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Study on Vehicle-Bridge Coupled Vibration of Curved Girder Bridges under Different Road Surface Grades

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Abstract: This study explores the impact of different levels of road surface smoothness on the dynamic response of bridges. By conducting a detailed analysis under five different conditions of road surface smoothness, the mechanisms by which road surface irregularities affect the dynamic characteristics and safety performance of bridge structures are revealed. The research employs the finite element simulation method to compare and analyze the changes in key dynamic indicators such as vertical displacement, torsional angle, torque, and bending moment of bridges under different grades of road surface smoothness. The results indicate that a decrease in road surface smoothness significantly increases the dynamic response of bridges. The findings provide important reference information for bridge engineers in the design and maintenance of bridges.

Keywords: Five-axle vehicle, curved beam axle, axle coupling, dynamic response.

1. Introduction

In modern transportation engineering, bridges as key transportation hubs, their performance directly affects the safety and efficiency of the transportation system. In particular, pavement smoothness, as an important factor affecting the dynamic characteristics of bridges, has a non-negligible impact on the dynamic response and long-term operational performance of bridge structures[1]. However, there are relatively limited systematic studies on the effects of different grades of pavement smoothness on the dynamic response of bridges, which limits the optimization of bridge design and maintenance strategies[2]. In view of this, this study analyzes the effects of five different grades of pavement smoothness on the dynamic response of bridges by in-depth analysis.

2. Establishment of Coupled Axle Vibration Equations

2.1. Vehicle Vibration Equation

The vehicle model selected in this paper is a five-axis vehicle, and the whole model contains eight degrees of freedom, which are: the translational motion of the vehicle in the direction of x-axis, y-axis, and z-axis, acceleration, lateral inclination, and body attitude change; the rotational degrees of freedom of the vehicle around the x-axis, y-axis, and z-axis, i.e., rollover, pitch, and traverse; the front and rear wheel angles of the vehicle, and the compression and extension of the suspension system.

The dynamics equations for the 8-degree-of-freedom vehicle model are as follows:

$$[M_V]\{\ddot{Y}\}+[C_V]\{\dot{Y}\}+[K_V]\{Y\}=\{F_{vb}\}$$

Formula M_v 、 C_v and K_v are the mass matrix, the damping matrix, and the stiffness matrix in the vehicle dynamics model, respectively; $\ddot{Y}$ 、 $\dot{Y}$ and Y represent the acceleration, velocity, and displacement in each degree of freedom in the vehicle dynamics model, respectively; F_{vb} vehicle-bridge interaction force vector consisting of interaction forces at each contact point between the vehicle and the bridge

The vibration equations for the 8-degree-of-freedom vehicle model are as follows:

$$[M_v]\{\ddot{Z}\}+[C_v]\{\dot{Z}\}+[K_v]\{Z\}=\{F_v\}$$

Formula M_v 、 C_v and K_v representation of the same meaning as in the preceding paragraph; $\ddot{Z}$ 、 $\dot{Z}$ and Z represent acceleration, velocity and displacement vectors respectively; F_v a column vector of inertial loads representing each degree of freedom during the vibration of the vehicle

2.2. Bridge Vibration Equation

The vibration equations for a curved girder bridge are as follows:

$$[M_b]\{\ddot{Q}\}+[C_b]\{\dot{Q}\}+[K_b]\{Q\}=[\varphi]^T\{F_{\mathrm{bv}}-F_g\}$$

Formula M_b 、 C_b and V_b represent the bridge structure mass matrix, damping matrix and stiffness matrix, respectively; F is the bridge load force vector for vehicle action.

2.3. Coupled axle vibration equations

According to the displacement coordination relationship of the axle contact points, the axle coupled vibration equations are established as follows:

$$M\{\ddot{X}\}+C\{\dot{X}\}+K\{X\}+H\{X^2\dot{X}\}+Q\{X^3\}=P$$

Formula M、 C and K are the axle coupled mass matrix, damping matrix, and stiffness matrix, respectively; H and Q for the axle coupling geometric nonlinear matrix; P is the axle coupling external force action vector; X is the axle coupling generalized displacement vector.

