Dynamic soil-structure interaction effects on 3D integral railway bridge under high-speed moving loads

Abstract:

In the present article, a double-ballastless track five-span integral bridge subjected to China Railway High-speed (CRH) train loading is studied. Soil-structure interaction (SSI) is considered to assess the resonant response of each span of this bridge. Finite element method is used to analyze the 3D bridge model. Four soil conditions viz. fixed base, hard soil, medium soil and soft soil are considered to investigate the bridge's dynamic response. For each soil condition and for all the spans, it is observed that the resonant speeds correspond to the higher modal frequencies. This study reveals the occurrence of resonance phenomenon for all the spans of an integral bridge, suggesting the importance of moving load analysis. Finally, the vertical resonant responses of the central span of an integral bridge and a continuous bridge are compared.

Keywords: Integral bridge, dynamic soil-structure interaction, moving loads, 3D FEM model.

Introduction

In the last few years, study on different aspect of integral railway bridges has gained the attention of many researchers. Integral bridge is a monolithic bridge construction. The advantages of such a construction is that it is ductile, durable, requires less maintenance cost, has no joints movement in the deck slab and transmits horizontal loads to the ground in much better manner compared to the conventional bridges [1]. The disadvantage of such a construction includes irregular displacements due to thermal expansion and contraction of the deck-slab at abutments and piers [2, 3]. The study of dynamic response of integral bridges subjected to seismic excitations is a significant research area [4, 5].

The effects of speed-induced vibrations on different types of railway bridges have been studied by numerous researchers, in the past [6-9]. Three dimensional bridge models with various boundary/soil conditions are also studied [10, 11]. The aforementioned bridges are either simply supported and/or continuous. The dynamic response of such bridges emphasized the importance of resonance excitation obtained under various train speeds.

For the integral bridges present in the world, the research study mainly focuses on the two aspects viz. cyclic variation due to temperature effects and, braking & seismic forces. However, the dynamic soil-structure interaction (SSI) analysis of a 2D portal frame subjected to various train loads is discussed in [12]; no substantial work related to the identification of resonance phenomenon of 3D multi-span integral bridge under the moving loads is seen. Thus, in the present study, moving loads analysis (MLA) is conducted to determine the dynamic response of aforementioned full-scale integral bridge. Ballastless double-track is assumed to be a part of this bridge. A simple approach of moving load analysis is adopted. Since, only the bridge-deck response in vertical and lateral directions is evaluated, the track irregularities need not be considered, and hence, neglected [13]. China Railway High-speed (CRH3) train loading is considered to be passing over a single-track of the five-span integral bridge. Four different soils below the foundations viz. fixed base, hard soil, medium soil and soft soil are considered and, the dynamic analysis for each soil type is carried out and compared. Eventually, for medium soil condition, the resonance response of integral and continuous bridge is compared.

The main purpose of this study is to provide the design engineers a simplified approach to assess the dynamic response of an integral bridge subjected to high-speed moving loads. Thus, a commercial software package SAP2000 [14] is used to conduct the dynamic SSI analysis.

Integral bridge model

An integral bridge model shown in Figure 1 is considered for the present study. The bridge consists of rails, ballastless tracks (2 numbers), bridge-deck slab, integral abutments and piers. Table 1 shows the details of various components of the integral bridge. Finite element model used to represent the bridge model is shown in Figure 2. The rails and piers are modelled as frame elements, bridge-deck and abutments as shell elements, and the soil is represented by springs and dampers (dashpots). The dynamic interaction between railway tracks and bridge-deck is simulated using spring-damper (link) elements. Figure 3 shows the connectivity details of a combined ballastless track element comprising of the rails, rail pads, cement asphalt mortar (CAM) layer and deck slab.

Moving load and soil model

CRH3 high-speed train of total length 200 m is assumed to be moving on one of the tacks. The axle loads for motor cars (2 numbers) and passenger cars (6 numbers) is taken as 160 kN and 146 kN, respectively. The characteristic distance *d* is considered as 25 m. A simple moving load model is adopted to study the soil-bridge interaction analysis which excludes the vehicle's inertia effect.

The soil stratum below the foundations of structures considerably affects the dynamic response of the structures. In this study, the dynamic soil spring constants in all the six directions are evaluated using the well established formulations presented by [18] (see Table 3). Four soil conditions namely fixed base, hard soil, medium soil and soft soil (depending on the shear wave velocities) are used. Different shear wave velocity values are given in Table 2 (as per soil classification given in Uniform Building Code (UBC, 2000)). The soil density is considered as 18 kN/m^3. The soil adjoining the abutments is considered as medium soil throughout the study. Evaluated values for the vertical, horizontal, lateral, rocking (about horizontal and lateral) and torsion components of dynamic stiffness and damping for the hard, medium and soft soil are provided in Table 4.

In Table 3, $\chi = A_b/4L^2 A_b$ is the area of the foundation considered; I_{bx}, I_{by} and I_{bz} are the moments of inertia about the *x*, *y* and z axes of the actual soil-foundation contact surface, respectively; *B* and *L* are half width and half length of a rectangular foundation, respectively; *G* is shear modulus of soil and ν is the Poisson's ratio of soil, and V_s and V_{La} are the shear-wave velocity and Lysmer's analog wave velocity, respectively. The values of the dynamic stiffness coefficients $\tilde{k}_x$, $\tilde{k}_y$, $\tilde{k}_z$, $\tilde{k}_{rx}$, $\tilde{k}_{ry}$ and $\tilde{k}_t$; and the dynamic damping coefficients $\bar{c}_x$, $\bar{c}_y$, $\bar{c}_{rx}$, $\bar{c}_{ry}$ and $\bar{c}_t$ can be obtained from the relevant charts proposed by [18].

MLA using Finite Element Method

The dynamic equations of the bridge system subjected to moving forces is represented as

$$[M]\{\ddot{U}_b\} + [C]\{\dot{U}_b\} + [K]\{U_b\} = \{F_b\} \quad (1)$$

where, $[M]$, $[C]$,$[K]$, respectively, represent the mass, damping and stiffness of entire bridge system, $\{U_b\}$ the bridge displacement,$\{\dot{U}_b\}$ the velocity, $\{\ddot{U}_b\}$ the acceleration and $\{F_b\}$ the external moving loads acting on the bridge. Equation (1) is a typical second order differential equation, which can be solved by number of time-marching schemes. Newmark-β method [22] with Newmark's parameters $\beta = 1/4$ and $\gamma = 1/2$, are used in this study to determine the dynamic response of the bridge. Rayleigh damping coefficients, evaluated using the modal damping ratio, are adopted. The first five natural frequencies are used in the present study [19]. Table 2 shows the modal analysis information of the integral bridge for all the considered soil types.

Analysis of integral bridge

The modal analysis is carried out to identify the resonance response of this bridge subjected to moving loads. First five mode shapes and modal frequencies are noted. Table 2 summarizes the modal information of different soil types along with their shear wave velocities below the pier foundations. The backfill soil behind the abutments is considered to be medium soil with shear wave velocity as $v_s = 250$ m/s.

The modal damping ratio is required for dynamic soil-bridge interaction analysis under moving loads. Table 5 shows the structural modal damping (%) values for different soil types obtained by the free vibration analysis considering 1 % modal damping for the fixed base condition [19]. A hypothetical case for the fixed base condition is studied to observe the mid-deck maximum acceleration response of the integral bridge. Single track loading is considered for the study. Figure 4 shows the variation of maximum mid-deck vertical acceleration for all the five spans of the bridge with the train speeds. The train speeds is considered to vary from 60 km/h to 600 km/h with an increment of 10 km/h.

Integral bridge response

From Figure 4 it can be observed that the maximum dynamic response is below 380 km/h. Most of the high-speed trains run at an operating speed ranging from 300 km/h to 350 km/h. Thus, for the further dynamic analysis, the train speeds are varied from 60 km/h to 380 km/h. The mid-span dynamic response of the bridge deck in both vertical and lateral directions is studied. The maximum displacement and acceleration values of the mid-span with respect to the varying train speeds on a single track for all the spans of the integral bridge in these two directions is evaluated and shown in Figures 5 to 9.

