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# SIMPLIFIED METHOD FOR SEISMIC PERFORMANCE ASSESSMENT OF SKEWED BRIDGES

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**Abstract.** *Damage and seismic movements observed in bridges in recent earthquakes have indicated that the response and failure modes of bridges with skew-angled abutments are significantly different from those of bridges with normal abutments. One significant manifestation of this difference is the inherent tendency of skewed bridges to rotate about their vertical axes under seismic excitation. In this study, with the aforementioned field observations in mind, we have conducted parametric response-sensitivity analyses in an effort to identify the key parameters that control the seismic behavior of skewed bridges. This paper describes our simplified modeling technique, which takes bridge-abutment interaction into account, along with the analysis results. Three short bridges located in California were used as subjects. These bridges have different arrangements of number of spans and number of columns per bent; and through nonlinear time-history analyses, we investigated the sensitivity of their various responses to variations in parameters such as torsional stiffness, span arrangement, column height, abutment skew angle, and ground motion characteristics.*

## 1 INTRODUCTION

Bridge with skew-angled abutments ("skewed bridges") are constructed to accommodate geometry constraints resulting from the alignment of a waterways or roadway crossing that occurs at an angle that is different form 90 degrees. In the present study we consider only "seat-type" abutments, which are very common in construction practice in California. A seat-type abutment is simpler to construct compared to an "integral abutment." It reduces service and seismic demands on foundations and allows the superstructure to move freely under thermal, and low-intensity mechanical (service or seismic) loads [1]. Despite having a fair amount of knowledge on the response of bridges with normal abutments [2], the engineering community still lacks quantitative knowledge on the seismic performance of skewed bridges with adequate certainty. As a result, somewhat gross approximations are employed in their design, and the implications of these approximations are not completely understood [3]. There has been a recent surge of studies that were aimed at providing guidelines for nonlinear seismic response-history analysis of regular bridges, primary motivated by developments in performance-based earthquake engineering (PBEE) [4-8]. The present study follows in the footsteps of these efforts, and provides an initial attempt at applying PBEE concepts to skew-angled bridges.

In a seat-type abutment (Figure 1), exterior shear keys are used to counter the deck movement along the transverse direction. They are proportioned and detailed to act as fuses that will break off under the design earthquake [9]. In the longitudinal direction, a backwall that holds an engineered backfill in place is designed to break off and allow the mobilization of the soil mass, which, in turn, generates passive resistance. Observations from past earthquakes indicate [10-12] that one of the primary causes of unseating of the skewed bridges is the pronounced in-plane rotation caused by the eccentric passive resistance of the backfill [13-16]. Post-earthquake reconnaissance reports also suggest that this rotational mode of response is exacerbated once the bridge is subjected to near-field motions [17]. However, there still remains significant uncertainty in predictive models that needs to be alleviated and addressed in order to better quantify such behavior.

In the present study, we adopt a performance-based seismic assessment approach, which starts with the selection of a representative suite of critical ground motions and repeated nonlinear response-history analyses of models with varied parameters. The output is a statistically scattered collection of response metrics. The trends in these measures are what we seek to identify. In what follows, we first describe the details of our modeling approach and the ground motion selection procedures. We then summarize and discuss the results.

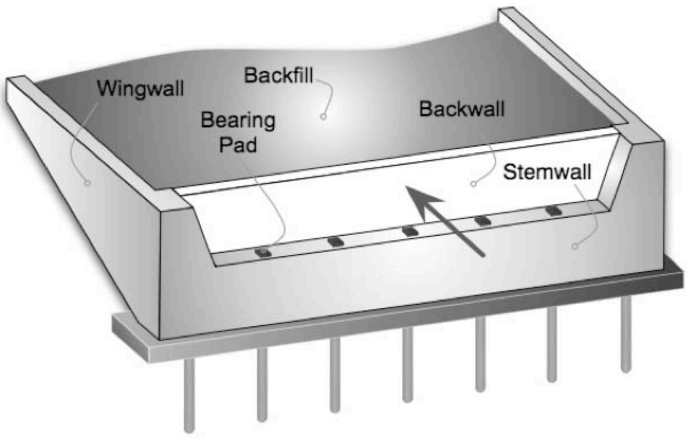



Figure 1: Configuration of typical seat-type abutment (adopted from [2]).