3. Analysis of Dynamic Response of Curved Girder Bridge By Pavement Grade

In previous studies of coupled vehicle-bridge vibration on bridge types such as simply supported girder bridges, continuous girder bridges and steel-tube concrete arch bridges, it has been concluded that pavement unevenness has a great influence on the dynamic response of the bridge, and the same consistent conclusion has been obtained for the study of curved girder bridges[3]. The poorer pavement unevenness will produce a larger vehicle impact effect, which in turn will cause damage to the pavement, and such a vicious coupling will bring great disadvantages to the maintenance and management of the bridge being used. Therefore, a more in-depth understanding of the role of this factor is essential[4].

In this study, five types of pavement unevenness, namely, smooth pavement, class A pavement, class B pavement, class C pavement, and class D pavement, are taken as the basis for systematic analysis. The dynamic response of curved continuous girder bridge under different pavement smoothness is analyzed under the condition of vehicle speed of 60Km/h, five-axle vehicle weight of 4622.5kg, bridge damping ratio of 0.05, and standard values of suspension stiffness K and suspension damping C. The dynamic response of curved continuous girder bridge under different pavement smoothness is also analyzed separately for side span and side span. And the effects on the side span and center span of the bridge are analyzed separately.

Bridge deck leveling was simulated using the triangular level method based on the power spectral density to calculate the bridge deck unevenness data:

$$G(n) = G(n_0)(n/n_0)^{-w}$$

Formula n is the spatial frequency, n_0 is the reference spatial frequency, w is the frequency index, $G(n_0)$ is the spectral value of the bridge deck.

3.1. Influence of different pavement grades on the mid-span dynamic response of bridge side spans

Figures 1-Figure 4 show the effect of different pavement grades on the vertical displacement, torsion angle, torque and bending moment in the side span of the bridge. The magnitude of vertical displacement, torsion angle, torque and bending moment can indicate the deformation of the bridge structure when subjected to external forces. It can be found by observation:

(1) Under the condition of smooth road surface, the vehicle has the least influence on the dynamic response of the bridge. At this time, the vibration produced by the road surface excitation on the vehicle is small, the vertical dynamic response of the vehicle-bridge coupling system is mainly affected by the static load of the vehicle, and the vertical displacement of the bridge is kept at a low level. As the pavement level decreases, the vibration generated to the vehicle increases, leading to an increase in the dynamic load transferred to the bridge, and therefore, the vertical displacement in the bridge side span increases. When the pavement grade is D, the bridge experiences a high amplitude vertical dynamic response.

(2) Under ideal smooth pavement conditions, the dynamic effects induced by vehicles passing over the bridge are minimized and the dynamic response of the bridge torsion angle is also at a low level. As the smoothness of the pavement decreases, the irregularity of the pavement leads to larger lateral and vertical dynamic loads generated by vehicles, and the asymmetric distribution of these loads exacerbates the torsional angle response of the bridge. When the pavement grade is D, the extreme unevenness of the pavement causes significant dynamic loads on vehicles, which in turn cause significant torsional dynamic responses in the side spans of the bridge.

(3) Under excellent pavement leveling (smooth) conditions, the dynamic interaction between the vehicle and the bridge system is relatively small. As a result, the torsional response in the side-span spans is also relatively low, showing that the bridge has high structural integrity and dynamic stability when subjected to vehicle loading. As the roadway leveling decreases, the dynamic loading of the bridge by the vehicle increases, leading to an increase in the torque response in the side span. This suggests that bridges are more sensitive to dynamic vehicle loading on uneven pavements and that increased attention to dynamic effects in design and maintenance needs to be considered.

(4) Under smooth pavement conditions, the moment response in the side span midspan of the bridge is relatively small, reflecting the lowest dynamic effect of vehicles on the bridge structure. As the pavement smoothness decreases, the moment response in the side span increases significantly, indicating that the dynamic effects caused by vehicle passage pose a serious challenge to the safety and stability of the bridge structure. In this case, the bridge design needs to pay special attention to increase the stiffness and strength of the structure to resist the increased loads due to pavement unevenness.

