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Monte Carlo Analysis of Longitudinal Behavior of Skew Bridge Abutments

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ABSTRACT: This study focuses on the estimation of the longitudinal force reaction in skew bridge abutments with non-rotating walls through numerical and analytical approaches. To this end, Monte Carlo analysis is conducted to develop a formula for predicting the longitudinal force capacity of skew abutments based on an extensive matrix of verified high-fidelity three-dimensional continuum finite element models. Accurate prediction of this force reaction can be quite effective in better understanding the complete cyclic behavior of skew bridge abutments, which will consequently result in efficient analysis and design of such structures.
Keywords: Skew bridge abutment, Longitudinal force reaction, Monte Carlo analysis, Finite element models

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Introduction

Longitudinal behavior of skew bridge abutments is highly unpredictable. This becomes especially critical under severe dynamic excitations such as seismic load cycles. During an earthquake, the backfill area of the abutment can cumulate deformations and cause system failures to the whole bridge. Among the bridge system failures is the bridge deck unseating from the abutment, which is caused due to excessive displacement of the abutment seating. Reaction of the abutment backfill soil due to the backwall's dynamic motion can be abridged into force and moment components. The longitudinal force reaction of a straight abutment with non-rotating walls is identical to the active and passive behaviors of a retaining wall which is very well-studied in the geotechnical literature. In spite of some limited reported studies on the behavior of skew bridge abutments, e.g. Rollins and Jessee [4] and Nojoumi and Zirakian [3], the capacity performance of skew walls has not been investigated sufficiently as yet.

This study provides an alternative approach (refer to Nojoumi and Zirakian's [3] study) to analyze the longitudinal force response of skew bridge abutments. A formula is propounded for estimating the longitudinal force capacity in skew abutments with non-rotating walls by conducting a Monte Carlo analysis based on numerous verified numerical simulations.

Model Description

The anatomy of a typical abutment and a plan view of a schematic skew abutment are depicted in Fig. 1. Fig. 2 shows the backfill reactions and deformation demands for torsionally-flexible and stiff bridges with skew abutments. Prior to the finite element analyses, the verification of models has been performed by comparing the numerical predictions with the results from a previously-established method, i.e. the Generalized Hyperbolic Force-Deformation (GHFD) method [1]. Subsequently, several finite element analyses have been performed to evaluate the behavior of skew bridge abutments. Parametric study of the finite element models includes several influential factors such as backfill soil properties, viz. internal soil friction and cohesion, and the abutment geometry, viz. abutment wall width and height.

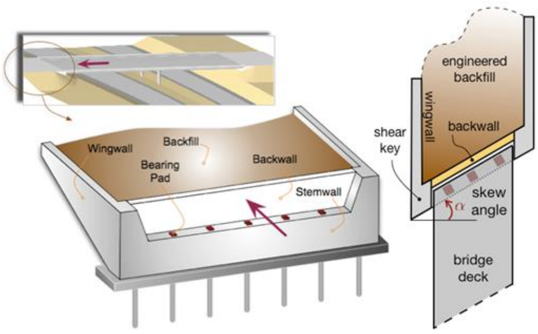

Fig. 1. Anatomy of a seat-type abutment (left) and plan view of a skew configuration (right)

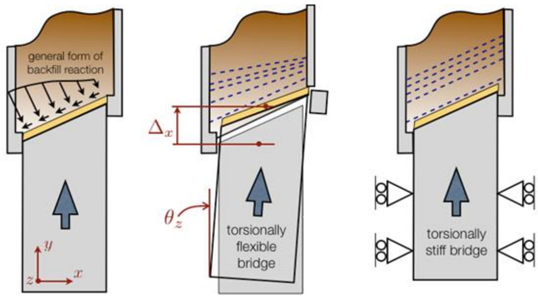

Fig. 2. Normal and tangential components of backfill reaction (left) and translational and rotational deformation demands for torsionally-flexible (middle) as well as stiff (right) bridges

To limit the influential parameters, the rotational degree of freedom of the backwall is neglected in this study. The only load scenario considered herein is the monotonic passive behavior of the backfill soil with the wall continually pushing the soil. This loading scenario guaranties the full contact between the backwall and backfill and considers the participation of all the backfill soil behind the wall. Since there is no rotation, no separation occurs in this configuration. This method assumes that the boundary effects are negligible, hence the plain strain condition is adopted. Therefore, the longitudinal reaction result is scalable by wall/deck width and the reaction per wall length is impervious to wall length.

The GHFD method provides the ultimate capacity of the backfill against a straight backwall, given the geometry of the backwall, i.e. width and height, and the soil parameters. It is obvious that due to the symmetry with respect to the centerline of a straight backwall, the moment reaction of the backfill is zero. Determination of the ultimate capacity for anon-skew benchmark model with a nominal straight wall is described in here.