## 2 ANALYTICAL MODEL

For the present study, we have selected three actual bridges as seeds for our parametric response-sensitivity analyses. These bridges are recently designed and built (ca. 2000) in Southern California, at regions with high seismicity. The first bridge is the *Jack Tone Road Overcrossing*, which over-crosses Route 99 at the City of Ripon. It has a typical configuration encountered frequently in California. Its total length is 67.2 m, consisting of two (33.1m and 34.1 m) spans with a single column. It has seat-type abutments with four elastomeric bearing pads on each seat. The superstructure is a three-cell continuous reinforced concrete box-girder. The bent-cap is integral with the deck and the concrete column. The column has a 1.68-m diameter and is supported on steel piles. Its longitudinal reinforcing steel ratio is approximately 2%.

The second bridge is the *La Veta Avenue Overcrossing*. It is also a two-span structure; but it is supported on a multi-column bent. As such, it has a larger global torsional stiffness than the single-column Jack Tone Road Bridge. The third bridge is the *Jack Tone Road Overhead*. It is a three-span and multi-column bridge, and has the largest global torsional stiffness among the three bridges studied here.

A representative analytical model used in the parametric studies is displayed in Figure 2. The modeling platform is OpenSees [18], which provides an adequate element and material response library, and enables scripted execution of repetitive nonlinear response-history analyses in which the model parameters and input ground motions can be systematically varied. The present modeling assumptions follow the general guidelines suggested in Caltrans' Seismic Design Criteria document [3], and the studies by Aviram *et al*. [6] and Kaviani *et al*. [19-20].

The superstructure is modeled as a three-dimensional spine that follows the alignment of the bridge with line elements located at the centroid of the cross-sections. The model features various nonlinear elements, which capture the behavior of components that significantly impact the response. These include column plastic hinges, transverse and longitudinal springs that mimic passive abutment reaction, and abutment gap elements. As no damage or significant nonlinear behavior is expected within the superstructure and the foundation system, the superstructure elements, the cap beam, and the foundation springs are all considered as linear elastic elements.

### 2.1 Column Bent Modeling

Progression of column yielding and damage is expected under strong ground motions, and thus nonlinear fiber-based force-based beam finite elements are used to represent the columns (Figure 3). In order to achieve a more realistic representation of their response, the beam finite elements representing them are endowed with the ability to respond inelastically at every quadrature point. All fiber sections are assigned with the *UniaxialMaterial* model tag of OpenSees [18]. Three different constitutive rules are used depending on which material a given fiber of the cross-section represents—*viz*., (*i*) confined concrete, (*ii*) unconfined concrete, and (*iii*) steel rebar.

The specific beam finite element of the OpenSees library used in the simulations is the *NonlinearBeamColumn*, which has a force-based formulation that enables a more accurate accounting of the moment distribution within the element [21]. A single force-based element with 10 quadrature points is used per column, and this is usually deemed to provide adequate accuracy. In order to model the portion of the column-bent embedded in the superstructure, a rigid element is attached to the top of the nonlinear beam-column element. The length of this rigid element was set equal to the distance between the centroid of the soffit-flange of the superstructure box-girder and the column top.

