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Dynamic effect of foundation settlement on bridge-vehicle interaction

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ABSTRACT

Foundation settlement is a common issue for bridges, which not only generates additional static stresses in continuous bridge members but also may affect the dynamic interaction between the bridge and vehicle traveling over it. In this paper, a new bridge-vehicle model with consideration of foundation settlement effect is created through the principle of virtual works to investigate the settled bridge and vehicle interaction responses. The correctness and accuracy of the model are validated with theoretical and numerical results. Based on the proposed model, numerical simulations have been conducted using the Newmark's β method to investigate the effects of settlement mode, vehicle traveling speed, road surface roughness and boundary condition. It is shown that foundation settlement has a significant effect on impact factors of the bridge at high vehicle speeds, and road surface roughness may act together with the settlement to have a coupling effect, which needs special attentions in bridge design.

1. Introduction

Like other structures, a bridge may experience foundation settlements in its lifetime, which could occur at the abutments or piers of the bridge. Foundation settlements may be caused by the compaction or consolidation of the bearing soil under the weight of the structure, high traffic loads, and/or scouring of the abutments or piers, etc. Settlement is detrimental, and causes serviceability issues and potential structural damage.

Grover [1] reported that 90% of the 68 bridges in his study suffered abutment settlements and 80% of them had settlements from 1 in. (25.4 mm) up to 4 in. (101.6 mm). Walkinshaw [2] conducted a survey on 35 bridges from 10 western states in 1975 and found that large settlements may be tolerable from a structural view of point but may lead to a poor riding quality once exceeding 2.5 in. (63.5 mm). Moulton et al. [3] conducted a comprehensive study on foundation movements of 314 bridges in U.S. and Canada and suggested a tolerable angular distortion (differential settlement/span length) of 0.4% for continuous bridges and 0.5% for simply-supported in 1985. AASHTO [4] adopts similar tolerable criteria for highway bridge settlement, angular distortions less than 0.004 and 0.008 for continuous and simple span bridges respectively. Schopen [5] and Wang et al. [6] performed refined settlement analysis on more rent bridges and obtained similar conclusions that moment induced by differential settlements can be as high as that due to dead and live loads alone, and strengthening bridge superstructures to tolerate settlement may be more economical than limiting foundation not to move. However, the preceding findings and criteria are mostly based on static and probabilistic analysis, with little consideration on dynamic effect of foundation settlement.

Due to the significant increase of heavy and high-speed traffics, bridge-vehicle interaction has gained increasingly attention in recent decades [7–21]. Au et al. [22] investigated the effects of deck surface roughness and long-term deflection of bridges on dynamic impact factors due to moving vehicles. Yin et al. [23] studied the lateral vibration of high-pier bridge under moving vehicular loads. Zhong et al. [24] analyzed the effect of prestress on bridge vehicle interaction responses. Cai et al. [25] and Zhang et al. [26,27] researched the effect of approach span settlement on dynamic behaviors of bridge and vehicle. Ahmari et al. [28] carried out dynamic analysis of a three-span continuous bridge with different support settlement scenarios. Effect of settlements on dynamic impact factors of bridges has been analyzed and compared with the AASHTO specification suggested limits (33%). In reality, bridges may be subjected to road surface roughness and foundation settlements simultaneously, which has not been studied in previous works.

In this paper, road surface roughness and foundation settlement have been incorporated into the bridge-vehicle interaction model through the principle of virtual works. The created model was first validated with theoretical and numerical results, and then used to compute the dynamic responses of the bridge and vehicle using Newmark's β method. Effects of settlement mode, vehicle traveling speed, road surface roughness and boundary condition were

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analyzed and discussed. It is anticipated that results obtained in this paper will help quantifying the settlement limit of the bridge in future.

2. Theory background

2.1. Equation of motion for bridges under foundation settlement

As shown in Fig. 1, a two-span continuous bridge subjected to central pier settlement can be modeled as a continuous beam having displacement at the middle support.

Based on the modal superposition principle, the vertical deflection $w(x,t)$ of the beam with support settlement can be described as

$$w(x,t) = \sum_{i=1}^{N} W_i(x) q_i(t) + w_{o,s}(x) \tag{1}$$

where $W_i(x)$, $q_i(t)$, N and $w_{o,s}(x)$ are the ith mode shape function of the beam, the corresponding modal amplitude of the beam, the selected number of mode shapes and the initial deflection of the beam due to support settlement, respectively.

