Lecture Notes in Civil Engineering

Volume 54

Effects of Random Road Roughness on Dynamic Impact Factor of multi-span Super T Girder Bridge with Link Slab due to Moving Vehicles

Xuan-Toan Nguyen[1], Duy-Thao Nguyen[2]

[1,2] The University of Danang -University of Science and Technology, 54 Nguyen Luong Bang Street, Danang city, Vietnam
Email: [1]nxtoan@dut.udn.vn; [2]ndthao@dut.udn.vn

Abstract. The purpose of paper analyzes influence of random road roughness on dynamic impact factor of Bridge subjected to a moving vehicle. The road roughness is assumed by a stationary random process. The bridge has three spans which is modeled by FEM. The moving vehicle has three axles and is idealized by 6-DOFs. Monte-Carlo method is used to create the random road roughness input. The governing equation of dynamic vehicle-bridge interaction is established by means of d'Alembert's principle. Galerkin method and Green theory are applied to discrete the governing equation in the space domain. In this paper, Runge-Kutta methodology was used to solve the governing equation in the time domain. After analyzing with a series profile of road roughness input, it is going to obtain the response of bridge output which is also the random process. The FEM analysis totally agrees with the test results of KhueDong Bridge. Furthermore, the road roughness also was investigated to clarify the effects on dynamic impact factor.
Finally, when road roughness condition changes from the type A to type E, dynamic impact factor has risen considerably.

Keywords: Dynamic impact factor (DIF), Road roughness, Truck, Super T Girder Bridge, Monte-Carlo method, Runge-Kutta methodology.

1 Introduction

The early structural engineers found that under moving loads, structural dynamic deformations and stresses can be significantly higher than those caused by corresponding static loads. Additional dynamic effects are accounted for by dynamic impact factors (DIF or IM) introduced in bridge design codes [1]. There are a large number of studies on this topic including experimental DIF, analytical methods and code specifications. The effect of road roughness on bridge dynamic behavior was investigated by Coussy et al. [2]. In this paper, the suspended moving loads were used. The results of this study showed that the DIF could be three times compared to international design standards recommendation. The frequency domain method was proposed by Lombaert and Conte [3] to analyze the interaction of vehicle and road roughness. The effect of vehicle braking force to bridge dynamic was studied by Xuan-Toan Nguyen et al. [4]. In this paper, three-axle vehicle-bridge interaction with

C. Ha-Minh et al. (eds.), *CIGOS 2019, Innovation for Sustainable Infrastructure*,
Lecture Notes in Civil Engineering 54,
https://doi.org/10.1007/978-981-15-0802-8_12

different velocity was analyzed. In general, previous studies on dynamic interaction of bridge-vehicle were for simple beam bridge. Nevertheless, only some of studies were mentioned about effect of road roughness on dynamic behavior of multi-span Super T Girder Bridge with link slab. Previous researches were lack of field measurement result comparison. Therefore, to obtain fully understanding about relation of vehicle – bridge interaction, further field measurements should be carried out. Current study uses self-developed FEM program to investigate the effect of road roughness on dynamic interaction of truck and three-span Super T concrete girder with link slab. Moreover, the FEM analysis and field measurement results at KhueDong Bridge showed very good agreement.

2 Analysis of the dynamic interaction of the coupled vehicle–bridge system

2.1 Model of the vehicle-bridge system

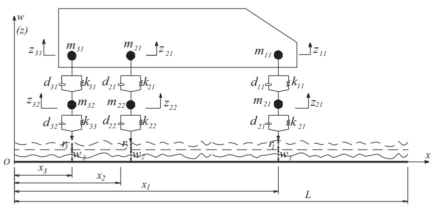

Fig. 1. Truck-bridge interaction model

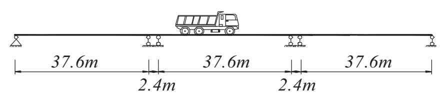

Fig. 2. Schematic of multi-span Super T

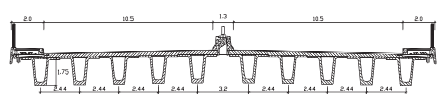

Fig. 3. Bridge cross section

The model of vehicle - bridge dynamic interaction considering road roughness can be seen in Figure 1. In detail, an Euler-Bernoulli beam with three-axle truck was used. The mass of truck and good can be allocated to each axle of vehicle m_{11}, m_{12} and m_{13} respectively. The weight of each axle denote m_{21}, m_{22} and m_{23} respectively. $w_i(x_i,t)$is the girder displacement in vertical direction at i^{th} axle; z_{1i} and z_{2i} denote the displacement of vehicle body and its axle in vertical direction at i^{th} axle; k_{1i} and k_{2i} are the spring stiffness of suspension and tire at i^{th} axle; d_{1i} and d_{2i} denote the dashpot of suspension and tire at i^{th} axle respectively; the location of the i^{th} axle was coordinated by x_i; r_i denote road roughness at i^{th} axle and can be determined by Sun [5]:

$$r(t)=\sum_{k=1}^{M}\sqrt{2S_r(\omega_k)\Delta\omega}.\cos(\omega_k t+\Phi_k)=\sum_{k=1}^{M}\sqrt{2S_r(\Omega_k)\Delta\Omega}.\cos(\omega_k t+\Phi_k) \tag{1}$$