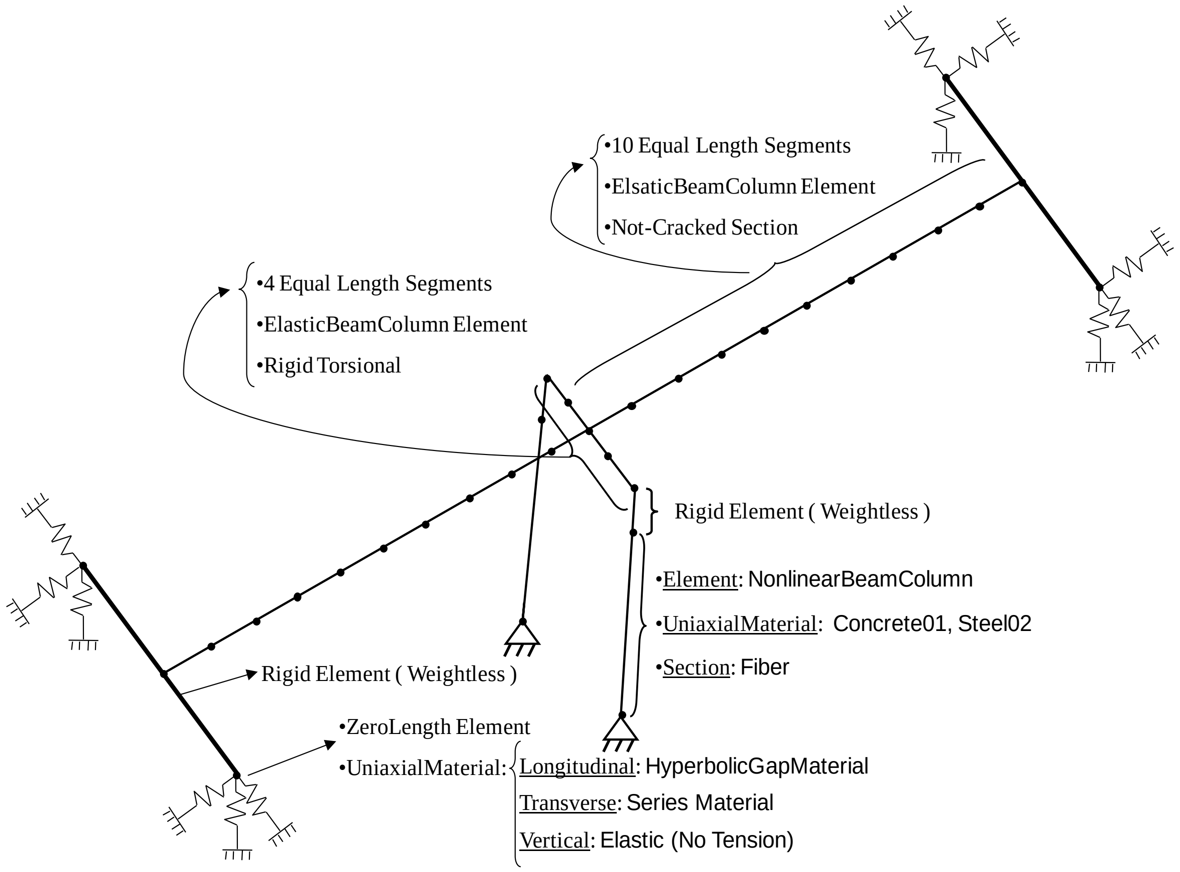



Figure 2: Typical analytical model used for nonlinear time-history analysis of skewed bridges.

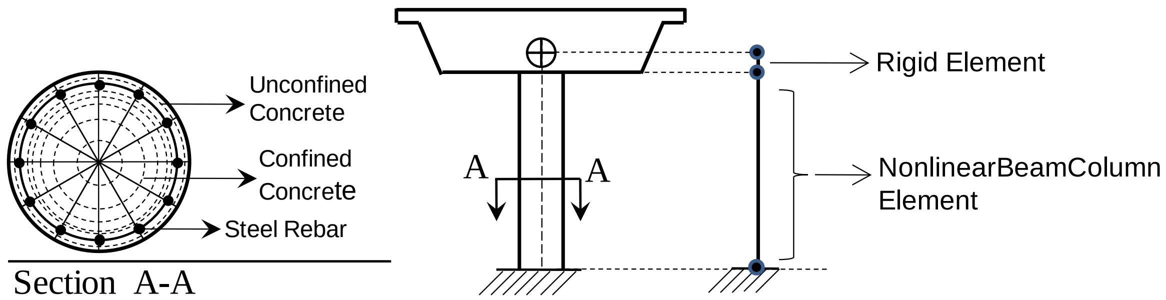



Figure 3: Column analytical modeling scheme.

## 2.2 Abutment Modeling

The model of the abutments is adopted from a simplified modeling technique (Figure 4) as recommended by Preistley et al. [22] and Aviram et al. [6]. Each abutment is modeled with a massless rigid element of length equal to the superstructure width, connected through a rigid joint to the superstructure centerline, and with a zero-length element at each.

In the longitudinal direction, the response is governed by a zero-length, tension-free (gap) element. In compression, it behaves as an elastic-perfectly-plastic material once the gap is closed. The gap size is proportional to the expansion joint detail as shown on the bridge as-built plans. The stiffness and the equivalent yield strength are defined according to Section 7.8 of Caltrans SDC [3]. The rotation about the longitudinal direction is not allowed.

In the transverse direction, the behavior is characterized as elastic compression-only response. The abutment stiffness and the backwall strength for the longitudinal direction are modified by corresponding wall effectiveness factor ($C_L$) of 2/3 and participation factor ($C_w$) of 4/3. The wingwall length is assumed to be 1/3 times the back wall length.

