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Seismic Assessment of Reinforced Concrete skewed Bridges under Near-Fault Ground Motions with Considering Soil-Structure Interaction- Case Study of Jack Tone Road On-Ramp Overcrossing Located in California

H. Soltani, F. Emami*, P. Javadi

Department of Civil Engineering, Science and Research Branch, Islamic Azad University, Tehran, Iran

ABSTRACT: Seismic behavior of skewed bridges, the backbone of modern transportation networks, has not been well studied compared to their ordinary straight counterparts. Investigating past earthquakes, it can be evident that such bridges have experienced intensive damages especially due to girder unseating under the torsional effects of seismic responses coupling in longitudinal and transverse directions, which will be aggravated by local crushing of deck concrete due to pounding between the abutments and adjacent spans. Additionally, bridges are usually supported on Cast-In-Drilled-Hole extended pile-shafts. The inelastic behavior of the superstructure during an earthquake is profoundly dependant on soil strength due to the effect of surrounding soil properties on substructure stiffness. So, the main purpose of the present research is to evaluate the seismic responses of R.C skewed overcrossing to variations in some structural parameters by applying analytical models capturing backfill-abutment and soil-pile nonlinearities under near-fault ground motions with high-velocity pulses, especially in their strike-normal component, comparing the results with fixed-base model and finally obtain the most efficient ground motion intensity measure. A set of nonlinear time history analyses was conducted using seven pulse-like ground motions containing horizontal and vertical components on a two-span skewed bridge. Then, the effects of abutment skew angle, base condition modeling approach and soil strength on the revision of various demands were assessed and compared for both flexible- and rigid-base conditions. Furthermore, various analyses were carried out with respect to possible changes in soil properties ranging from soft to stiff for clayey and loose to dense for sandy soils besides the skew angle variations. It was observed that most of the demands, despite the changes in soil strength, were sensitive to an increase in abutment skew angle as a factor of structural stiffness and will often increase incrementally with that, but deck rotation was significantly affected by these variations. Considering foundation flexibility by a set of nonlinear springs can refine structural responses in most cases, particularly by applying Direct Method, based on precise modeling of structural components besides a vast region of encompassed soil around, which will impose an improving effect on various demands relative to the fixed-base condition.

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1. INTRODUCTION

skewed bridges are identified by their skew angle, which is defined as the angle between the line perpendicular to the centerline of the bridge and the centerline of the bearings. Such bridges are commonly used to cut off roads, drains, or railways that are not parallel to the bridge alignment; therefore in the case that the intersecting crossing paths do not extend at a right angle, using skewed bridges for conquering space constraints will be inevitable. Investigating past earthquakes, it became evident that such bridges would be severely subjected to massive destruction during intense ground motions due to their inherent tendency to rotate about their vertical axis. Additionally, the collapse possibility of these bridges will be accentuated by being exposed to near-fault ground motions with a high potential of destruction. Most of the distinctive features of these earthquakes are primarily due to the directivity effect and their vertical component impacts.

When external forces such as earthquakes affect the bridge structure, neither structural displacements nor ground displacements are independent to each other. This association is denoted as soil-structure interaction.

Most of the previous researches with this view that incorporating *SSI* effects will result in conservative estimations of seismic demands had neglected or greatly simplified these effects. Moreover, the vulnerability potential of highway skewed bridges due to the neglect of ground motions vertical component is an important issue, which still remains obscure. Hence, the present study is intended to explore how the aforementioned cases, along with skew

