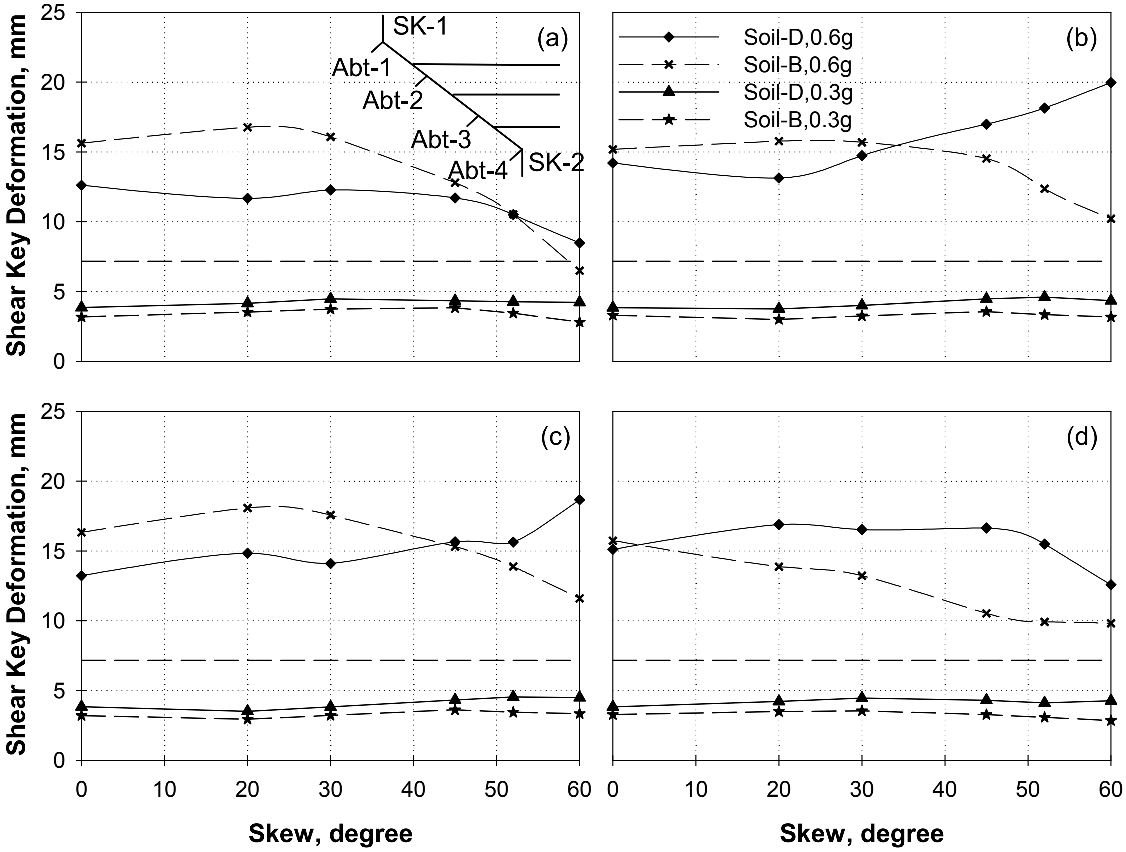

Figure 6. Average Shear-key deformation (a) SK-1, (b) SK-2, (c) SK-3, and (d) SK-4

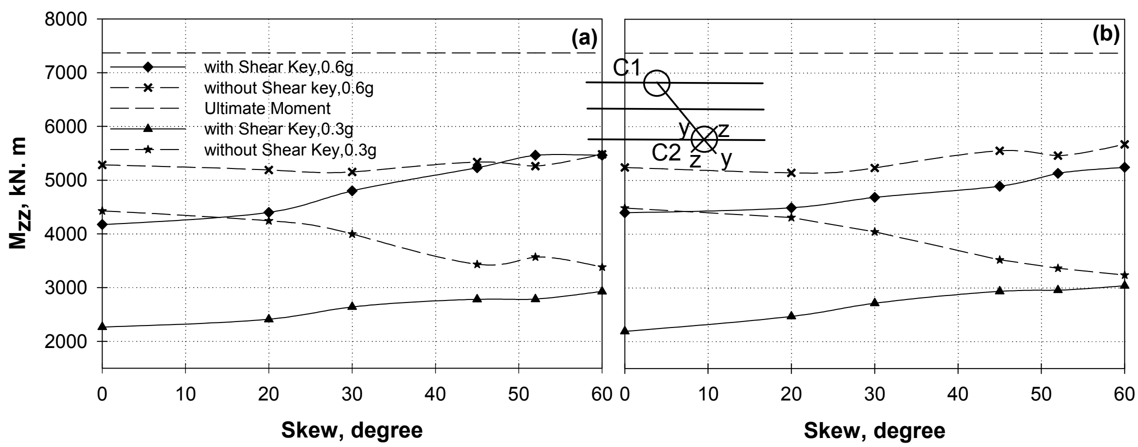

Figure 7. Average Moment about Z-Direction of (a) C1 and (b) C2 of Models on Soil-D