In the vertical direction, only simple elastic material properties associated with the bearing pads are included upon assuming that the response in this direction does not significantly impact the horizontal movements,

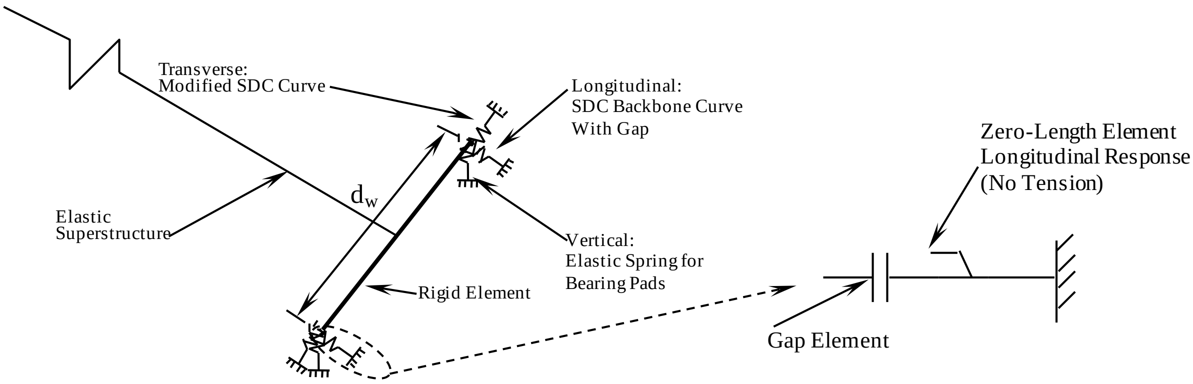



Figure 4: Simplified abutment model

## 3 GROUND MOTIONS

To investigate the sensitivity of bridge responses to a sufficiently diverse range of ground motions that are representative of those recorded in California, three sets of ground motions were selected from the “EQ Library” that was developed as part of the *PEER Transportation Research Program* [23]. These sets are denoted as “Soil,” “Rock,” and “Pulse.” Each set comprises forty ground motions. Figures 5, 6, and 7 show the fault-normal and fault-parallel spectra for these three ground motion sets, respectively. The EQ Library motions do not represent motions that are specific to the site of the bridges considered in this study; they are generic and are merely used to observe the general trends within the seismic responses. The ground motions in the EQ Library are originally selected from a subset of the PEER NGA Project ground motion library [24] representing mid- to large-magnitude earthquakes occurring at close distances. Selected motions have a variety of spectral shapes, durations, and directivity periods. For each set, the mean and variance of the natural logarithm of spectral acceleration match the generic $M_w = 7$ and $R = 10$ km scenario for California.

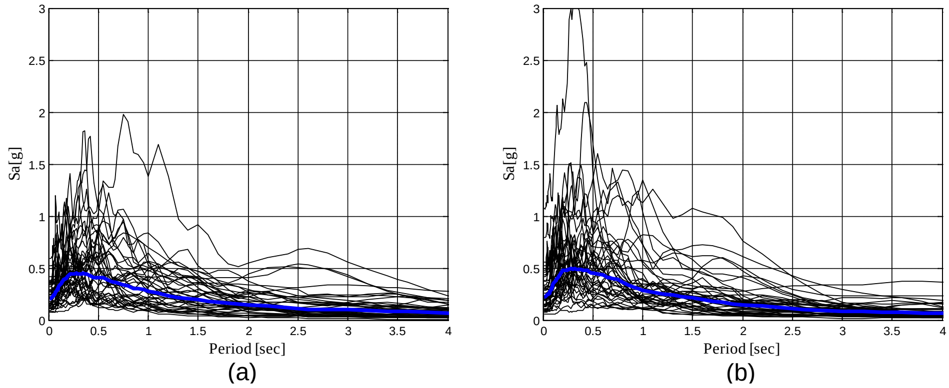



Figure 5: Response spectra of Soil-type ground motions:
(a) Fault-normal component, (b) Fault-parallel component