In which $S_r(\omega_k)$ and $S_r(\Omega_k)$ are the power spectral density of road roughness in terms of frequency and wave number which are classified by ISO 8608:1995 [6]; ω and Ω represents frequency and spatial frequency; M and Φ_k denote a positive integer and independent random variable with uniform distribution from 0 to 2π.

2.2 Equation of motion for the vehicle-bridge interaction

From truck-bridge interaction model in Fig.1 and using dynamic balance principle, the equation of motion of the vehicle on the vertical direction can be determined by:

$$m_{1i}.\ddot{z}_{1i} + d_{1i}.\dot{z}_{1i} - d_{1i}.\dot{z}_{2i} + k_{1i}.z_{1i} - k_{1i}.z_{2i} = -m_{1i}.g \quad (2)$$

$$m_{2i}.\ddot{z}_{2i} - d_{1i}.\dot{z}_{1i} + \left(d_{1i} + d_{2i}\right).\dot{z}_{2i} - k_{1i}.z_{1i} + \left(k_{1i} + k_{2i}\right).z_{2i} = k_{2i}\left(w_i + r_i\right) + d_{2i}.\left(\dot{w}_i + \dot{r}_i\right) - m_{2i}.g \quad (3)$$

Governing equation of bridge girder can be written by Ray's formula [7]:

$$EJ.\left(\frac{\partial^4 \omega}{\partial x^4} + \theta \frac{\partial^5 \omega}{\partial x^5.\partial t}\right) + \rho_m.\frac{\partial^2 \omega}{\partial t^2} + \beta.\frac{\partial \omega}{\partial t} = \sum_{i=1}^{n}\left[-\left(m_{1i} + m_{2i}\right).g - m_{1i}.\ddot{z}_{1i} - m_{2i}.\ddot{z}_{2i}\right].\delta\left(x - x_i\right) \quad (4)$$

Where ρ_m, EJ, θ and β denote the initial value of bridge girder as: mass per unit length of girder, bending stiffness, coefficient of internal friction and external friction of bridge girder respectively; $n=3$ which is the axle number. $\delta(x\text{-}xi)$ denote the Dirac delta function.
By using Galerkin method and Green theory, equation 2 to equation 4 was transferred into matrix as following:

$$[M_e].\{\ddot{q}\} + [C_e].\{\dot{q}\} + [K_e].\{q\} = \{f_e\} \quad (5)$$

Where $\{\ddot{q}\}$, $\{\dot{q}\}$, $\{q\}$, $\{f_e\}$ denote acceleration vector, velocity vector, displacement vector and forces vector of both truck and bridge girder.

$$\{\ddot{q}\} = \begin{Bmatrix} \ddot{w} \\ \ddot{z}_1 \\ \ddot{z}_2 \end{Bmatrix}; \{\dot{q}\} = \begin{Bmatrix} \dot{w} \\ \dot{z}_1 \\ \dot{z}_2 \end{Bmatrix}; \{q\} = \begin{Bmatrix} w \\ z_1 \\ z_2 \end{Bmatrix}; \{f_e\} = \begin{Bmatrix} F_w \\ F_{z1} \\ F_{z2} \end{Bmatrix}; \{w\} = \begin{Bmatrix} w_{y1} \\ \phi_1 \\ w_{y2} \\ \phi_2 \end{Bmatrix} \quad (6)$$

in which w_{y1}, w_{y2} denote the displacement in vertical direction in the both end points of bridge girder; φ_1 and φ_2 denote rotation angle in the both end points of bridge girder; $[M_e]$, $[C_e]$ and $[K_e]$ denote the mass matrix, damping matrix and stiffness matrix of both truck and bridge girder, respectively;

$$\left[M_e\right] = \begin{bmatrix} M_{ww} & M_{wz1} & M_{wz2} \\ 0 & M_{z1z1} & 0 \\ 0 & 0 & M_{z2z2} \end{bmatrix}; \left[C_e\right] = \begin{bmatrix} C_{ww} & 0 & 0 \\ 0 & C_{z1z1} & C_{z1z2} \\ C_{z2w} & C_{z2z1} & C_{z2z2} \end{bmatrix}; \left[K_e\right] = \begin{bmatrix} K_{ww} & 0 & 0 \\ 0 & K_{z1z1} & K_{z1z2} \\ K_{z2w} & K_{z2z1} & K_{z2z2} \end{bmatrix} \quad (7)$$

where M_{ww}, C_{ww} and K_{ww} denote mass matrix, damping matrix and stiffness matrix of the bridge girder, respectively, which can be determined in Zienkiewicz [8]. Matrices M_{zizi}, M_{wzi}, C_{zizi}, C_{ziw}, K_{zizi}, K_{ziw} are calculated by Xuan-Toan Nguyen et al [4] when neglect rotational inertial moment of vehicle.

