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Structural Performance of Highway Bridges under Given Foundation Settlements

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***Abstract*—This paper presents a study of structural performance of highway bridges under given foundation settlements. The ultimate objective of this research is to analyze and develop acceptable levels of bridge foundation settlements under ultimate and service limit states, which are not adequately addressed in current bridge design standards. In order to design modern bridges to accommodate any expected foundation settlements, structural engineers need to consider foundation movements and quantify their impacts on the performance of bridge superstructures. In this paper, one type of widely used highway bridges, cast-in-place posttensioned concrete box girder bridges, is considered and settlement analyses are performed to study the induced bridge girder stresses due to foundation or pier settlements. Two sets of bridge examples are studied with different bridge skew angles and horizontal curve radii, to investigate the effects of these parameters. A state-of-art bridge analysis finite element (FE) program is used to analyze various bridge responses. It is shown that the bridge girder curvature and skew angle can impact the girder stresses due to foundation or pier settlements, and the trends are plotted using a numerical parametric study. Based on the evaluation of stress increase due to settlements, an acceptable pier settlement limit can be further determined based on allowable girder stresses in the next stage of the study.**

Keywords*—*foundation settlement; numerical study; cast-in-place concrete; highway bridges; finite element (FE)

I. INTRODUCTION

Bridge designs in real world need to consider foundation movements, since there are many situations where settlements could occur at the foundations of a bridge's abutments or piers. Foundation settlements can be induced due to the compaction or consolidation of soils, higher traffic loads, and poor drainage, etc. In order to design modern bridges to accommodate the expected overall and differential movements to bridge performance requirements, structural engineers need to use the foundation movements estimated by geotechnical engineers. It is important to accurately predict the short-term and long-term effects due to settlements from bridge piers or abutments.

Settlement study of bridge structures and foundations has been performed for a long time [1-5]. However, the study of bridge foundation settlements has been primarily focused on approach slabs in the literature [2-5]. Bridge settlement criteria are not adequately addressed in the current bridge design standards, such as the AASHTO specifications [6]. There is a need to study bridge settlements and improve bridge design practice to adequately address bridge foundation settlements, and their short-term and long-term impacts on the bridge superstructures, such as bridge girders and decks.

The ultimate objective of this research is to analyze and develop acceptable levels of bridge foundation overall and differential movements considering service and strength limit states. In this paper, cast-in-place posttensioned concrete box girder bridges are considered, which are widely used in highway bridge constructions. Settlement analyses are performed to study the induced bridge girder stresses due to various foundation or pier settlements. Two sets of bridge examples are adopted with different bridge skew angles and horizontal curve radii, to study the effects of these parameters on additional bridge girder stresses due to pier settlements. A state-of-art FE program for bridge analysis - *CSI-Bridge* [7] is used to analyze the bridge responses.

II. BRIDGE SETTLEMENT STUDY

A. *Cast-In-Place Highway Bridge*

Highway bridges with various structure types are constructed in practice, depending on the span ranges of the bridges. Cast-in-place posttensioned concrete box girder bridges are widely used for highway bridges spanning up to 600 feet, since they provide many advantages in terms of appearance, safety, economy, and maintenance [8]. In this paper, this type of highway bridges is considered. Two posttensioned concrete highway bridges are shown in Figure 1, representing typical 3-span and 2-span cast-in-place concrete bridges constructed in California.