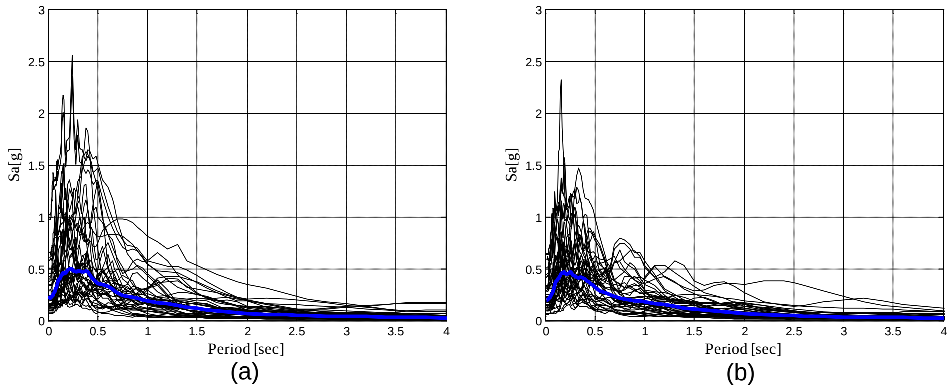



Figure 6: Response spectra of Rock-type ground motions:
(a) Fault-normal component, (b) Fault-parallel component

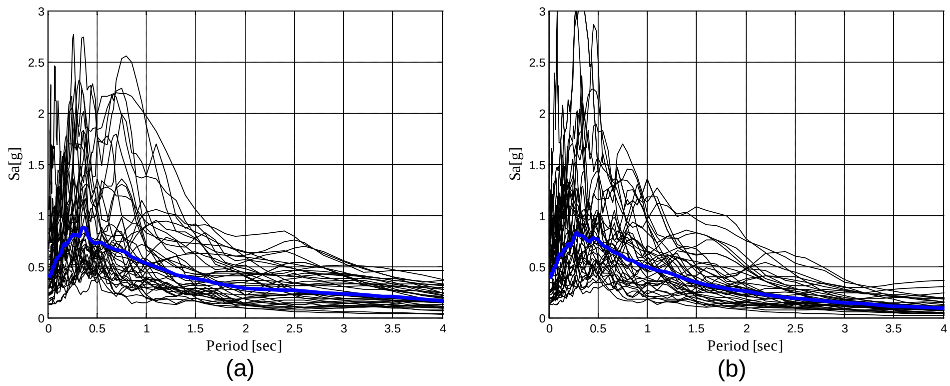



Figure 7: Response spectra of Pulse-type ground motions:
(a) Fault-normal component, (b) Fault-parallel component

## 4 OBSERVATIONS

We investigated the sensitivities of seismic responses of the specimen skewed bridges to variations in their structural properties by analyzing each instance of the models under each ground motion. The four response measures—henceforth referred to as *Engineering Demand Parameters* (EDPs)—that we selected were the maximum values of deck rotation, column drift ratio, abutment unseating, and transverse abutment displacement.

### 4.1 Deck Rotation

The results indicate that deck rotation is highly sensitive to bridge structural properties and ground motion characteristics. Figure 8 shows the variation of deck rotation as a function of abutment skew angle of the Jack Tone Road Overcrossing for different types of ground motion. The solid lines show the estimated median, and the individual data points are depicted with solid dots on the plot. Figures 8(a) and 8(b) show deck rotation variation due to the abutment skew angle increment; however, they differ in span arrangement. In the asymmetrical span arrangement of the bridge (Figure 8(b)), the span lengths differ by 20%.

Results in Figures 8(a) and 8(b) indicate that by increasing the abutment skew angle from $0^o$ to $30^o$, the median estimate of deck rotation increases, regardless of the type of applied ground motion or span configuration. However, for higher skew angles ranging from $30^o$ to $60^o$, the deck rotation increases for the symmetric-span configurations (i.e., Jack Tone Overcrossing); whereas the increasing trend continues on for the asymmetrical one. This behavior is particularly pronounced for pulse-like ground motions.