$$F_w = \sum_{i=1}^{n} \left[-\left(m_{1i} + m_{2i} \right) g \right] . P_i \; ; F_{z1} = \begin{Bmatrix} -m_{11}.g \\ \vdots \\ -m_{1i}.g \\ \vdots \\ -m_{1n}.g \end{Bmatrix} ; \; F_{z2} = \begin{Bmatrix} -m_{21}.g + k_{21}.r_1 + d_{21}.\dot{r}_1 \\ -m_{22}.g + k_{22}.r_2 + d_{22}.\dot{r}_2 \\ \cdots \\ -m_{2i}.g + k_{2i}.r_i + d_{2i}.\dot{r}_i \\ -m_{2n}.g + k_{2n}.r_n + d_{2n}.\dot{r}_n \end{Bmatrix}_{n \times 1} \tag{8}$$

Using Runge-Kutta method to solve the equation 5 and obtain responses of bridge girder in the time domain.

3 Numerical simulation and field measurement on KhueDong Bridge

3.1 Parameters of KhueDong bridge and truck

KhueDong Bridge is multi –span super T girder with link slab, which located in Danang city, Vietnam. The decks of KhueDong Bridge are connected at flexible joints with 2.4m of length (Fig.2). The cross section bridge is illustrated in Fig. 3. The parameters of Super T girder are referenced from design: L=36(m), E=30(Gpa), θ=0.027, β=0.01, A=1.21(m^2), J=0.537(m^4); the properties of link slab (deck): h=0.2(m), A=0.488(m^2), J=0.00163(m^4). The parameters of truck are given by the manufacture catalogue and rechecked by site measurement: m_{11}=5000(kg), m_{21}=260(kg), m_{12}= m_{13}=9000(kg), m_{22}= m_{23}=870(kg), $k_{11}=k_{12}=k_{13}$= 2x10^6(N/m), $k_{21}=k_{22}=k_{23}$= 3.8x10^6(N/m), $d_{11}=d_{12}=d_{13}$= 4000(N.s/m), $d_{21}=d_{22}=d_{23}$= 8000(N.s/m).

3.2 Numerical analysis

By the site investigation, the road surface condition of KhueDong Bridge is assumed at Type C-road (ISO 8608:1995): roughness coefficient $S_r(\Omega_0)$= 256×10^{-6} m^3/cycle; exponential γ=2; M=1000; the spatial frequency (Ω_k) change from 0.011to 2.83 cycle/m. Road roughness profiles can be simulated by Monte-Carlo method. A random road roughness profile can be seen in Fig.5. In addition, the vehicle velocity on the bridge is 36 Km/h (10 m/s). For every road roughness input, equation 5 is solved by the Runge-Kutta methodology to achieve the static and dynamic displacement of super T Bridge. The detail of analysis result will be discussed in section 3.3.

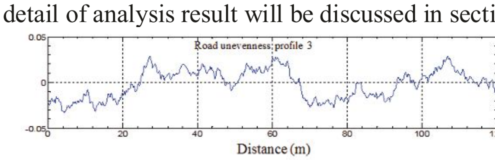

Fig.5. The profile of road roughness

3.3 Field measurement results

To compare with numerical results in section 3.2, field measurement of dynamic response for super T concrete girder was conducted at KhueDong Bridge in Danang city, Vietnam. Displacement sensors were located on the middle of 1st span to check the dynamic displacement of super T girder. Using the excitation from the truck, the girder vibration will be measured with various velocities. The truck velocity at 10, 20, 30 and 40 km/h were used due to the traffic speed regulation of bridge operator. The dynamic displacement of super T girder was recorded and compared with the numerical results (Fig. 6).

The numerical results were totally agreed with the field measurement results. The maximum differences of dynamic displacement between theory and experiment on the middle of 1^{st} span are 1.43%; 6.29%, 8.19% and 8.78% with truck velocity 10, 20, 30 and 40 km/h respectively. Thus, the numerical model mentioned in section 3.2 is reliable.