According to the principle of virtual displacement, the external virtual work δW_E is equal to the internal virtual work δW_I:

$$\delta W_E = \delta W_I \tag{2}$$

The virtual displacements$\delta q_i W_i(x)$, $i = 1,2,\ldots,N$ are selected to be consistent with the assumed shape functions. The external virtual work is the sum of the works (δW_{in}, δW_{gL}, δW_{mL} and δW_C) performed by the inertia force $\left(\bar{m}\frac{\partial^2 w}{\partial t^2}\right)$, the gravity load ($\bar{m}g$), the moving load ($F_b^{int}$) and the damping force $\left(-c_{bi}\frac{\partial w}{\partial t}\right)$, which can be written as,

$$\delta W_E = \delta W_{in} + \delta W_{gL} + \delta W_{mL} + \delta W_C \tag{3}$$

where

$$\delta W_{in} = -\delta q_i \int_0^L W_i(x) \bar{m} \frac{\partial^2 w}{\partial t^2} dx \tag{4.a}$$

$$\delta W_{gL} = -\delta q_i \int_0^L \bar{m} g \frac{\partial^2 w}{\partial t^2} dx \tag{4.b}$$

$$\delta W_{mL} = \delta q_i \int_0^L \sum_{k=1}^{2} F_b^{int}(k) \delta[x - \widehat{x_k}(t)] W_i[\widehat{x_k}(t)] dx \tag{4.c}$$

$$\delta W_C = -\delta q_i \int_0^L c_{bi} \left(\frac{\partial w}{\partial t}\right) W_i(x) dx \quad c_{bi} = 2\bar{m}\omega_i \zeta_i \tag{4.d}$$

and $\bar{m}$ is the mass of the beam per unit length; ω_i, ζ_i, c_{bi} is the natural frequency, damping ratio and damping coefficient for the ith mode of the beam respectively; $F_b^{int}(k)$ is the kth interaction force between the wheel of the vehicle and the bridge; $\widehat{x_k}(t)$is the location of the kth interaction force $F_b^{int}(k)$; $\delta(x)$ is the Dirac function; $W_i'(x)$ denotes the first derivative of $W_i(x)$ with respect to x; g is the acceleration of gravity.

The internal virtual work performed by the bending moment is:

$$\delta W_I = \delta q_i \int_0^L EI \left(\frac{\partial^2 w}{\partial x^2}\right) W_i''(x) dx \tag{5}$$

where EI is flexural rigidity of the beam; $W_i''(x)$ denotes the second derivative of $W_i(x)$ with respect to x.

Substituting Eq. (1) and Eqs. (3)–(5) into Eq. (2) and cancelling δq_i at both sides give

$$\sum_{j=1}^{N} \ddot{q}_j M_{bij} + \sum_{j=1}^{N} \dot{q}_j C_{bij} + \sum_{j=1}^{N} q_j K_{bij} = (W_{mL})_i + (W_{gL})_i + (W_{w_{o,s}})_i \tag{6}$$

where

$$M_{bij} = \int_0^L \bar{m} W_i(x) W_j(x) dx \tag{7.a}$$

$$C_{bij} = \int_0^L c_{bi} W_i(x) W_j(x) dx \tag{7.b}$$

$$K_{bij} = \int_0^L EI W_i''(x) W_j''(x) dx \tag{7.c}$$

$$(W_{mL})_i = \sum_{k=1}^{2} F_b^{int}(k) W_i(\widehat{x_k}(t)) \tag{7.d}$$

$$(W_g)_i = -\int_0^L \bar{m} g W_i(x) dx \tag{7.e}$$

$$(W_{w_{o,s}})_i = -\int_0^L EI W_i''(x) w_{o,s}''(x) dx \tag{7.f}$$

$\dot{q}_j$ and $\ddot{q}_j$ denote the first and second derivative of $q_j(t)$ with respect to time t.

Corresponding to the N independent virtual displacements$\delta q_i W_i(x)$, $i = 1,2,\ldots,N$, there are N virtual work equations in the form of Eq. (6). Together they can be expressed in matrix form as,

$$\boldsymbol{M_b \ddot{Q}} + \boldsymbol{C_b \dot{Q}} + \boldsymbol{K_b Q} = \boldsymbol{W_{mL}} + \boldsymbol{W_{gL}} + \boldsymbol{W_{w_{o,s}}} \tag{8}$$

where

$$\boldsymbol{Q} = \{q_1(t), q_2(t), \ldots, q_N(t)\}^T \tag{9.a}$$

$$\boldsymbol{W_{mL}} = W_b F_b^{int} \tag{9.b}$$

$$\boldsymbol{W_b} = \begin{bmatrix} W_1(\widehat{x_1}(t)) W_1(\widehat{x_2}(t)) \\ \vdots \\ W_N(\widehat{x_1}(t)) W_N(\widehat{x_2}(t)) \end{bmatrix} \tag{9.c}$$

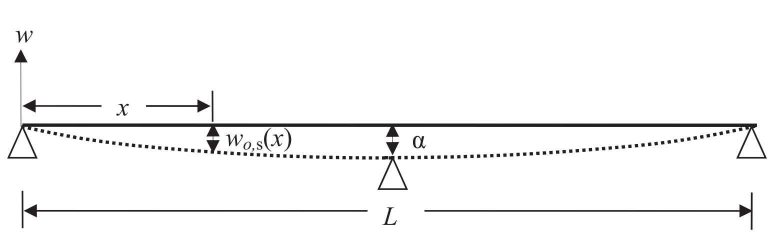

Fig. 1. Schematic of a continuous bridge with central pier settlement.