Figure 5 (a) represents mid-span vertical displacement of span1 for various soil conditions. The train load enters span 1 and departs span 5. For a bridge subjected to moving loads the resonant speed can be evaluated by Equation 2 [20]:

$$v_{brn} = \frac{3.6. f_{bn}. d}{i} (n = 1,2,3 \ldots; i = 1,2,3 \ldots) \quad (2)$$

where, v_{brn} is the resonant moving trains velocity (km/h); f_{bn} is the *n*th natural frequency of the beam (Hz); d is the characteristic distance of the moving high speed trains (m) (considered as 25 m in the present study); i represents the number of complete oscillation cycles for the *n*th mode of the bridge to vibrate during the passage of two adjacent loads.

Two resonance peaks of span 1 mid-span corresponding to the mode numbers 4 and 5 are observed for fixed base, hard and medium soils. It can be observed that with the increase in the speed the displacement and acceleration increases. At resonance, the peak values differ; this is due to the fact that the amplitude of resonance reduces with higher damping ratio. For soft soil, single resonance peak is observed corresponding to the mode number 5. Same response for the mid-span vertical acceleration of span 1 is seen in Figure 5 (b). Figure 5 (c-d) shows the mid-span lateral displacement and acceleration values of the span 1 for various soil conditions.

Figures 6 (a-b) shows the span 2 mid-span vertical displacement and acceleration plot with increasing train speed. These responses increase with the speed for the considered soil types. From the vertical acceleration response, the resonant speed is adjacent to mode number 5. Figures 6 (c-d) represents the mid-span lateral displacement and acceleration values of span 2 for different soil conditions.

Figures 7 (a-b) shows the mid-span dynamic response of span 3 (centre span). This span represents a single resonant peak for all soil types. It can be noted that the peaks obtained for fixed base, hard and medium soils are mostly at similar resonant speeds. From Table 2 it is evident that natural frequencies for mode number 4 (for the fixed base, hard and medium soils) are comparable. Figures 7(c-d) represents the mid-span lateral displacement and acceleration values of span 3 for different soil conditions.

Figures 8 (a-b) shows the dynamic response of span 4 for various soil conditions with increasing train speed. Resonant velocity is obtained at mode number 5. Figures 8 (c-d) represents the mid-span lateral displacement and acceleration values of span 4 for different soil conditions.

Figures 9 (a-d) represents the mid-span vertical and lateral displacement and acceleration response.

Table 6 represents the information of resonant speeds corresponding to the mode number/s for all the four soil conditions. It is observed that for middle span 3, resonance is obtained at mode number 4. Also, the magnitude of the dynamic response for this span for each soil condition is more compared to other spans at the speed of 300 km/h. Thus, this span is considered for the further study. The lateral response of each span is similar to the vertical response. Since, track irregularities and the vehicle's inertia effects are neglected, accurate lateral bridge response is difficult to justify in the absence of an experimental study. Nevertheless, owing to the 3D bridge modeling, a fair amount of dynamic response in the lateral direction may be anticipated.

Analysis of continuous bridge

Keeping all the parameters (dimensions, cross section details of super and sub-structure, material properties and soil type) of the aforesaid integral bridge and, the external loading condition same, a continuous bridge is modelled by altering the bridge deck's support conditions. Figure 10 shows the details of continuous bridge considered for the moving load analysis on a single track. Medium soil type below the piers foundations is considered to compare the dynamic response of integral and continuous bridge. The dynamic soil spring and damping values for medium soil type are referred from Table 4. The essential dynamic soil-bridge interaction analysis parameters for this continuous bridge are summarized in Table 7.

Comparison of continuous and integral bridge response

The dynamic response of a continuous bridge certainly shows variation compared to the integral bridge. As discussed earlier, the centre span 3 of integral bridge being a critical one, its dynamic response is compared with the span 3 of continuous bridge. A comparison between the maximum mid-span vertical displacement and acceleration response varying with the increasing moving loads speeds of the integral and continuous bridges is shown in Figure 11. It can be noted that for both the bridges, the resonance response is obtained at mode number 4 (shown by vertical black solid lines in Figure 11) and hence, at higher speeds. Also, the dynamic responses increase with the increase in the train speed. Integral bridge being stiff compared to the continuous bridge, an obvious shift (more than continuous bridge) of both the vertical displacement and acceleration response at resonance can be clearly seen. The difference in the resonant speeds is not much since; the resonance frequencies of these two bridges for medium soil condition are comparable. Figures 12 and 13, show the time histories of mid-span vertical displacement and acceleration at resonance for the continuous and integral bridge, respectively. It is evident from these two figures that the displacement and acceleration response of the continuous bridge is more than the integral bridge till resonance is obtained. From Figures 12 (a) and 13 (a), it can be observed that the mid-span vertical displacement at resonance of integral bridge is 27% more compared to the continuous bridge. Thus, for the present study, the vertical resonant response of integral bridge is high compared to the continuous bridge.

In this paper, the mid-region vertical and lateral responses of all the spans of a 3D full-scale integral bridge are discussed. Since, the moving loads/forces are considered in the analysis; the vehicle's inertial effects are neglected. This, perhaps, deceive the lateral response of the bridge structure. However, the vertical response is not affected much [21]. This study is related to the effects of SSI on the resonance excitations, produced due to high-speed moving loads, of the superstructure alone. Thus, the vehicle (train) response is of less importance and hence, not discussed. Nevertheless, for assessing the passenger comfort, train-bridge interaction study is essential. This may form the extension to the present study. Further, analysis of a 3D full-scale double track integral model, under high-speed moving trains on both the tracks crossing each other, can be carried out.

Observations and Discussion

Two types of multi-span bridges are analyzed viz. integral and continuous. For the integral bridge, different soil conditions below the pier foundations to carry out a dynamic soil-bridge interaction analysis subjected to high-speed moving loads running on a single trackare considered. The resonance response (vertical and lateral) of mid-span of each span of the bridge deck is studied. From the analyses it can be stated that:

- For all the five spans and for all the considered soil conditions, the resonance peaks (vertical response) are obtained at the speeds corresponding to the higher modal frequencies (mode numbers 4 and 5).
- For the lateral response of all these spans, similar condition discussed in the above point is obtained. These values are too small and are presented in this study merely to show the contribution of moving loads in lateral direction on a full-scale 3D bridge finite element model.
- Resonance peaks and resonant speeds for the corresponding lower modal frequencies (mode numbers 1-3) cannot be seen.

- Span 3 (middle span) is a critical span; since, the magnitude of its resonance peak corresponding to the mode number 4 is more compared to the other spans with same mode number. This is true for all soil types.
- Fixed base condition overestimates the dynamic response of the superstructure. The dynamic SSI analysis shows the reduction of resonance amplitude, thus, emphasizing its importance.

A comparative dynamic analysis of the integral and continuous bridge for medium soil condition is worked out. The middle span of both these bridges is analysed to know its vertical resonance response. From this, following is noted:

- For both the bridges, the resonance response is obtained at higher mode number 4.
- The magnitude of resonance response for the integral bridge is more than that of continuous bridge.

Thus, from the above discussion it can be concluded that the resonance response is certainly observed for different spans of an integral bridge under high-speed moving loads on a single track. The variation of resonance peak is evident for different soil conditions and hence, for different modal damping ratios. From this study, it is clear that a detailed dynamic SSI analysis under high-speed moving loads is essential to know the resonance response of integral bridges. A detailed investigation of the dynamic soil-integral bridge interaction under high-speed trains moving on both the tracks is suggested.