GHFD Results and Numerical Predictions

The results obtained from the GHFD method for cohesive as well as granular soil types and a 15-ft wide and 5.5-ft high straight abutment wall are shown in Fig. 3. In Fig. 3(a), the lateral capacity is plotted against cohesion (C) for different soil internal friction angles (φ), while Fig. 3(b) shows the plots of lateral capacity versus the soil internal friction angle for five different cohesion levels. From the figures, it is evident that the lateral capacity increases by increasing of the soil cohesion for a given soil internal friction angle, and also increasing of the soil internal friction angle results in increasing of the capacity for a given cohesion level.

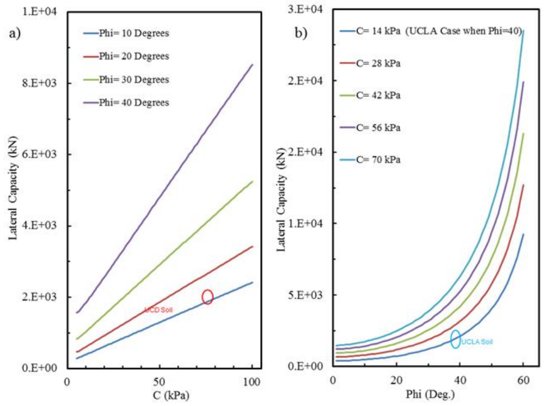

Fig. 3. Effects of soil parameters on backfill's lateral capacity
a) Lateral capacity vs. soil cohesion, b) Lateral capacity vs. soil internal friction angle

Several numerical models were developed using the finite element software package ABAQUS in order to investigate the behaviors of straight and skew abutments. The numerical predictions were verified through comparison with the GHFD results for straight abutments. Fig. 4 illustrates the failure pattern in the backfill soil of a straight abutment predicted by the ABAQUS software (Fig. 4(a)) as well as the GHFD method (Fig. 4(b)). From the figures, the agreement between the numerical predictions and the GHFD-method results is evident.

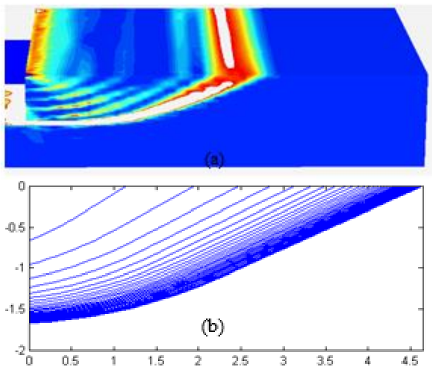

Fig. 4. Failure pattern in backfill soil of a straight abutment
(a)Incremental deviatoric strain distribution for a straight 15-feet-wide wall predicted by ABAQUS, (b) Failure surfaces obtained from GHFD model

Following the verification of the numerical modeling, skew bridge abutment models were developed to explore the effect of skew angle on the longitudinal reaction force of the backfill. To this end, different finite element models with varying geometry and backfill soil properties were developed. Fig. 5, for instance, illustrates the finite element model of a 60-ft wide deck bridge abutment, pushed into a granular soil with internal friction angle of 40°and cohesion of 14 kPa. These soil properties mimic the ones used as engineered soil in the University of California, Los Angeles (UCLA) tests between the years 2006 and 2009 [2]. Fig. 5(a) illustrates the backfill deformations in an exaggerated manner. Figs. 5(b) and 5(c) show the formation of failure surface in the backfill. As expected, it is observed that the effect of boundary area is more considerable in skew models than in the straight abutment ones. Abundant number of similar models with varying geometry and soil properties were developed and results were used to find a pattern in the force response reaction versus the skew angle.

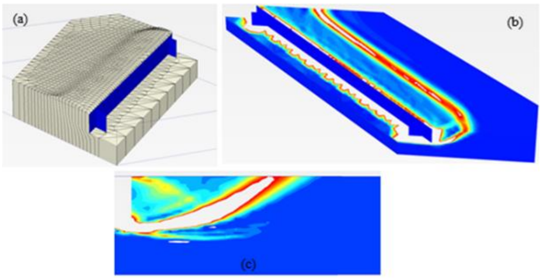

Fig. 5. Typical finite element model comprising 53,000 elements
(a) Backfill deformations (exaggerated), (b) Deviatoric strain distribution plot within backfill indicative of failure surface formation, (c) Backfill side-view

Monte Carlo Analysis and Proposed Formula

In this section, the details of the Monte Carlo analysis which has resulted in the development of a formula for predicting the longitudinal capacity of a skew abutment wall are discussed. Extensive numerical results were used in the development of the proposed formula which correlates the longitudinal force reaction of a skew abutment with the capacity of a straight abutment.