*Corresponding author's email: f-emami@srbiau.ac.ir

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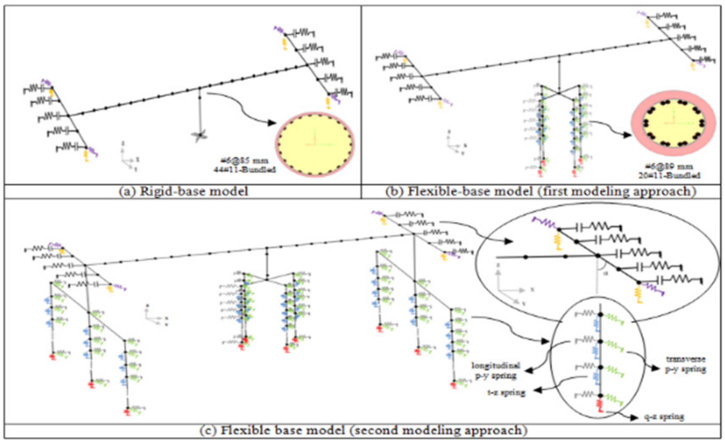

Fig. 1. 3D analytical finite element modeling scheme of the specimen bridge

angle variation and *SSI* elements incorporation, will affect the functionality of skewed bridges that are widely used in highway transportation systems currently.

2. METHODOLOGY

The specimen bridge is Jack Tone Road On-Ramp Overcrossing, having two spans supported on a single circular column-bent. The superstructure consists of a three-cell continuous pre-stressed RC box girder. The seat-type abutments are about 33 ˚ skewed, containing four elastomeric bearing pads [2].

The bridge was modeled once with the assumption of a rigid base and then with considering a flexible base, three-dimensionally as a *spine-line* model in *OpenSees* finite element platform.

In order to determine the dynamic characteristic of the bridge, mass assignment is required [1]. So that, the translational and rotational mass were assigned to each node [1, 3]. Defining a linear geometric transmission system from the local system of the element to the global system of the structure is necessary to model the R.C box-girder deck by applying *elasticBeamColumn* elements. No reduced stiffness is recommended for multi-cell pre-stressed concrete box girder sections [1].

Since the progression of column yielding and destruction under intense excitations was expected, after node introduction, mass assignment and redefining a transition system with considering *P*-Δ effect, a single force-based *nonlinearBeamColumn* element with 10 integration points was assigned to simulate nonlinear geometry and nonlinear behavior of the materials with a fiber distribution based cross-section. *Concrete01* material was adopted for confined and unconfined concrete, while the reinforcing bars were modeled by *Steel02* material. Then, the embedded portion of the column in the deck was defined as a rigid element using a single *elastic* element with high stiffness and a length equal to the deck centroid length.

Based on *Skewed Abutment Model* [2], three different types of spring elements were used to simulate the longitudinal response related to passive lateral resistance of the backfill, the transverse response of the exterior shear keys plus the vertical response of the bearing pads and back-wall, attaching to a rigid element representing the transverse portion of the deck. As the backfill volume that can be mobilized in a unit weight of the wall during the back-wall failure is estimated to be larger by moving from the obtuse corner to the acute corner of the deck, it was assumed that the stiffness and the strength of longitudinal springs increase linearly with skew angle increasing trend as well as the distance from the obtuse corner [2]. The stiffness and force of the longitudinal springs were determined by hyperbolic force-displacement formulation (*HFD*) [4]. The shear-key response was modeled using a tri-linear backbone curve, indicating observed behavior during a series of full-scale empirical studies. Then, the *hyperbolicGap*, *Concrete02* and *ElasticBilin* materials were adopted to represent longitudinal, transverse and vertical springs, respectively, and a zeroLength element was assigned to each of them.

In order to simulate the pile foundation system, *nonlinearBeamColumn* elements with distributed plasticity and fiber cross-section were used, then 50 elements with 3 integration points were assigned to each of them. The pile group under the abutments was modeled once by applying the simplified assumptions based on considering the stiffness of 7.0 KN/mm for each pile [1] in addition to using *ENT* material, which acts in parallel with the springs representing the backfill and the shear keys. As the second method, each of the abutment piles was simulated similarly to pier piles.

Additionally, the effect of *SSI* was considered by assigning *PySimple1* material for *p-y* springs indicating lateral soil responses in both longitudinal and transverse directions, *TzSimple1* material for *t-z* springs along the pile height simulating the friction between the pile and its surrounding soil, and finally *QzSimple1* material for *q-z* spring simulating end bearing capacity of the pile [5]. Then, each of these components was defined by a *zeroLength* element. Pile-cap was also defined as a rigid element. The detailed configurations of the adopted modeling approaches are illustrated in Figure 1.