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Table 1. Parameters considered for the Integral Bridge Structure

Description	Value	Unit	Reference
	Rails		
Young's modulus	2.1×10^{8}	kN/m^2	
Flexural moment of inertia about minor axis of cross section	3.2×10^{-5}	m^4	
Flexural moment of inertia about major axis of cross section	5.24×10^{-6}	m^4	[15]
Mass per unit length	60.64	kg/m	
	Rail pads		
Horizontal stiffness	50×10^{3}	kN/m	
Horizontal damping	60	kN-s/m	
Vertical stiffness	30×10^{3}	kN/m	[16]
Vertical damping	50	kN-s/m	
Interval/spacing	0.60	m	
	Cement Asphalt Mortar (CAM) Layer		
Stiffness	0.9×10^{3}	MN/m	
Damping	80	kN-s/m	[17]
	Girder, Abutments, Piers and Pier Foundations		
Young's modulus	2.9×10^{7}	kN/m^2	
Height of piers	12	m	
Diameter of piers	1.0	m	[2]
Abutment width	14.4	m	
Abutment height	3.3	m	
Foundation (L×B×H)	(7×5×1.5)	m	

Table 2. Modal information of the Integral Bridge for different soil conditions

Mode number	Modal frequencies (Hz) for various soil types (shear wave velocity v_s) and nature of each mode			
	Fixed base (-)	Hard (400 m/s)	Medium (250 m/s)	Soft (150 m/s)
1	1.626 (lateral floating)	1.616 (lateral floating)	1.607 (lateral floating)	1.581 (lateral floating)
2	2.300 (1st vertical symmetrical bending)	2.297 (1st vertical symmetrical bending)	2.285 (1st vertical symmetrical bending)	2.270 (1st vertical symmetrical bending)
3	2.780 (2nd vertical symmetrical bending)	2.769 (1st vertical anti-symmetrical bending)	2.747 (1st vertical symmetrical bending)	2.696 (vertical anti-symmetrical bending)
4	3.390 (vertical anti-symmetrical bending)	3.364 (2nd vertical symmetrical bending)	3.321 (2nd vertical symmetrical bending)	3.200 (2nd vertical symmetrical bending)
5	3.944 (twisting)	3.900 (2nd vertical anti-symmetrical bending)	3.832 (2nd vertical anti-symmetrical bending)	3.653 (lateral bending)

Table 3. Equivalent dynamic spring stiffness and dashpot values along various degrees of freedom [18]

Degrees of freedom	Stiffness of equivalent soil spring	Radiation dashpot coefficient
Vertical	$(\tilde{K}_z) = (2GL/(1-v))(0.73+1.54\chi^{0.75}) \cdot (\tilde{k}_z)$	$C_z = (\rho V_{La} A_b) \cdot \bar{c}_z$
Horizontal(lateral direction)	$(\tilde{K}_y) = (2GL/(2-v))(2+2.50\chi^{0.85}) \cdot (\tilde{k}_y)$	$C_y = (\rho V_s A_b) \cdot \bar{c}_y$
Horizontal(longitudinal direction)	$(\tilde{K}_x) = (\tilde{K}_y-(0.2/(0.75-v))GL(1-(B/L))) \cdot (\tilde{k}_x)$	$C_x = (\rho V_s A_b)$
Rocking(about the longitudinal, *x*-axis)	$(\tilde{K}_{rx}) = (G/(1-v))I_{bx}^{0.75}(L/B)^{0.25}(2.4 + 0.5(B/L)) \cdot (\tilde{k}_{rx})$	$C_{rx} = (\rho V_{La} I_{bx}) \cdot \bar{c}_{rx}$
Rocking(about the lateral, *y*-axis)	$(\tilde{K}_{ry}) = (3G/(1-v))I_{by}^{0.75}(L/B)^{0.15} \cdot (\tilde{k}_{ry})$	$C_{ry} = (\rho V_{La} I_{by}) \cdot \bar{c}_{ry}$
Torsion	$(\tilde{K}_t) = 3.5GI_{bz}^{0.75}(B/L)^{0.4}(I_{bz}/B^4)^{0.2} \cdot (\tilde{k}_t)$	$C_t = (\rho V_s I_{bz}) \cdot \bar{c}_t$

Table 4. Dynamic stiffness and dashpot values for different soil conditions

Description	Degree of freedom	Hard soil	Medium soil	Soft soil
Dynamic Stiffness (kN/m)	$\widetilde{K}_x$	7.32×10^6	2.86×10^6	1.03×10^6
	$\widetilde{K}_y$	7.39×10^6	2.89×10^6	1.04×10^6
	$\widetilde{K}_z$	9.21×10^6	3.60×10^6	1.29×10^6
	$\widetilde{K}_{rx}$	2.24×10^6	7.1×10^5	3.11×10^5
	$\widetilde{K}_{ry}$	4.3×10^6	1.68×10^6	5.99×10^5
	$\widetilde{K}_t$	1.84×10^6	8.70×10^5	2.57×10^5
Dynamic Damping (kN-s/m)	$\tilde{C}_x$	5.30×10^4	3.31×10^4	1.99×10^4
	$\tilde{C}_y$	5.30×10^4	3.31×10^4	1.99×10^4
	$\tilde{C}_z$	1.75×10^5	1.09×10^5	6.56×10^4
	$\tilde{C}_{rx}$	3.17×10^3	2.07×10^3	1.31×10^3
	$\tilde{C}_{ry}$	7.67×10^3	4.99×10^3	3.16×10^3
	$\tilde{C}_t$	8.93×10^2	6.39×10^2	5.20×10^2

Table 5. Modal damping ratios for various soil types

Soil type	Modal damping (%)
Fixed base	1.0
Hard	1.4
Medium	1.7
Soft	2.3

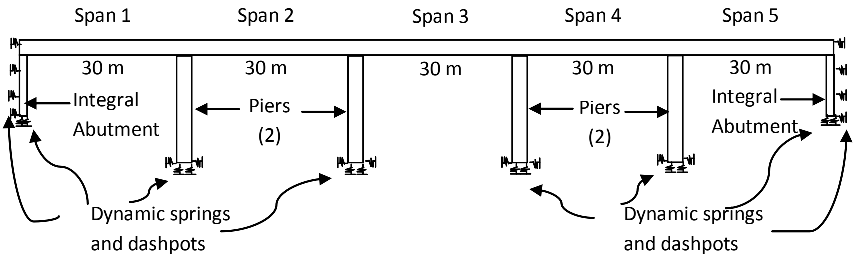
Table 6. Mid-span resonance response of all the spans of integral bridge

Pier foundation	Span 1		Span 2		Span 3		Span 4		Span 5	
	Resonant speed (km/h)	Corresponding mode number	Resonant speed (km/h)	Corresponding mode number	Resonant speed (km/h)	Corresponding mode number	Resonant speed (km/h)	Corresponding mode number	Resonant speed (km/h)	Corresponding mode number
Fixed base	300, 350	4, 5	350	5	300	4	350	5	300, 350	4, 5
Hard soil	300, 350	4, 5	350	5	300	4	350	5	300, 350	4, 5
Medium soil	300, 350	4, 5	350	5	300	4	350	5	350	5
Soft soil	325	5	325	5	288	4	325	5	328	5

Table 7. Dynamic SSI properties required for the analysis of continuous bridge

Mode number	Frequency (Hz)	Modal damping (%)	Rayleigh damping constants
1	1.612 (lateral floating)	1.7	a_0= 0.2411 s^{-1}, a_1= 1.007 x10^{-3} s
2	2.286 (1^{st} vertical symmetrical bending)		
3	2.739 (1^{st} vertical anti-symmetrical bending)		
4	3.297 (2^{nd} vertical symmetrical bending)		
5	3.764 (2^{nd} vertical anti-symmetrical bending)		

(a)



(b)

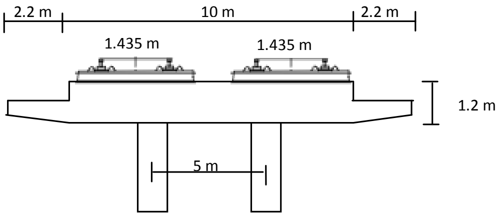


Figure 1. Elevation (a) and cross-sectional details (b) of the integral bridge.