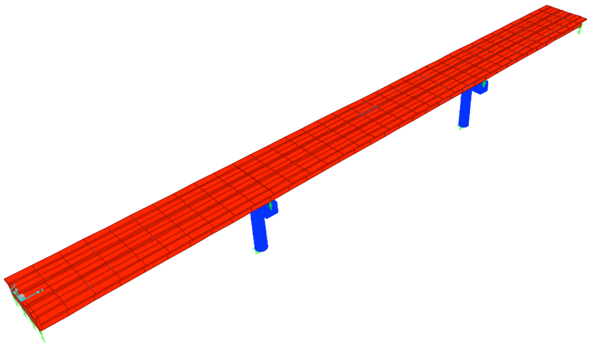
B. *Two Bridge Models*

Example 1 (EX1) is a 3-span posttensioned cast-in-place concrete box girder bridge with a mid-span of 150 feet and 100 feet on each side span, as shown in Figure 1(a). There are two piers and two abutments in EX1. Example 2 (EX2) is a 2-span concrete box girder bridge with a typical span of 150 feet. There are one pier and two abutments in EX2. In both examples, the bridge piers are 30 feet tall, with 6 feet in diameter. A commercial FE code, *CSI-Bridge* [7] is used to model and analyze the bridges. In the two examples, the following general conditions are assumed:

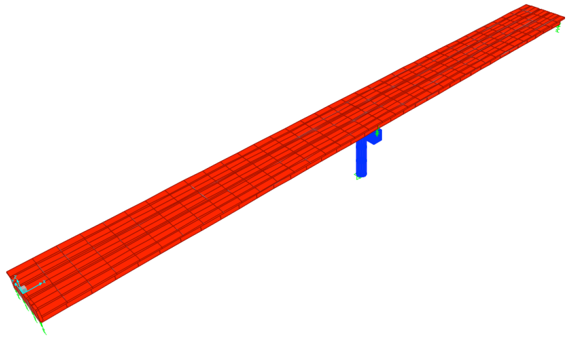
- The concrete strength is 4 ksi.
- The bases of the piers are considered as fully fixed, and the abutments are assumed to be roller-supported.
- The foundation or pier settlements are defined at the bases of the piers.
- An integral cap beam is adopted for all the bridges.
- The piers are modeled with three-dimensional (3D) frame elements, and the girder slabs are modelled using 3D shell elements.
- An overlay of 20 psf is considered. Traffic barriers are used on each side of the bridge girders, and the distributed weight is 1.2 klf.

C. *Bridge Evaluation Matrix*

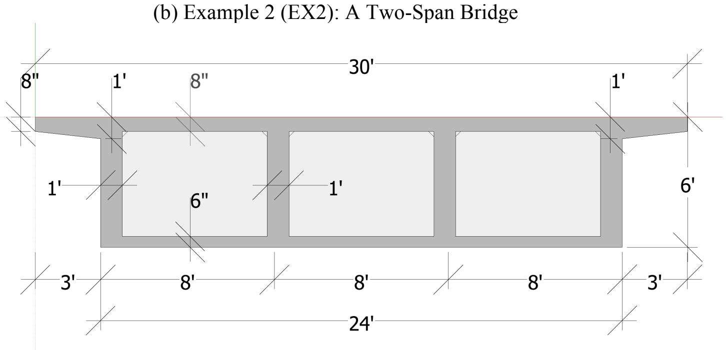
Various bridge design cases are examined using FE simulations to provide a basis for evaluating the settlements and corresponding bridge girder stresses. Table 1 lists the bridge evaluation matrix defined in this study. Four bridge girder horizontal curve radii and five bridge skew angles are selected. Bridges and settlements are evaluated based on the following parameters:



(a) Example 1 (EX1): A Three-Span Bridge



(b) Example 2 (EX2): A Two-Span Bridge



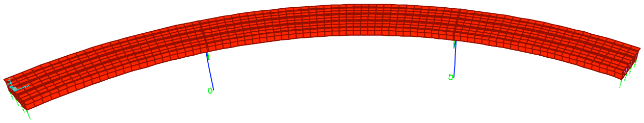
(c) Cross Section of the Concrete Box Girders