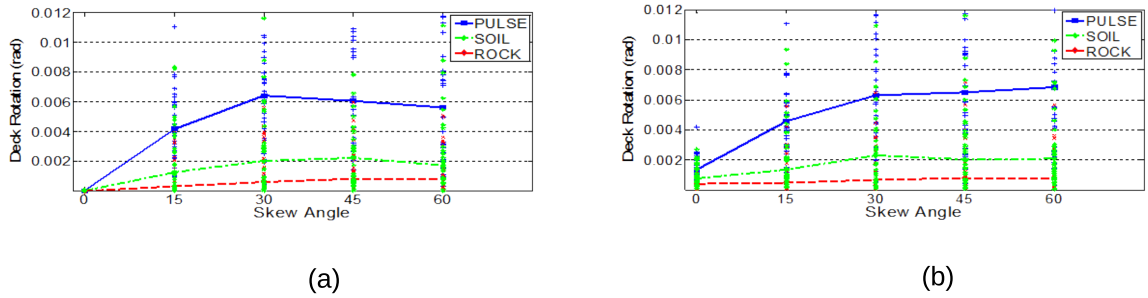



Figure 8: Deck Rotation Sensitivity to span arrangement: (a) Symmetrical spans, (b) Asymmetrical spans

The effect of abutment gap-size variation on the selected EDPs is shown in Figure 9. Four abutment gap-sizes (0.25, 0.5, 1.0, and 2.0 in.) are investigated. For deck rotation, it is observed that for skew angles less than 40°, the curves corresponding to different abutment gap-sizes are approximately matched. However, for larger skew angles the bridge with the 0.25-in. gap distance rotates more, in comparison to that with a 2-in. gap. This trend indicates that with reducing gap-distance, the bridge rotates more for higher skew angles. Less gap-distance between the deck and the backwall results into more effective impact forces impose to the superstructure by backfill soil.

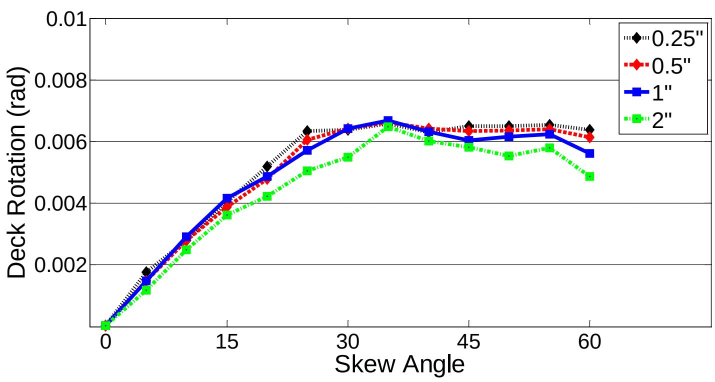
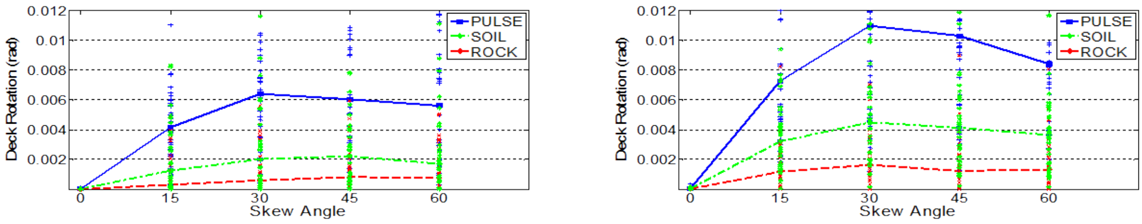



Figure 9: Deck rotation sensitivity to abutment gap size

Considering the variations in column height, the general observation is that for a given skew angle, bridges with taller and more flexible columns tend to have larger deck rotations. Figure 10 shows this general trend.

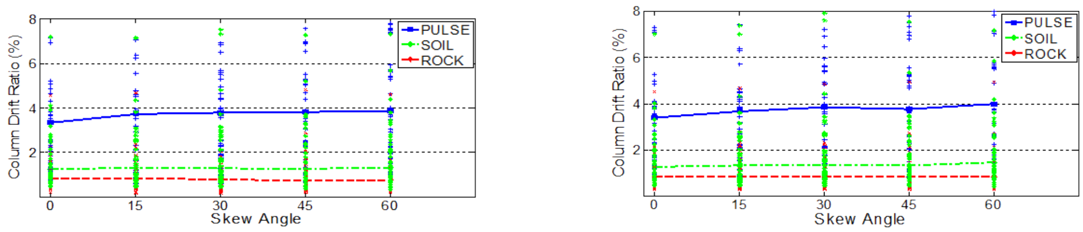



(a) (b)

Figure 10: Deck rotation sensitivity to column bent elevation: (a) Lower column, (b) Higher column