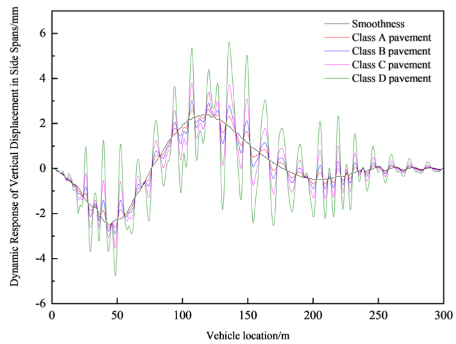

Figure 1. Relationship between different pavement grades and vertical displacement

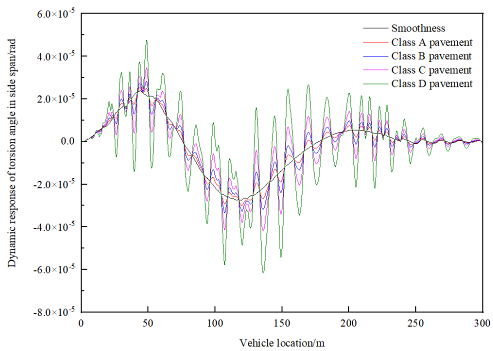

Figure 2. Relationship between different pavement grades and torsion angles

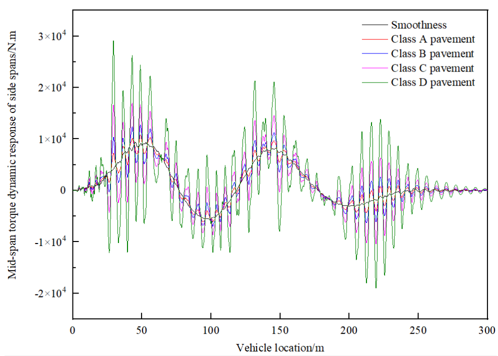

Figure 3. Relationship between different pavement grades and torque

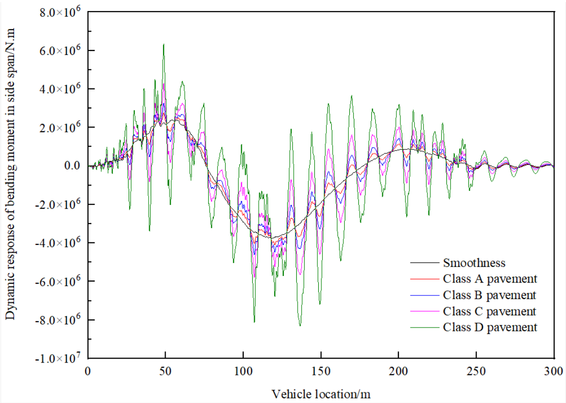

Figure 4. Relationship between different pavement grades and bending moments

3.2. Effect of different pavement grades on the mid-span dynamic response of bridge center spans

Figures 5 - 8 show the effect of different pavement grades on vertical displacement, angle of torsion, torque and bending moment in the mid-span of the bridge. It can be found by observation:

(1) Under smooth pavement conditions, the vertical displacements in the center span of the bridge are minimized, indicating that under ideal or near-ideal pavement conditions, the dynamic effects of vehicles on the bridge are low. As the pavement smoothness decreases, the vertical displacement in the midspan increases relatively, which indicates that the unevenness of the pavement has begun to have an effect on the dynamic interaction between the vehicle and the bridge system, increasing the dynamic load of the bridge, which leads to an increase in the vertical displacement.

(2) The pavement leveling has a significant effect on the dynamic response of the torsion angle in the mid-span of the bridge. With the decrease of pavement smoothness, i.e., from smooth to class D pavement, the dynamic response of torsion angle of the bridge shows a significant increasing trend. The analysis recognizes that; the increase in pavement unevenness leads to a greater dynamic load acting on the bridge, which increases the dynamic response of the torsion angle of the bridge.

(3) The smooth pavement has the least effect on the mid-span mid-torsion torque of the bridge, and the dynamic response of the bridge is mainly caused by the static weights of the bridge and the vehicle. As the smoothness of the roadway decreases, the dynamic loading of the bridge by the vehicle increases, resulting in a more significant dynamic amplification of the mid-span mid-torque. This leads to stress concentrations in the bridge structure and increases the potential for structural fatigue.