Figure 1. Two Examples: Posttensioned Concrete Bridges

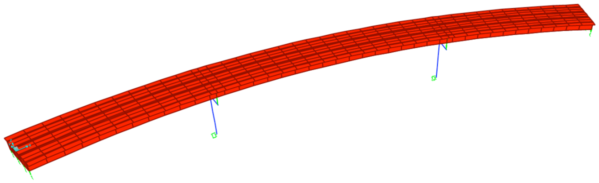
1. *<u>Horizontal Curve Radii</u>*: the four different bridge girder curve radii considered are 250 feet, 500 feet, 1000 feet, and infinite radius, respectively. The last case represents a straight bridge. The 3-span bridges in Example 1 with various horizontal curve radii are illustrated in Figure 2.
2. *<u>Skew Angles</u>*: To study the effects of bridge skew angles on bridge girder settlement stresses, five different bridge skew angles are considered in this study, namely 0˚, 15˚, 30˚, 45˚, and 60˚. These are shown in Figure 3.
3. *<u>Settlement Cases</u>*: Bridge pier settlement cases, including both one-pier settlement and two-pier settlement, are considered in the FE simulations. Figure 4 shows the simulation setups for both one-pier settlement and two-pier settlement. The settlements are defined at the bottom of the piers, as seen in Figure 4, representing the foundation settlement below one pier, or simultaneous settlements underneath two piers. The magnitude of pier settlements is denoted as Δs, as shown in Figure 4. For Example 2, only one-pier settlement is possible. For both one-pier settlement and two-pier settlement, two different pier settlement magnitudes are considered in this study, namely 0.5 inch and 1.0 inch. The consideration of a settlement of 0.5 inch is to verify the bridge FE analysis results obtained using 1.0 inch as the pier settlement. For the rest of the paper, only the FE analysis results based on the one-inch settlement are presented.

Table 1. Bridge Evaluation Matrix

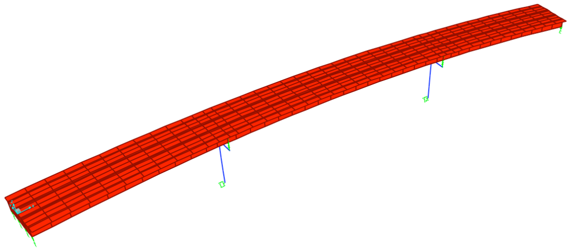
Curve Radius (ft)	Skew Angle (Degree)	Pier Settlement (in)
250	0	0.5
500	15	1.0
1,000	30	
Infinity	45	
	60	



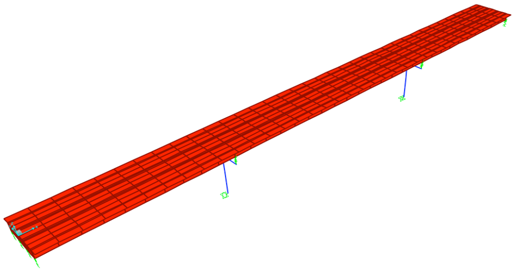
(a) Radius = 250 feet



(b) Radius = 500 feet

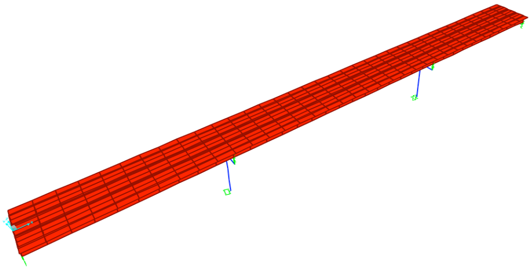


(c) Radius = 1,000 feet

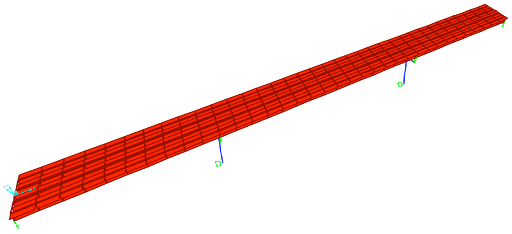


(d) Radius = Infinite (straight bridge)

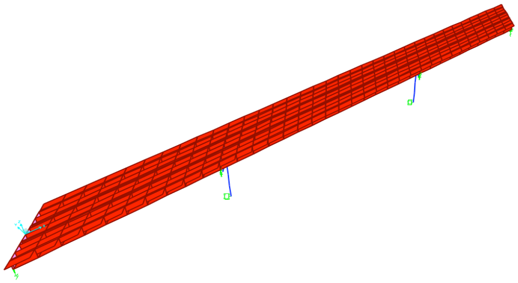
Figure 2. Example 1: 3-Span Bridges with Various Radii (EX1)