## 4.2 Column Drift Ratio

Results for the two-span single-column bridge (i.e., Jack Tone Overcrossing) indicate that the column drift ratio (CDR) for smaller values of column height is insensitive to abutment skew angle (Figure 11). This behavior is likely due to the particular mode shape of vibration for the single column bridge in which the rotation of the deck increases as the skew angle increases, but the column usually remains near the center of rotation. However, for higher columns (Figure 12), CDR increases with increasing skew angle. For instance, for lower values of column height (the actual height of the Jack Tone Overcrossing), the CDR varies smoothly around 4%. However, for higher values (as a common assumption in design practice, we considered higher-level height of the columns as eight times its diameter), the CDR ranges from 2.5% to more than 4%; and it has greater values for the 60° skew angle. This trend demonstrates that if column stiffness is decreased, then the sensitivity of CDR to abutment skew angle increased.




(a) (b)

Figure 11: Column drift ratio sensitivity (lower column) to span arrangement:
(a) Symmetrical spans, (b) Asymmetrical spans

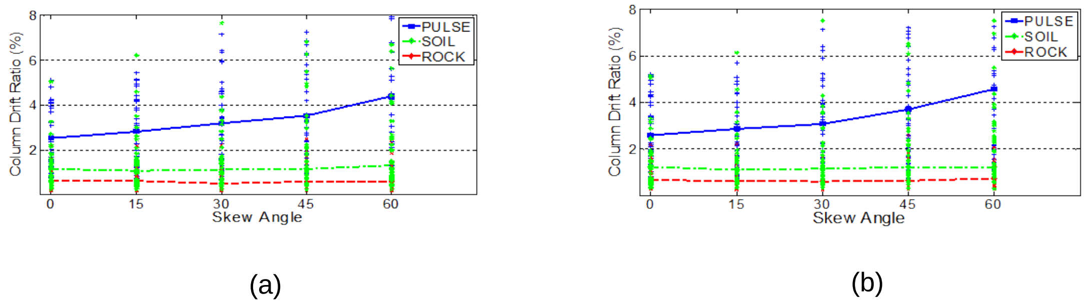



Figure 12: Column drift ratio sensitivity (higher column) to span arrangement:
(a) Symmetrical spans, (b) Asymmetrical spans

### 4.3 Abutment Unseating

As displayed in Figure 13, incidence of the unseating of abutment is increased by skew angle, particularly for the higher range of skew angles. As expected, the abutment unseating increases with increasing skew angles, because the effective stiffness of the abutment in the longitudinal direction is reduced for larger skew angles.

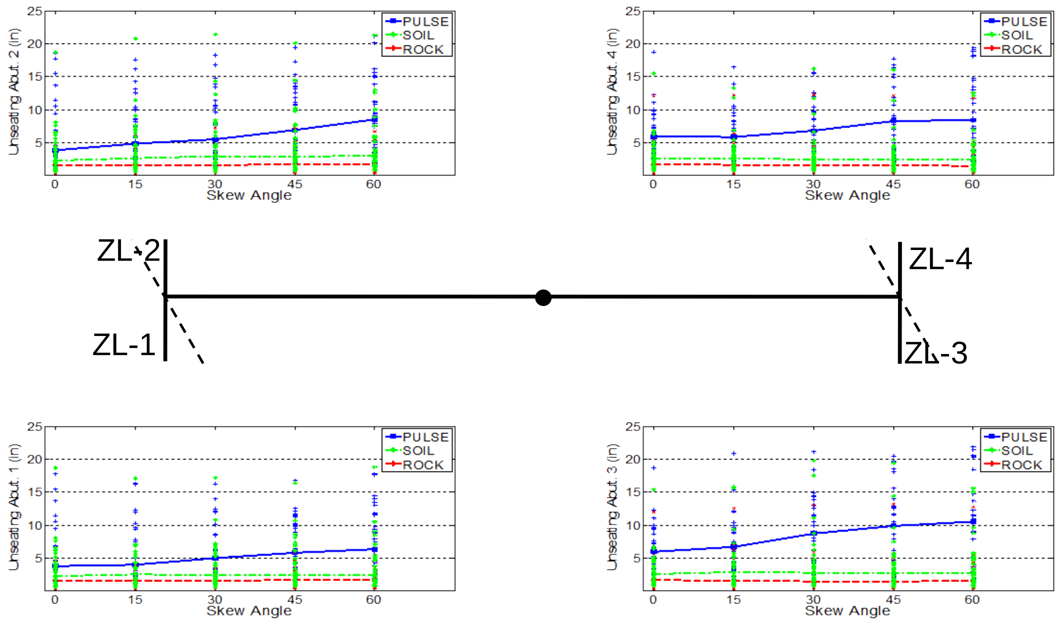



Figure 13: Abutment unseating for symmetrical span arrangement (recorded form the ZeroLength elements, located at each abutment corner)