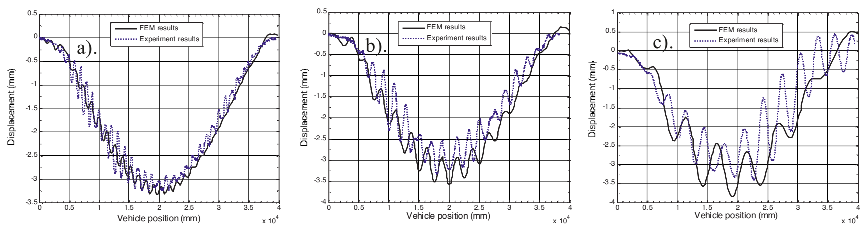

Fig.6. Dynamic displacement with different velocity: a) v=10 km/h; b) v=20 km/h; c) v=40 km/h

3.4 Effect of road roughness on DIF of KhueDong Bridge

Table1. Statistical characteristics of DIF at 1^{st} mid-span

Items	Dynamic Impact Factor (1+IM) $S_r(\Omega_o)$ x10^{-6} m^3/cycle					
	0	32	128	512	2048	8192
Mean value	1.156	1.16	1.17	1.187	1.243	1.622
Maximum	-	1.199	1.248	1.31	1.501	2.455
Minimum	-	1.122	1.093	1.063	0.986	0.79
Standard deviation	-	0.023	0.045	0.072	0.151	0.488

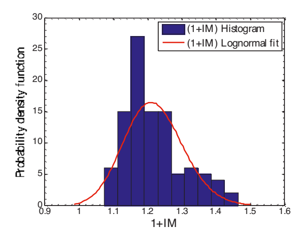

Fig.7. Dynamic impact factor at 1^{st} mid-span (grade B)

From the reliability of numerical model of above discussion, dynamic vehicle-bridge interaction with various road roughness conditions will be investigated. Roughness coefficient $S_r(\Omega_0)$ were varied by range of [0, 32, 128, 512, 2048, 8192]×10^{-6} m^3/cycle corresponding to the road roughness: ideal surface, Type A, B, C, D and E (according to ISO 8608:1995). In these analyses, the truck velocity was fixed at 36km/h. Then, Monte-Carlo simulation method is used to created 100 road roughness profiles for each the road roughness condition. With each road profile, static and dynamic displacements output of super T Bridge can be obtained by using Runge-Kutta method to solve the equation 5. Consequently, dynamic impact factor was summarized in Figure 7. In addition, the details about statistical characteristics of DIF calculation are described in Table 1. Obviously, when road roughness changed from type A, type B, type C, the mean value of IM went up 0.63%, 1.09% and 3.0%, respectively. Particularly, DIF value can rise to 11.26% and 54.47% as road roughness is type D and E. Therefore, DIF value can exceed the recommended value in design standard [1].

4 Conclusion

The effect of road roughness on DIF of super T girder was investigated by numerical and experimental methods. The Monte-Carlo and Runge-Kutta method were applied in this study. In addition, field measurement also carried out at KhueDong Bridge. The theoretical analysis showed good agreement with experimental measurement. Currently, the obtained results are as following:

- ∞ Various road roughness conditions were simulated by Monte-Carlo methodology. From each roughness, DIF was calculated.
- ∞ DIF value can be exceeded the recommendation value in design code when rough roughness are type D and E. In this study, dynamic impact factor can rise 54.47% when the road roughness changes to be type E.
- ∞ Road surface condition should be carefully considered when analyze DIF of bridge structure. Especially, when the pavement have been deteriorated significantly (type D and type E).

References

1. AASHTO, LRFD Bridge Design Specifications, AASHTO, Washington, DC, USA (2012).
2. Coussy, O., Said, M., and Van Hoore, J.P. "The influence of random surface irregularities on the dynamic response of bridges under suspended moving loads". Journal of Sound and Vibration, 130(2): 3 13-320 (1989).
3. Geert Lombaert and Joel P. Conte. "Random vibration analysis of Dynamic Vehicle-Bridge interaction due to Road Roughness". Journal of Engineering Mechanics. 816-825 (2012).
4. Xuan-Toan Nguyen, Van-Duc Tran, Nhat-Duc Hoang. "A Study on the Dynamic Interaction between Three-Axle Vehicle and Continuous Girder Bridge with Consideration of Braking Effects". Journal of Construction Engineering, Volume 2017 (2017).
5. L. Sun, "Simulation of pavement roughness and IRI based on power spectral density", Mathematics and Computers in Simulation 61(2003) 77–88.
6. ISO 8608:1995 ''Mechanical vibration – Road surface profiles – Reporting of measured data'' issued by the International Organization for Standardiazation (ISO).
7. Ray, W. C., and Joseph, P. Dynamics of structures. 3rd Ed. Computers & Structures, Berkeley, California (1995).
8. O.C. Zienkiewicz, R.L. Taylor, J.Z. Zhu. The Finite Element Method: Its Basis and Fundamentals, Seventh Edition. Butterworth-Heinemann, (2013).