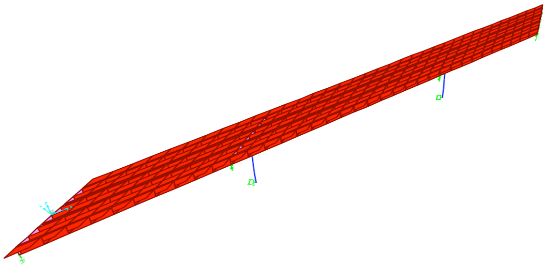
(a) Skew Angle = 15 Degrees



(b) Skew Angle = 30 Degrees

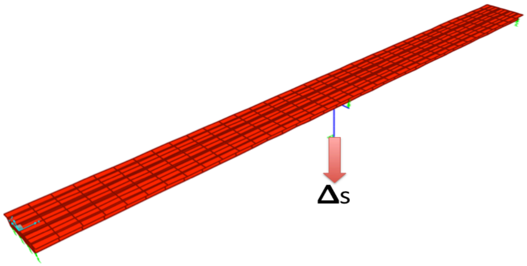


(c) Skew Angle = 45 Degrees

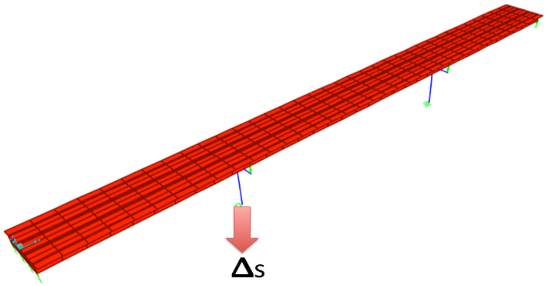


(d) Skew Angle = 60 Degrees

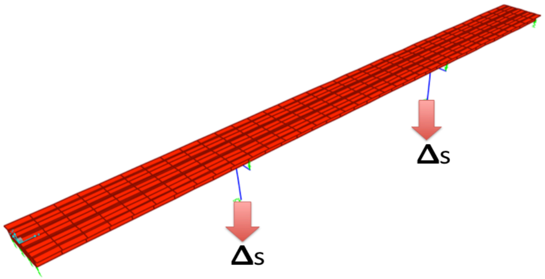
Figure 3. Example 1: 3-Span Bridges with Various Skew Angles (EX1)



(a) Example 1: One-Pier Settlement



(b) Example 2: One-Pier Settlement



(c) Example 2: Two-Pier Settlement

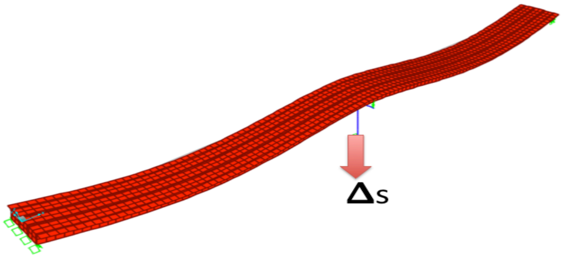
Figure 4. Pier Settlement Cases

III. RESULTS AND DISCUSSION

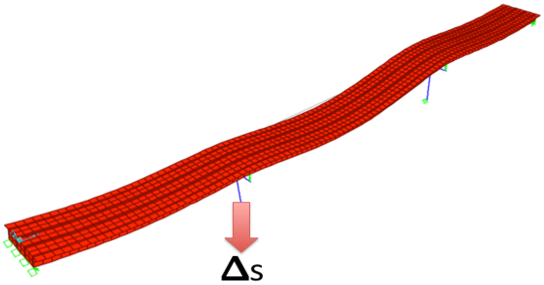
A. Bridge Deformation and Stress Plots

The deformed shapes of the bridge girders for the two examples under both dead load and pier settlements are plotted in Figure 5. As expected the dead load deformation is dominant in both examples, where the maximum girder deformation is found at mid-span between the piers, and piers and abutments. For Example 2, the deformed shapes for one-pier settlement and two-pier settlement cases are similar.