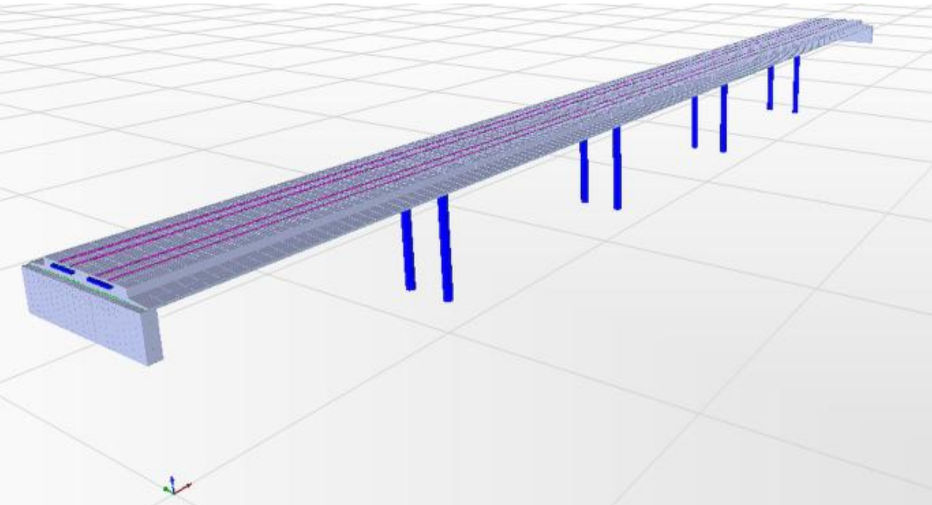


Figure 2. Full-scale 3D finite element model of the integral bridge.

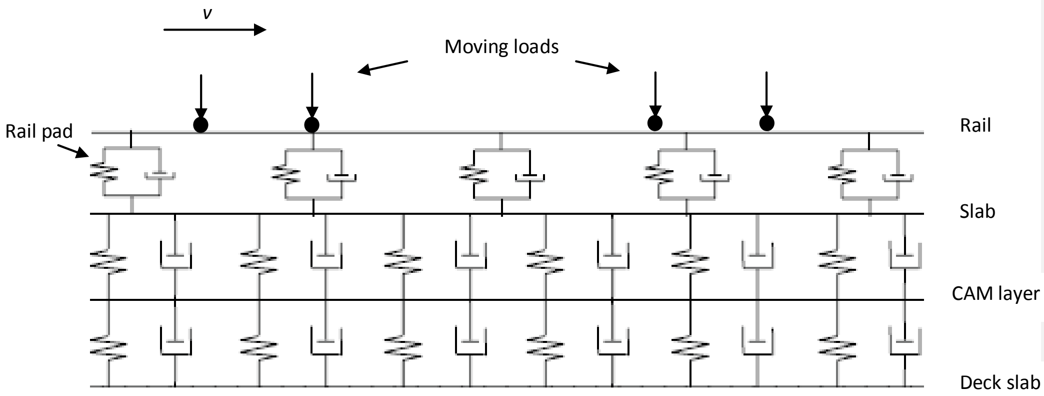


Figure 3. Ballastless bridge deck slab model (longitudinal section).

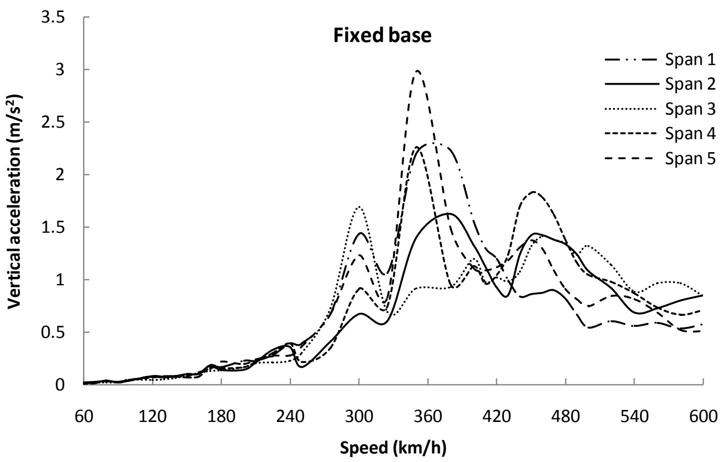
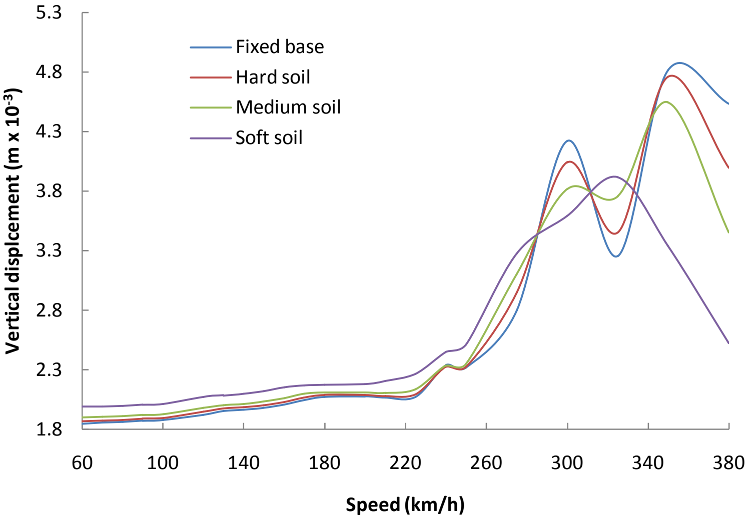
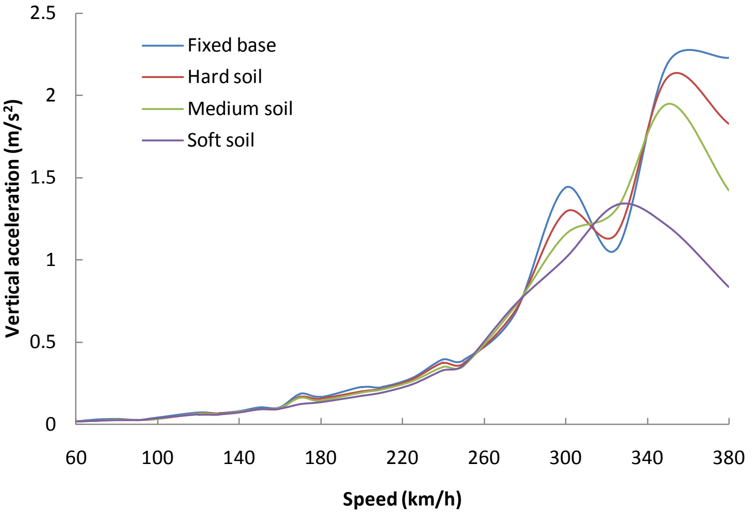


Figure 4. Maximum mid-span bridge deck vertical acceleration response with varying train speeds.

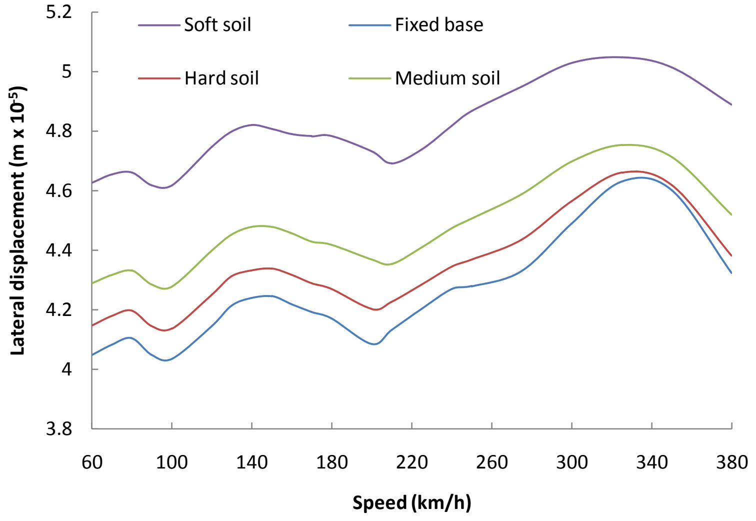
(a)


5.3
4.8
4.3
3.8
3.3
2.8
2.3
1.8
Vertical displcement (m x 10⁻³)
Fixed base
Hard soil
Medium soil
Soft soil
60
100
140
180
220
260
300
340
380
Speed (km/h)

(b)


2.5
2
1.5
1
0.5
0
Vertical acceleration (m/s²)
Fixed base
Hard soil
Medium soil
Soft soil
60
100
140
180
220
260
300
340
380
Speed (km/h)