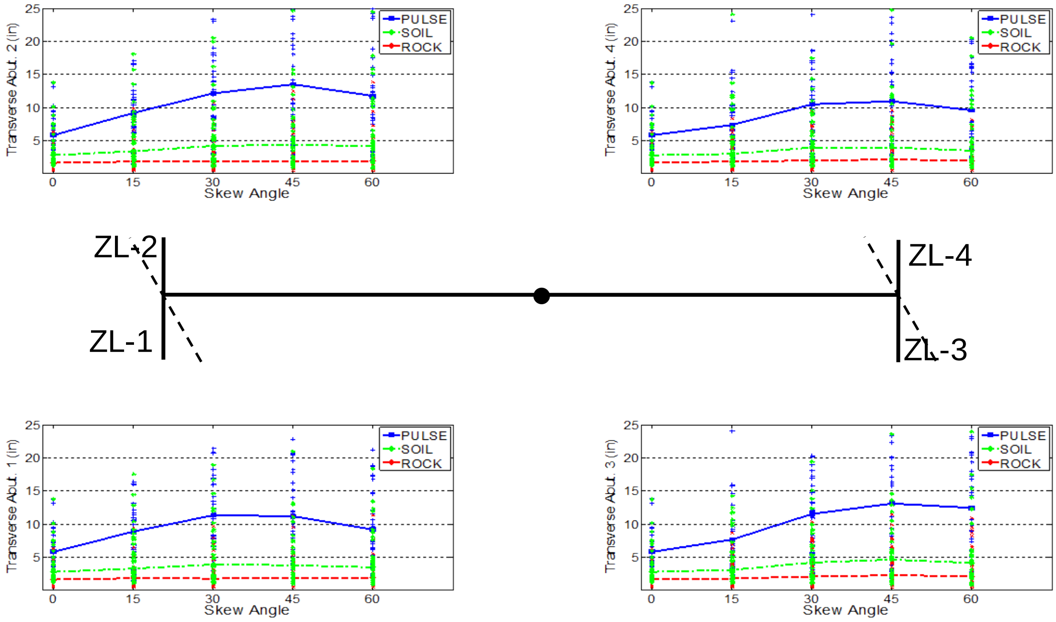



Figure 14: Transverse abutment displacement for symmetrical span arrangement (recorded form the ZeroLength elements, located at each abutment corner)

### 4.4 Transverse Abutment Displacement

As the deck rotational response here is calculated by dividing the difference between abutment transverse displacements at both ends of the bridge to the bridge length, the abutment transverse displacement is expected to follow a similar trend as the deck rotation. As expected, the transverse abutment displacement increases with increasing skew angle from 0° to 30°, but slightly decreases thereafter, particularly for symmetrical span arrangements (Figure 13).

## 5 SUMMARY

In this study, we investigated the sensitivity of seismic response of skewed bridges to variations in critical parameters using simulations carried out as nonlinear time-history analyses. Seismic response parameters that we looked into include deck rotation, column drift ratio, abutment unseating, and transverse displacement of abutment. We used three bridges located in California as seeds for our parametric study. These bridges mainly differ in their global torsional resistance. Multiple analytical bridge models were generated from each of three seed bridges by varying the original bridges' geometrical properties, which included abutment skew angle, span arrangement, and column height. In addition, we studied effects of ground motion characteristic on the seismic response of skewed bridges by introducing three types of ground motions into our response-sensitivity analyses. These were soil-site, rock-site, and pulse-like ground motions. We observed that less gap size between the deck and the backwall results in more effective impact forces that mobilize the backfill soil and leads to higher deck rotation; especially when the bridge is subjected to pulse-like ground motions. Column drift ratio is significantly sensitive to the column height, abutment skew angle, and number of columns in each bent. Abutment unseating increases by increasing skew angle, particularly for bridges with tall columns.

## ACKNOWLEDGEMENTS

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