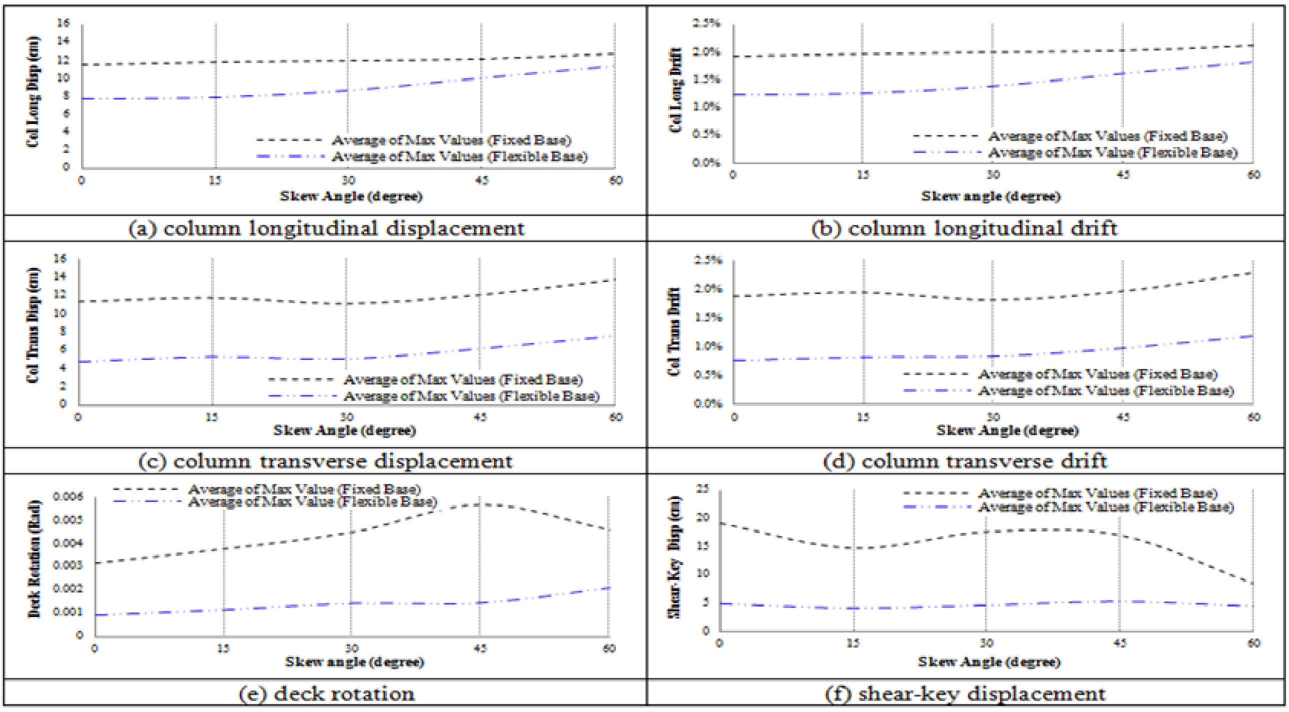

Fig. 2. Sensitivity of Maximum values' median to skew angle variations for the flexible and the fixed base conditions