(4) Smooth and Class A pavements have a relatively small effect on the mid-span mid-torque of bridges, primarily because pavement smoothness reduces the vehicle impact with the bridge deck, which in turn reduces the dynamic response of the bridge. As the pavement smoothness decreases, it significantly increases the dynamic response of the bridge midspan mid-span bending moment.

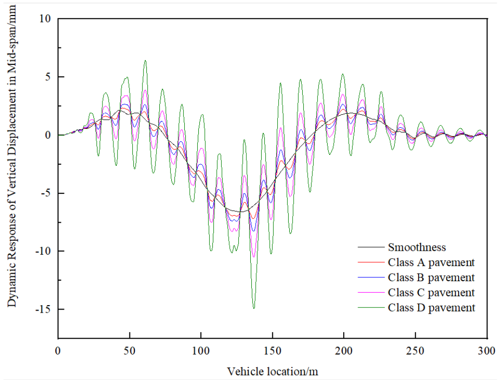

Figure 5. Relationship between different pavement grades and vertical displacement

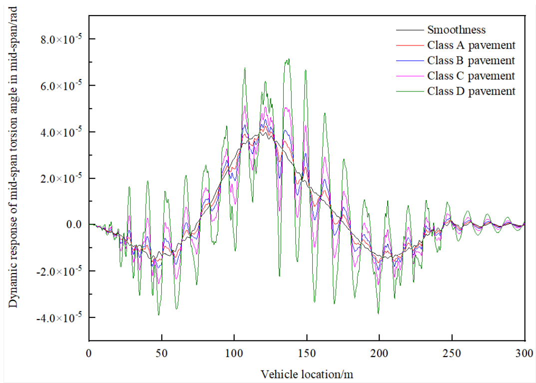

Figure 6. Relationship between different pavement grades and torsion angles

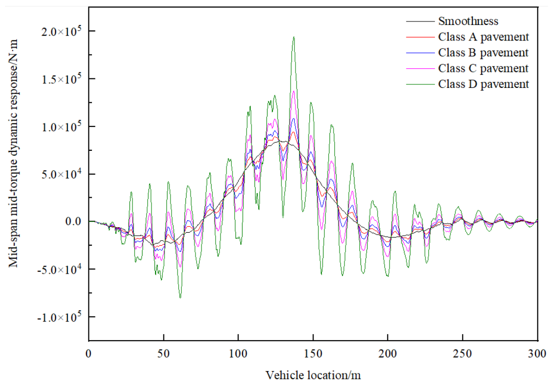

Figure 7. Relationship between different pavement grades and torque

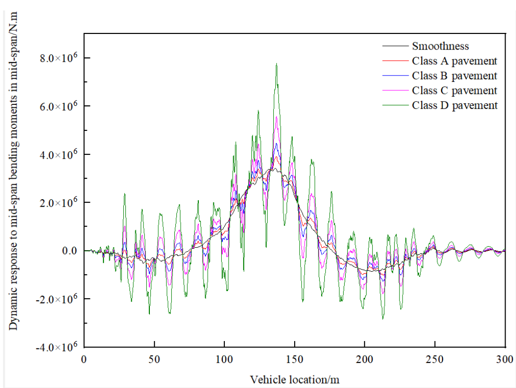

Figure 8. Relationship between different pavement grades and bending moments

4. Conclusion

The following conclusions were drawn from the systematic analysis of the coupling effects of different pavement grades under the vehicle and bridge in this study:

(1) It was found that pavement leveling has a significant effect on the vertical displacement of bridges. The vertical displacement of bridges increases significantly with higher pavement unevenness, which may lead to accelerated fatigue damage of the bridge structure, thus reducing the service life and safety of the bridge.

(2) The torsion angle and torque response of the bridge also increase when the pavement is poorly graded. This increase may affect the structural stability of the bridge and the safety of vehicle travel. Therefore, improving pavement smoothness not only reduces the vertical displacement, but also reduces the adverse effects caused by bridge torsion and torque.

(3) Pavement smoothness also has an important effect on the dynamic response of the bridge to bending moments. With the increase of pavement unevenness, the moment response of the bridge increases significantly, which increases the stress level in the curved portion of the bridge, which in turn may lead to premature damage of the bridge.

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