(c)



(d)

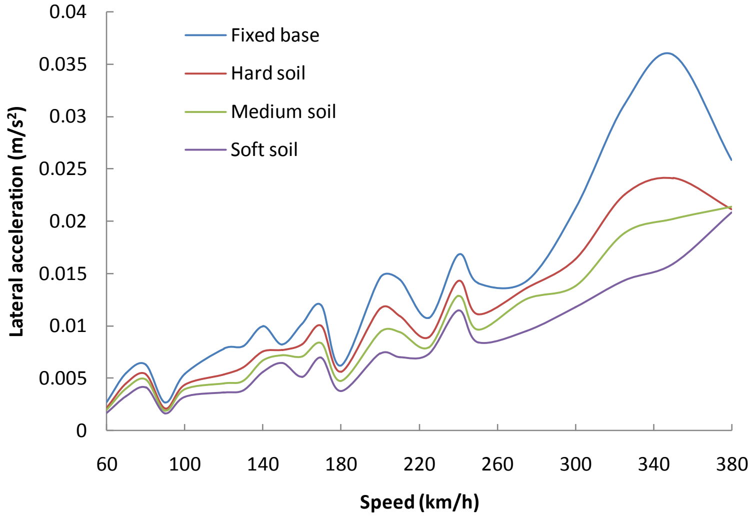
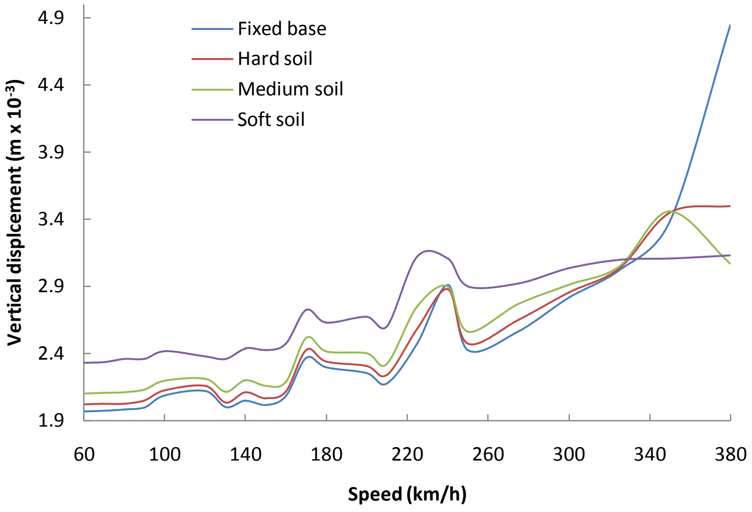
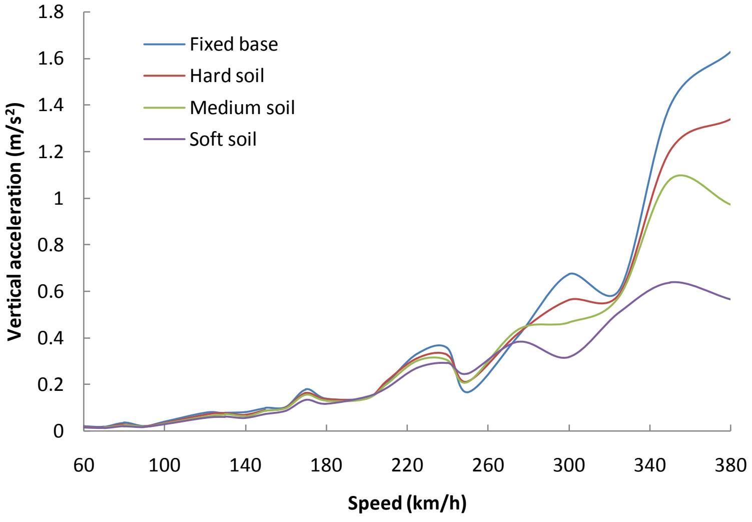


Figure 5. Mid-span maximum vertical and lateral displacement (a, c) and acceleration (b, d) response with varying train speeds of span 1of integral bridge.

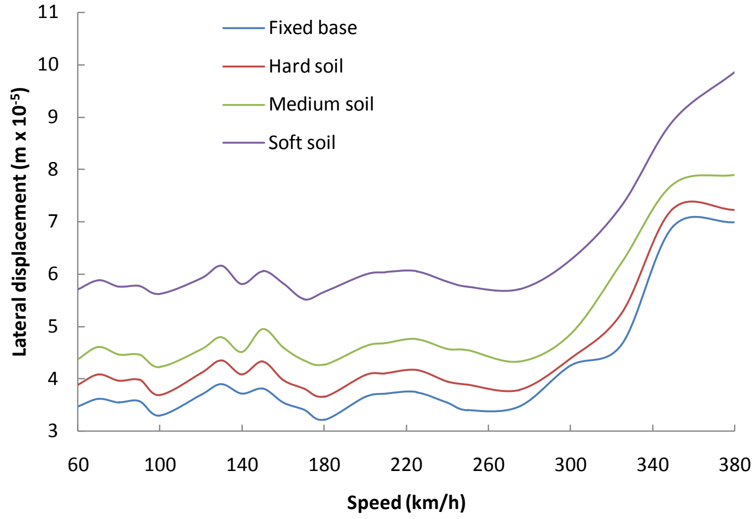
(a)


Fixed base
Hard soil
Medium soil
Soft soil
Vertical displcement (m x 10⁻³)
Speed (km/h)
4.9
4.4
3.9
3.4
2.9
2.4
1.9
60
100
140
180
220
260
300
340
380

(b)


Fixed base
Hard soil
Medium soil
Soft soil
Vertical acceleration (m/s²)
Speed (km/h)
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
60
100
140
180
220
260
300
340
380

(c)



(d)

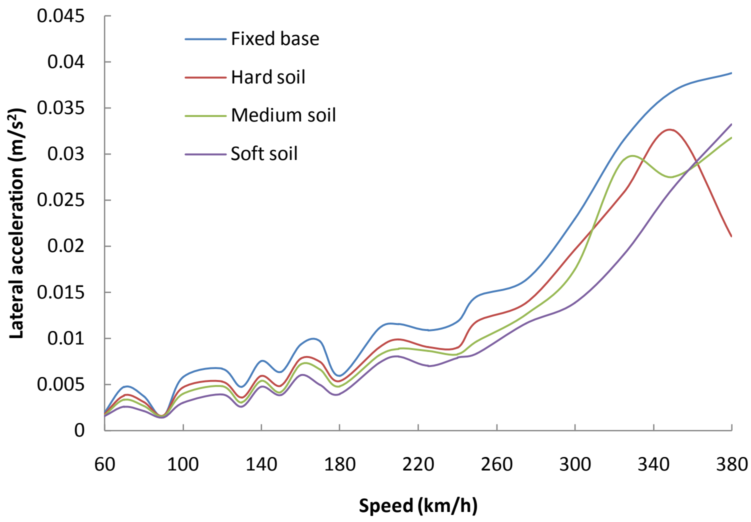
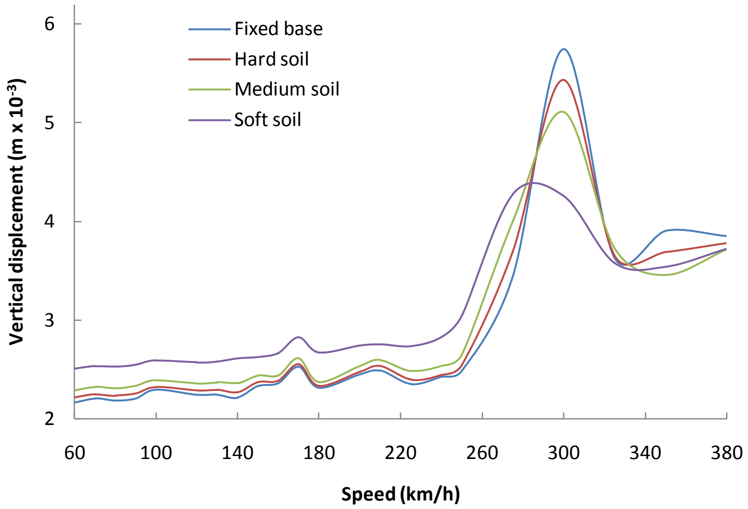
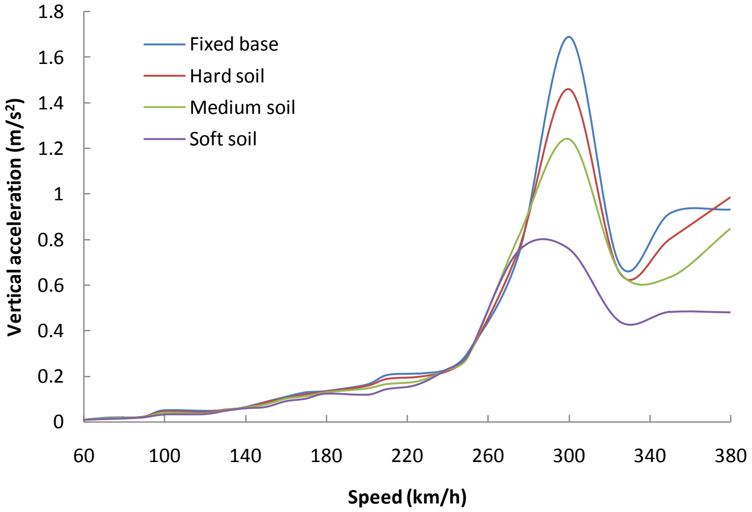