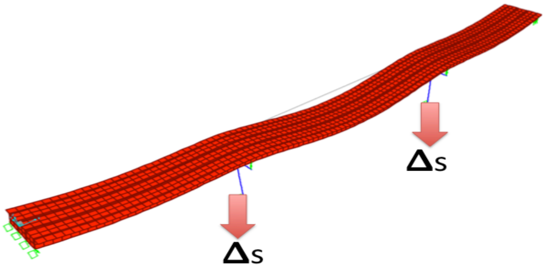
Figure 6 shows the bridge girder stress contour plots under both dead load and pier settlements for the two examples. It is found that the girder stress induced by pier settlements has maximum (tension) and minimum (compression) values at the pier supports.



(a) Example 1: One-Pier Settlement

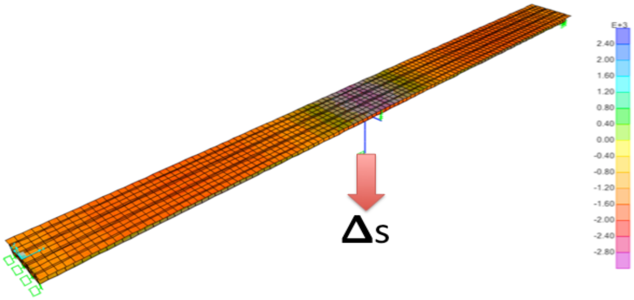


(b) Example 2: One-Pier Settlement

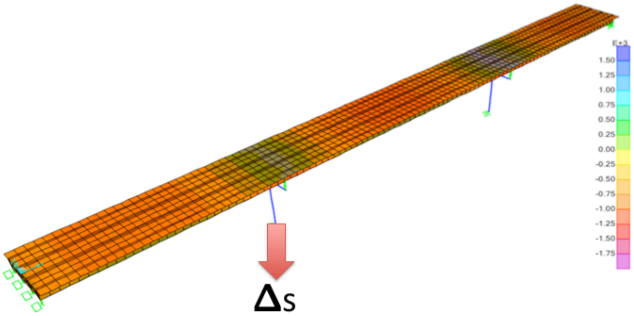


(c) Example 2: Two-Pier Settlement

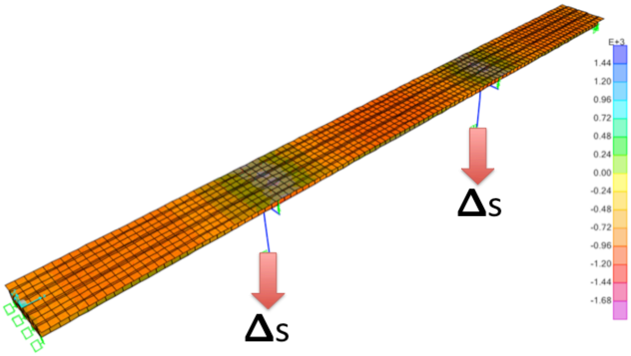
Figure 5. Bridge Girder Deformed Shapes (Dead Load + Settlement)