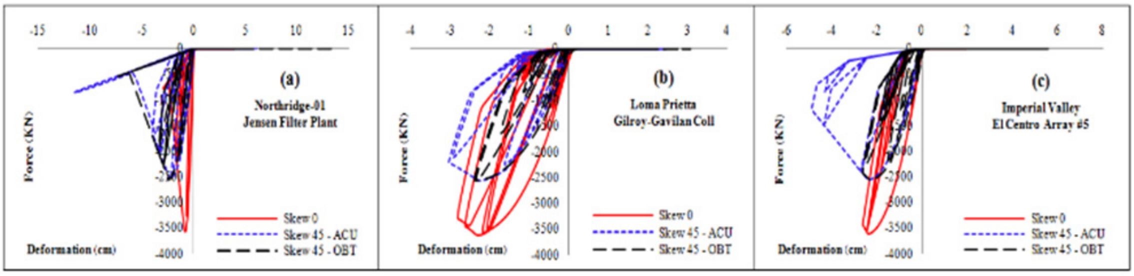

Fig. 3. Hysteresis behavior of the exterior shear keys

Containing strong velocity pulses with directivity effect in strike-normal (*SN*) component, locating the recording station at 3 to 10 km distance from the construction site and the moment magnitude (M_w) of 6 to 7 were the prominent factors for opting the input set of seven pulse-like ground motions. The strike-normal (*SN*) and strike-parallel (*SP*) components were applied in longitudinal and transverse directions, respectively.

3. RESULTS AND DISCUSSION

The obtained outputs from the analyses overtly indicate the increase in most of the demands as well as the residual values with the increasing trend of the skew angle, despite the broad range of soil strength from soft to stiff for clayey soils and loose to dense for sandy ones (Figure 2). Applying the first modeling approach of flexible-base, maximum displacement and drift ratio of the column in the longitudinal and transverse direction as well as deck rotation and shear-key deformation have been reduced by about 18%, 20%, 49%, 50%, 74% and 70% moderately.

The second modeling approach has led to a striking reduction of responses, especially the deck rotation, and also has reduced the amount of residual displacement and drift of the column besides residual deformation of the shear-key to a zero extent at the end of the excitations.

According to Figure 3, the shear-key located in the acute corner of the deck has experienced more deformation while showing less resistance against transverse loads, which will amplify its failure probability, significant deck rotations, deck unseating relative to abutment and eventually more vulnerability of the abutment foundation system. However, these defections will be degraded by considering *SSI* in modeling procedures.

It was found that probably the most realistic approach would be to introduce the most appropriate indicator in terms of having the least dispersion for each of the intended demands separately. Generally, PGA_{SN} can be introduced as the best *IM* with the lowest dispersion rate among all (Figure 4).

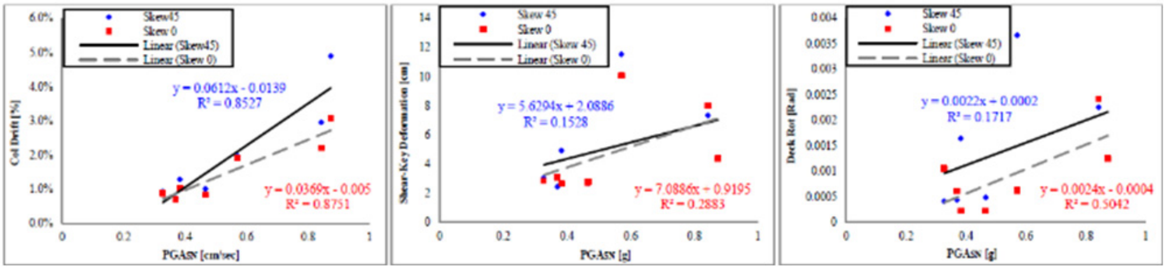

Fig. 4. Demands to PGA_{SN} for the flexible-base condition

4. CONCLUSIONS

The main conclusions of the present study are as follows:

1. Extreme and non-uniform loading condition appearing in near-fault excitations with high-velocity pulses has tended to large displacements in one direction, imposing significant rotations and permanent residual displacements on bridges with skewed abutments. Therefore, these effects will be diminished by the incorporation of *SSI* elements.

2. Considering *SSI* effects compared to the fixed base model has led to a reduction in most of the engineering demand parameters (*EDPs*), especially with applying the second modeling approach denoted *Direct Method*. Of course, most of the intended demands have increased with the increase of abutment skew angle. Deck rotation has shown the most sensitivity to skewed angle variations, probably due to the non-uniform formation of passive soil wedges behind the abutment back-wall.

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