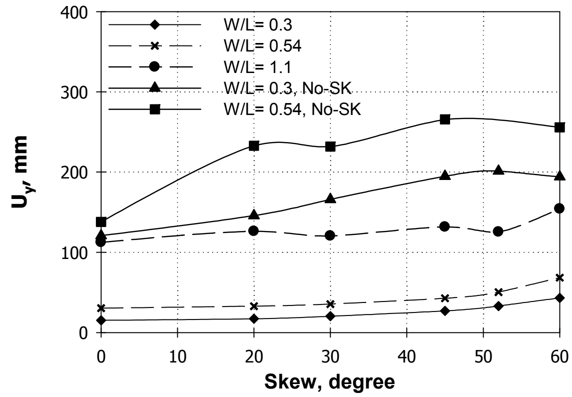

Figure 8. Average Displacement in Y-Direction at Abutment for Models with Aspect Ratios 0.3, 0.54, and 1.1 on Soil-D with Pinned Foundations with and without Shear Keys

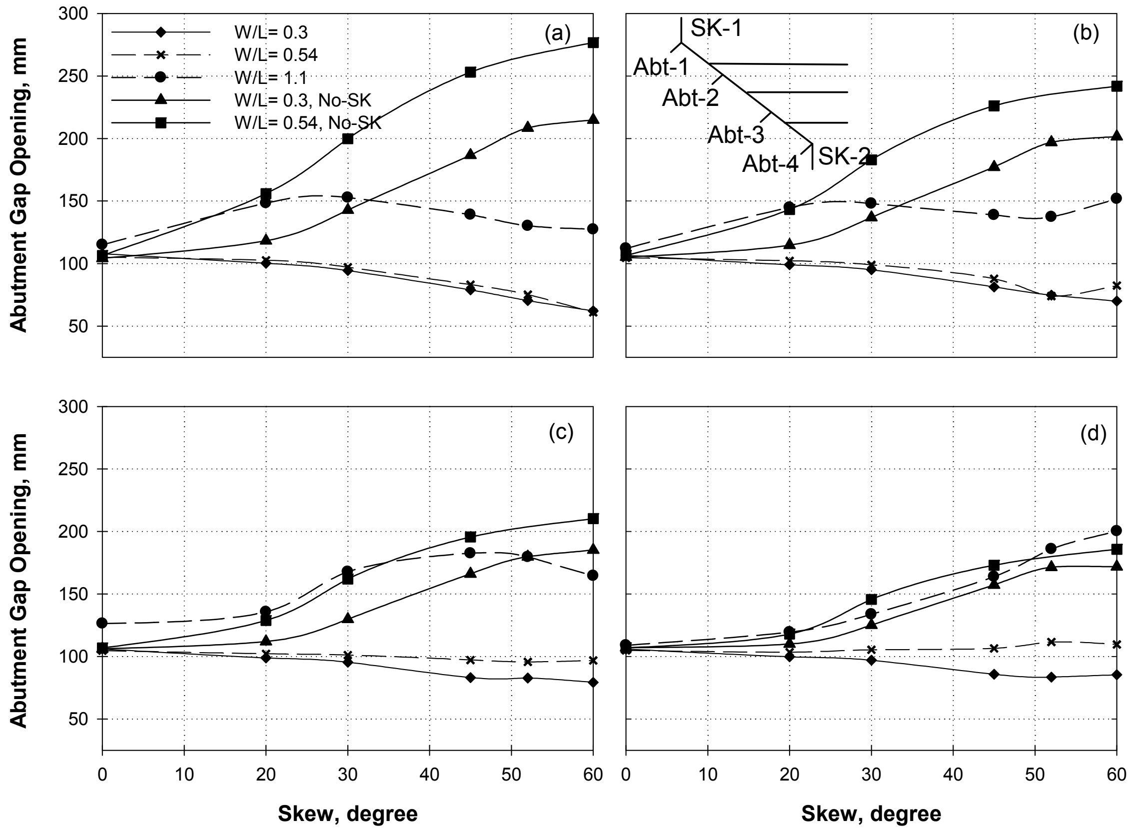

Figure 9. Average Displacement "away" from Abutment's (a) Abt-1, (b) Abt-2, (c) Abt-3, and (d) Abt-4 for Models with Aspect Ratios 0.3, 0.54, and 1.1 on Soil-D with Pinned Foundations with and without Shear Keys