(a) Example 1: One-Pier Settlement



(b) Example 2: One-Pier Settlement

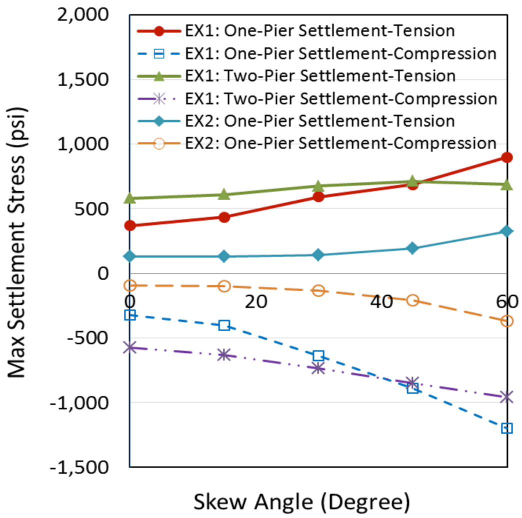


(c) Example 2: Two-Pier Settlement

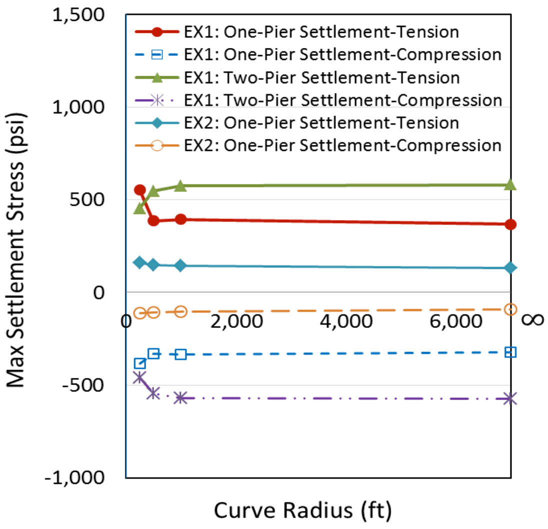
Figure 6. Bridge Girder Stress Contour Plots (Dead Load + Settlement)

B. Bridge Settlement Stress Analysis

The maximum bridge girder tensile and compressive stresses in the two examples due to one-inch pier settlements corresponding to various bridge skew angles and horizontal curve radii are plotted in Figure 7. It can be seen from Figure 7(a) that for both examples, the maximum girder stresses due to pier settlements increase as the skew angle increases. The bridge horizontal curve radius does not significantly impact the maximum girder stresses due to pier settlements, as can be seen from Figure 7(b). The maximum girder settlement stress curves become flat when the bridge horizontal curve radius is more than 500 feet. For Example 1, as expected that two-pier settlement typically induces larger settlement tensile and compressive stresses in bridge girders than one-pier settlement, when skew angle is less than 40 degrees and curve radius is more than 500 feet.

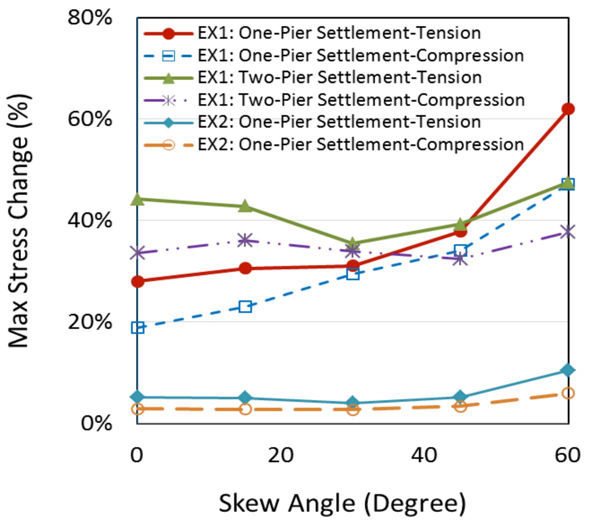


(a) Maximum Settlement Stress vs. Skew Angle

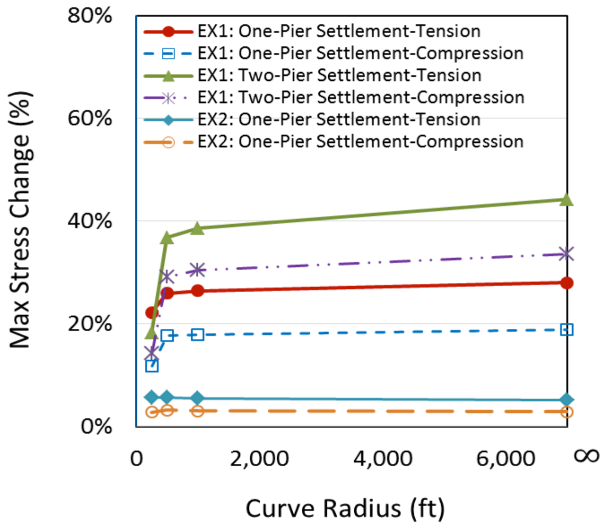


(b) Maximum Settlement Stress vs. Curve Radius

Figure 7. Maximum Bridge Girder Stress Due to Pier Settlements (1 inch)