Figure 6. Mid-span maximum vertical and lateral displacement (a, c) and acceleration (b, d) response with varying train speeds of span 2 of integral bridge.

(a)


Fixed base
Hard soil
Medium soil
Soft soil
Vertical displcement (m x 10⁻³)
6
5
4
3
2
60
100
140
180
220
260
300
340
380
Speed (km/h)

(b)


Fixed base
Hard soil
Medium soil
Soft soil
Vertical acceleration (m/s²)
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
60
100
140
180
220
260
300
340
380
Speed (km/h)

(c)

(d)

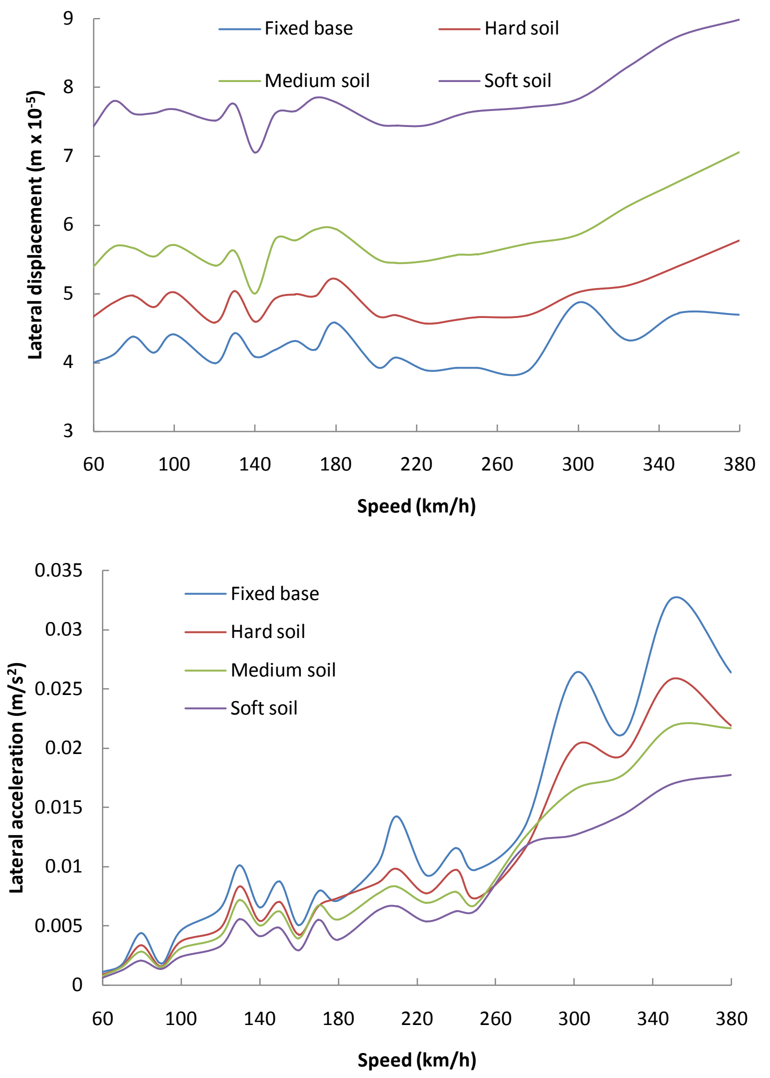
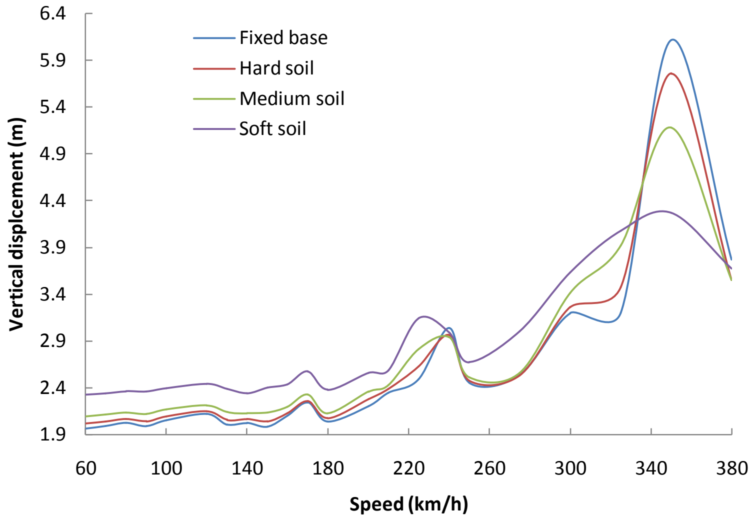
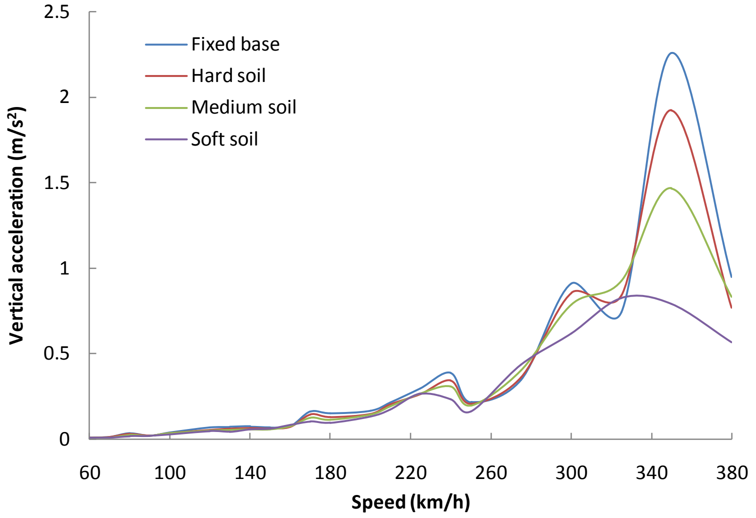


Figure 7. Mid-span maximum vertical and lateral displacement (a, c) and acceleration (b, d) response with varying train speeds of span 3 of integral bridge.