In the first step, the longitudinal force reaction capacities obtained from the finite element models were normalized by the surface area of each skew abutment wall, as expressed by Eq. (1). In this equation, capacity is the ultimate reaction force reached in the backfill in the longitudinal (traffic) direction and CAW_α is determined for any specific wall with skew angle α.

$$CAW_\alpha = \frac{\text{Capacity}}{\text{AreaoftheWall}} \quad (1)$$

In order to have a comparative parameter to show the effect of the skew angle on CAW, $CAW_\alpha$was in turn normalized by$CAW_{Nominal}$, the CAW of astraight (α = 0°) abutment wall. The new parameter, expressed by Eq. (2), is denoted by CNR which stands for Capacity-over-wall-area Normalized Ratio. Moreover, as shown by Eq. (3), the normalized skew angle (ν) was introduced by dividing the skew angle (α) by 90°. This parameter (ν) ranges from zero (i.e. α = 0° indicative of a straight abutment) to a hypothetical value of one (i.e. α = 90° which is practically not possible). The CNR-ν datapairs obtained based on numerous finite element analyses were then plotted and the best-fitting trendline representing the data was found through regression analysis. Fig. 6 shows the plot of CNR-ν datapoints and the obtained trendline.

$$CNR = \frac{CAW_\alpha}{CAW_{Nominal}} \quad (2)$$

$$\nu = \frac{\alpha}{90^o} \quad (3)$$

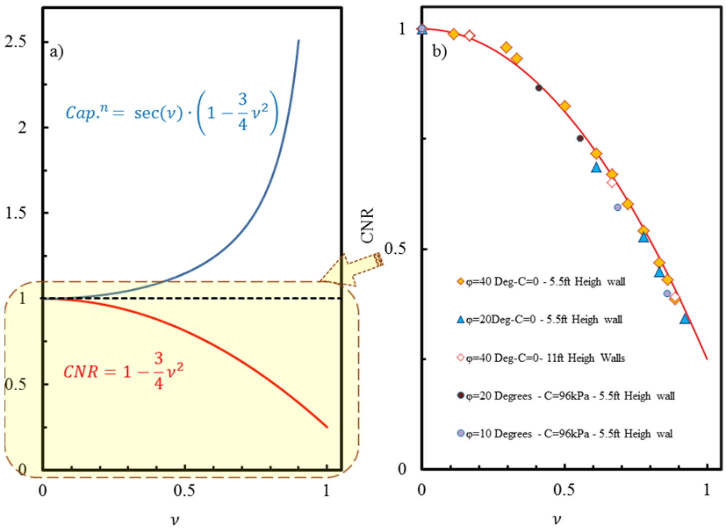

Fig. 6. Plot of CNR versus ν
a) The obtained trendline best representing the data, b) Plot of CNR-ν datapoints and the best-fitting line

As shown in Fig. 6, the CNR and ν parameters were consequently related by Eq. (4). It is reiterated that the CNR-ν datapoints were obtained on the basis of numerous finite element analyses of skew abutments with different soil types and geometries.

$$\mathrm{CNR} = 1 - \frac{3}{4}\nu^2 \tag{4}$$

Finally, Eq. (5) was derived based on the conducted Monte Carlo analysis for estimating the capacity of a skew abutment wall, denoted by $\mathrm{Cap.}_{\alpha}$. In this equation, $\mathrm{A_{Nominal}}$ is the area of the straight wall and $\mathrm{CAW_{Nominal}}$ can be taken from other reported methods, e.g. the log-spiral hyperbolic (LSH) [5] or GHFD methods.

$$\mathrm{Cap.}_{\alpha} = \mathrm{A_{Nominal}} \cdot \sec\left(\frac{\pi}{2}\nu\right) \cdot \left(1 - \frac{3}{4}\nu^2\right) \cdot \mathrm{CAW_{Nominal}} \tag{5}$$

It is important to note that this study is part of a comprehensive research endeavor on the behavior assessment of skew abutments which focused on the estimation of the longitudinal force reaction of a skew abutment area parallel to the traffic direction. The study of other reaction components is currently underway and will be reported upon completion.

Conclusion

This paper reported a study on the development of a formula to estimate the longitudinal force reaction in skew abutments with non-rotating walls. Numerous finite element models were developed for investigating the behaviors of straight and skew abutments. Initially, the numerical predictions were verified through comparison with the GHFD results for straight abutments. Subsequently, skew bridge abutment models with different soil types and geometries were developed and analyzed to explore the effect of skew angle on the longitudinal reaction force of the backfill. Following the regression analysis of the numerical data, Monte Carlo analysis was conducted for development of a formula for prediction of the longitudinal capacity of skew bridge abutments. The proposed formula correlates the longitudinal force reaction of a skew abutment with the capacity of a straight abutment.

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