(a) Maximum Stress Change vs. Skew Angle



(b) Maximum Stress Change vs. Curve Radius

Figure 8. Bridge Girder Stress Change (%) Due to Pier Settlements (1 inch)

Figure 8 shows the bridge girder stress changes due to one-inch pier settlements. The maximum stress change is calculated based on the maximum girder stress due to pier settlements divided by the maximum dead load stress in the girder, expressed as a percentage. The maximum bridge girder stress changes in the two examples due to pier settlements corresponding to various bridge skew angles are plotted in Figure 8(a). It can be seen that for Example 1, the maximum girder stress change increases as the skew angle increases, from about 20% to 40% when skew angle is zero, to 40% to 60% when skew angle is 60 degrees. For Example 2, the maximum girder stress change increases as the skew angle increases, from about 3% to 5% when skew angle is zero, to 6% to 10% when skew angle reaches 60 degrees. Figure 8(b) shows the maximum bridge girder stress change in the two examples due to pier settlements corresponding to various bridge girder curve radii. For Example 1, the girder stress change increases as the curve radius becomes bigger. When the bridge girder curve radius is more than 500 feet, the change of girder stress becomes very small, as can be seen from the flat curves plotted. For Example 2, the girder curve radius does not significantly impact the bridge girder stress change due to pier settlements. For Example 1, as expected that in the two-pier settlement case, larger stress changes in bridge girders are typically induced than in the one-pier settlement case, when bridge skew angle is less than 40 degrees and horizontal curve radius is more than 500 feet.

From the observation and analysis above, it can be seen that:

(1) Bridge girder stress and percentage of stress change due to bridge pier settlements is affected by bridge skew angle and horizontal curve radius. Generally speaking as the skew angle increases, the girder stress and percentage of stress change due to pier settlements increase. Their magnitudes increase by 100 percent as the skew angle increases from 0 to 60 degrees. When horizontal curve radius is more than 500 feet, the impact of horizontal curve radius to girder stress induced by pier settlements is insignificant.

(2) Two-pier simultaneous settlements typically induce larger stress and percentage of stress change in bridge girders than one-pier settlements, when bridge skew angle is small and horizontal curve radius is large.

(3) For two-span bridges, a one-inch pier settlement produces an average of 5-10% stress increase in bridge girders. For three-span bridges, a one-inch pier settlement results in an average of 20-40% stress increase.

(4) Based on the bridge girder stress increase due to pier settlements, an acceptable pier settlement limit can be determined based on allowable girder stresses. This will be addressed in the next stage of this study.

IV. FUTURE RESEARCH

The focus of this research is to study the structural performance of highway bridges under given foundation settlements. Two cast-in-place concrete bridge examples were adopted to study different foundation settlement scenarios and their impact on the bridge superstructures. FE models of the bridges were built and the girder stresses were calculated. It was shown that the bridge girder curvature and skew angle could impact the settlement stresses and the trends were plotted using a numerical parametric study.

The advantage of the proposed method is the simple application based on FE analysis and associated software. More work, especially nonlinear structural modeling and analysis is deemed to be beneficial to study the topic. Nonlinear bridge analyses, including concrete creep, shrinkage analysis, and bridge staged-construction simulation, will provide useful results in addition to the linear elastic analysis models. To make the research results applicable for practical applications, bridges with different structural types and other forms of bridge settlements such as rotations and differential settlements of piers shall be considered. Verification is required to calibrate the numerical models. Note that there is no verification from field testing is available at this point. We would like to propose field testing on bridges to verify the numerical analytical models.

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