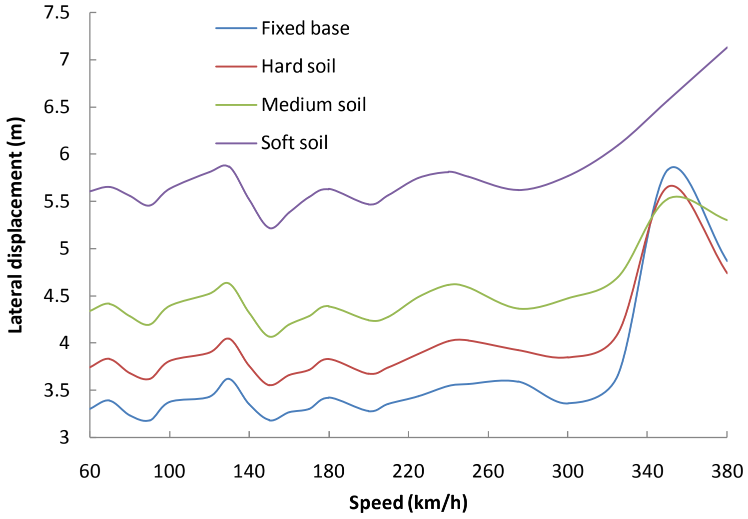
(a)


6.4
5.9
5.4
4.9
4.4
3.9
3.4
2.9
2.4
1.9
Vertical displcement (m)
Fixed base
Hard soil
Medium soil
Soft soil
60
100
140
180
220
260
300
340
380
Speed (km/h)

(b)


2.5
2
1.5
1
0.5
0
Vertical acceleration (m/s²)
Fixed base
Hard soil
Medium soil
Soft soil
60
100
140
180
220
260
300
340
380
Speed (km/h)

(c)



(d)

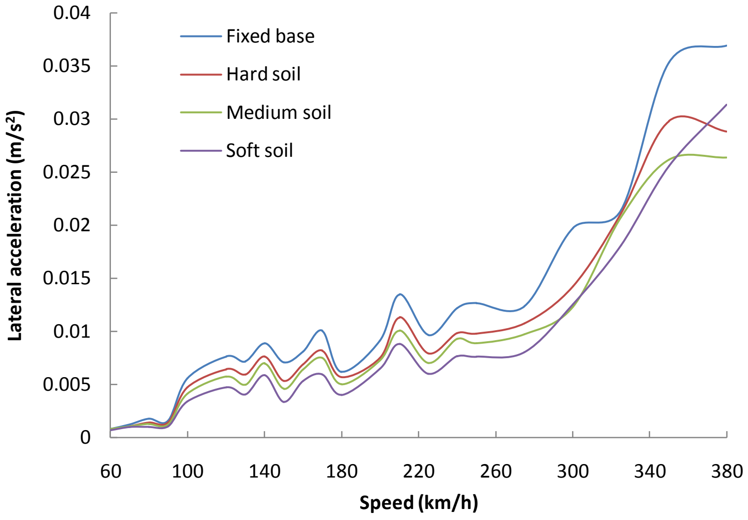
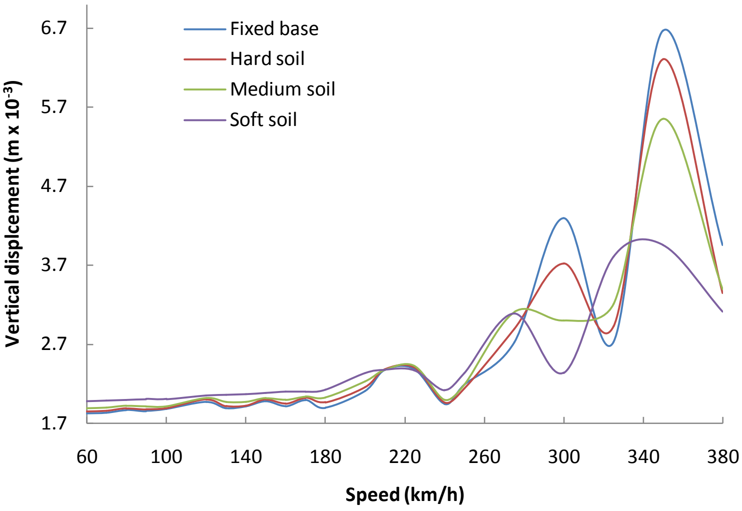


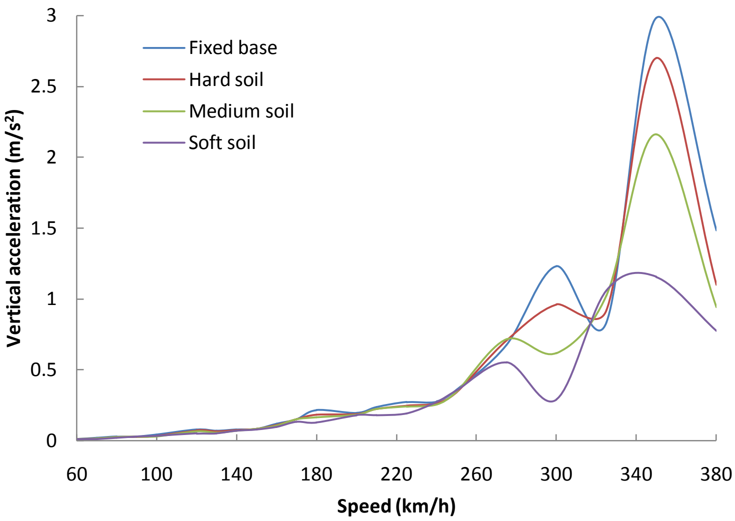
Figure 8. Mid-span maximum vertical and lateral displacement (a, c) and acceleration (b, d) response with varying train speeds of span 4 of integral bridge.

(a)



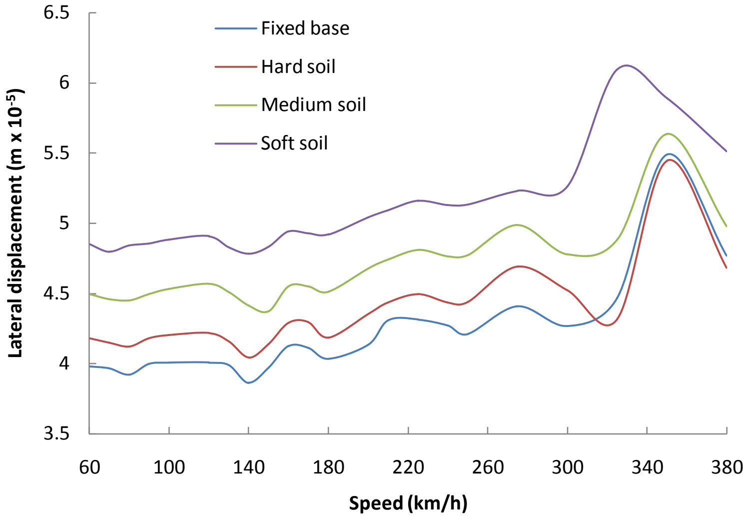
Fixed base
Hard soil
Medium soil
Soft soil
Vertical displcement (m x 10^-3)
Speed (km/h)

(b)



Fixed base
Hard soil
Medium soil
Soft soil
Vertical acceleration (m/s²)
Speed (km/h)

(c)



(d)

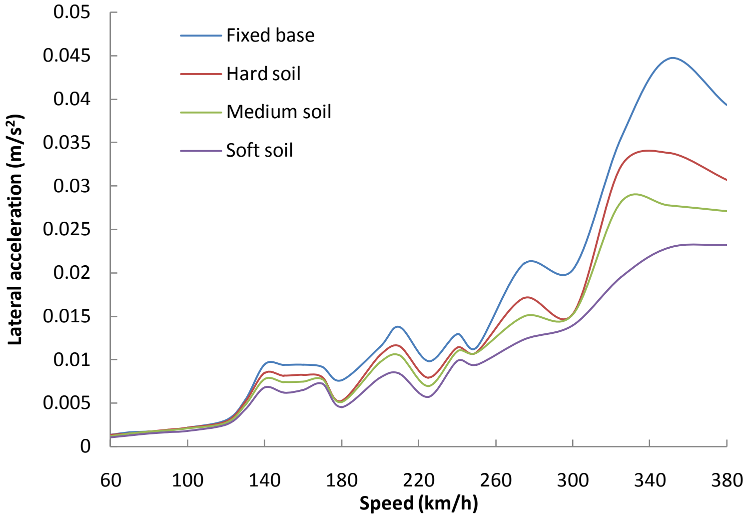


Figure 9. Mid-span maximum vertical and lateral displacement (a, c) and acceleration (b, d) response with varying train speeds of span 5 of integral bridge.

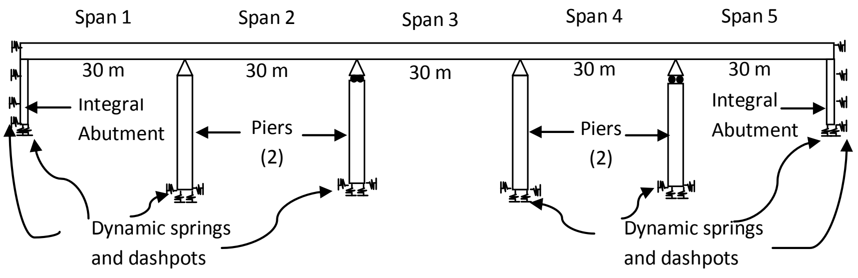
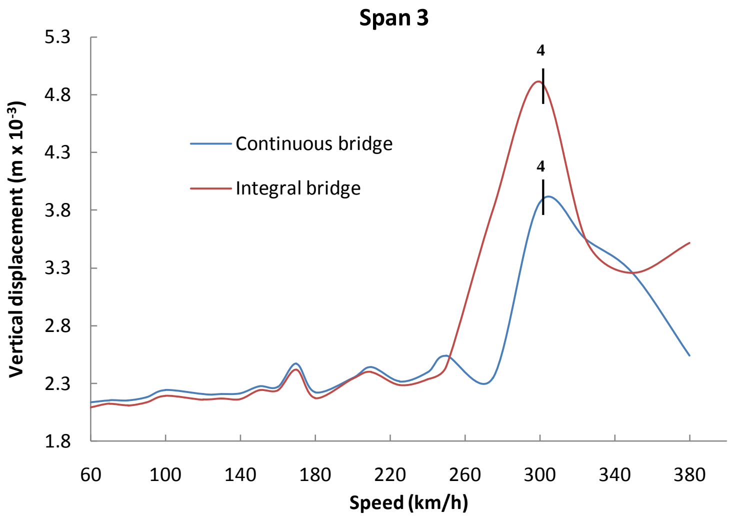


Figure 10. Continuous bridge considered for the dynamic soil-structure interaction analysis.

(a)



(b)

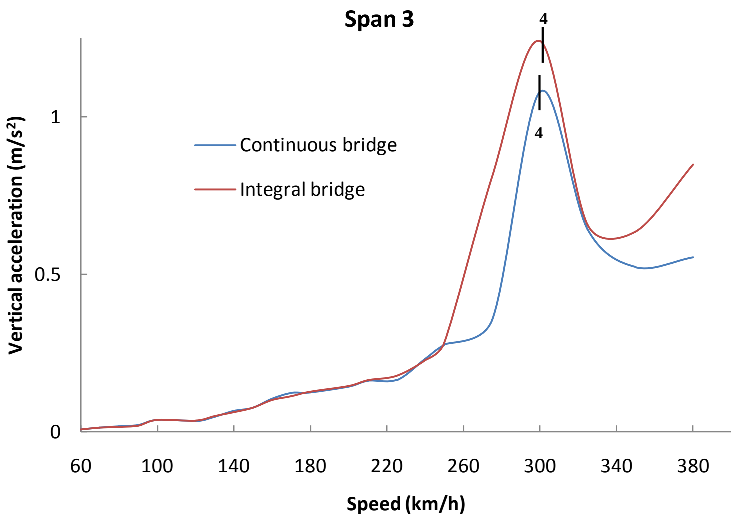
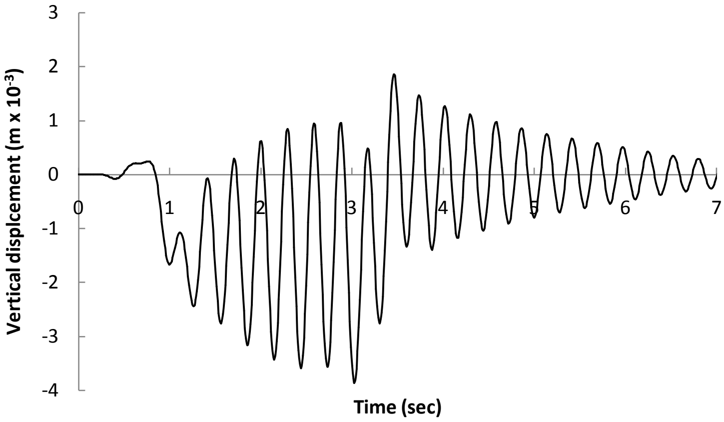


Figure 11. (a) Maximum mid-span displacement and (b) acceleration response of the continuous and integral bridge deck with varying moving loads speeds. Vertical solid black lines and the numbers represent the resonant mode numbers.

(a)



(b)

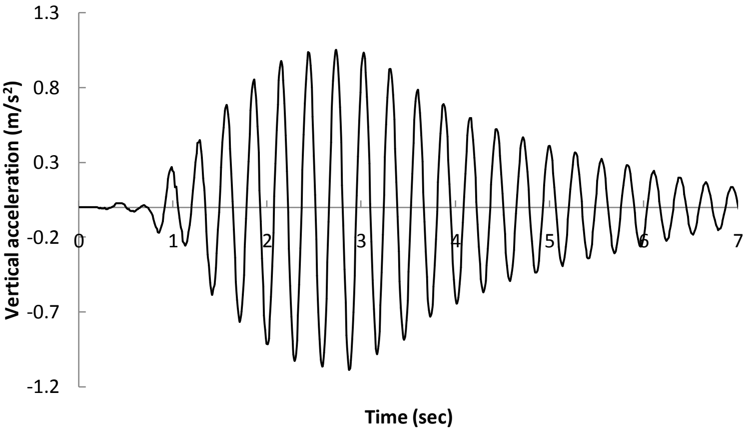
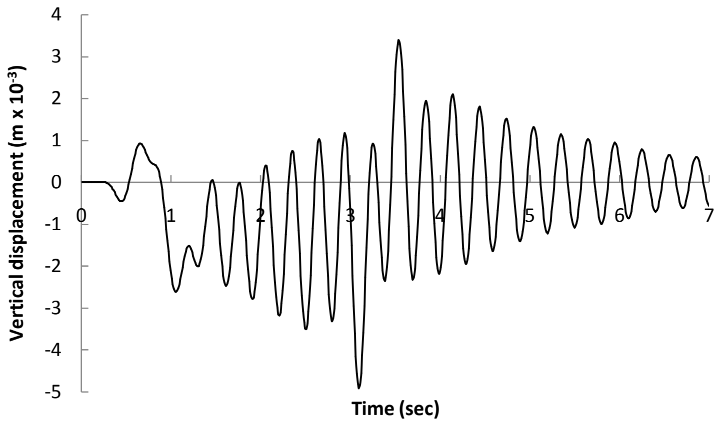


Figure 12. Time histories of (a) vertical displacement and (b) vertical acceleration of mid-span (span 3) of continuous bridge at resonance.

(a)



(b)

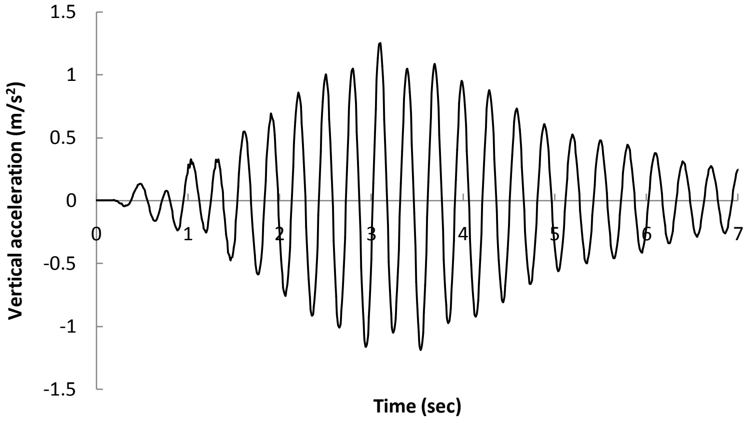


Figure 13. Time histories of (a) vertical displacement and (b) vertical acceleration of mid-span (span 3) of integral bridge at resonance.