

Seismic Pounding and Protection Measures of Simply-Supported Beams Considering Interaction between Continuously Welded Rail and Bridge

Bin Yan, Dr.; Gonglian Dai, Prof., College of Civil Engineering, Central South University, Changsha, China.

Contact: Binyan1984@gmail.com

DOI: 10.2749/101686613X13439149157191

Abstract

The pounding effect between neighboring simply-supported beams can damage a bridge and even cause collapse of a beam. However, previous pounding studies did not consider the influence of the continuously welded rail (CWR) during earthquakes, thus overestimating the seismic response of the railway bridge, yielding uneconomic design and neglecting the influence of seismic pounding on track forces. Therefore, the main focus of this paper is to investigate the influence of CWR on bridge pounding through numerical modeling. In the simulation, nonlinear bar element was used to model longitudinal resistance of the track. Large-mass method was used to obtain multi-support excitation and the Kelvin model was applied to simulate the beam pounding. In addition, a number of detailed effects were taken into account, including the nonlinear behavior of the bearing, the moment–curvature relationship of the pier and the interaction of the piles and soil. Taking the three-span 32 m simply-supported box beams on the Shanghai–Kunming line as an example, this paper also studies the influence of temperature loads, train braking load, traveling wave effect, line resistance, track expansion device, buffer device and beam connection device on the bridge pounding effect and the pier force. The numerical results showed that the track can significantly mitigate the pounding effect of the bridge. The traveling wave effect could significantly increase the force in track and bridge, which can result in pounding. If the high-speed railway train brakes on the bridge during an earthquake, the rail may be destroyed near the location of abutment. The use of track expansion devices and small resistance fasteners could result in the pounding effect between the neighboring beams while the use of buffer device and beam connection device can mitigate the pounding effect and eventually reduce force on the pier.

Keywords: railroad bridges; continuously welded rail; earthquake; pounding effect; track–bridge interaction.

Introduction

During earthquakes, the pounding effect between neighboring simply-supported beams is one of the major causes of damage to the bearing and caging device or even leading to collapse of the beam. Most earlier studies^{1,2} have focused on the pounding effect in highway bridges. Although some studies^{3–5} analyzed the pounding effect and the protection measures of simply-supported railway beams, the influence of the track structure was not taken into account. In addition, several

works^{6,7} analyzed the seismic response of the CWR and bridges, without considering the pounding effect of the beam, the influence of the bearing, the nonlinear behavior of the pier as well as multi-support excitation.

The main focus of this paper is to investigate the influence of CWR on the bridge pounding through numerical modeling. In the simulation, nonlinear bar element was used to simulate track–bridge contact. Kelvin pounding model was used to simulate the pounding and large-mass method was used to analyze the traveling wave effect of earthquake motion.⁸ Considering the nonlinearity of the bearing and pier as well as the pile–soil interaction, the track–bridge interaction model for simulating nonuniform excitation and beam pounding effects was

established. Considering double-track three-span 32 m simply-supported box beams on the Shanghai–Kunming line in China as the prototype, the pounding effect of high-speed railway simply-supported beams excitation was analyzed under an earthquake. The study included the investigation of the effect that track structure had on the pier force, beam pounding frequency and pounding force under the uniform and nonuniform excitation. The effect of track type, the thermal effect, the train braking load, expansion device and other parameters were compared. On this basis, when using small resistance fastener for CWR on bridge, the buffer device and connecting bar device were shown to successfully mitigate the pounding effect.

Finite Element Model

To consider the travelling wave effect the element used at the structural support was assigned a very high mass (up to 10E+08 times the total structural mass). Carrying out transient dynamic analysis, the constraint of the support was released in the excitation direction and dynamic time history P_b was applied to simulate the base motion:

$$P_b = M_L \ddot{u}_g \quad (1)$$

In the equation, $\ddot{u}_g$ is the acceleration of earthquake motion. This method could guarantee that the acceleration at the support was almost equal to the input excitation acceleration.

In the simulation, the Kelvin pounding element paralleled by linear spring and damper was used, as shown in Fig. 1.

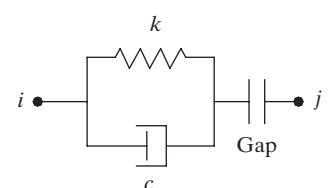


Fig. 1: Pounding element model



Peer-reviewed by international experts and accepted for publication by SEI Editorial Board

Paper received: August 26, 2012
Paper accepted: October 12, 2012

The relation between its stiffness K and element displacement at nodes I and J could be expressed as:

$$K = \begin{cases} 0 & u_i - u_j < \text{gap} \\ k & u_i - u_j \geq \text{gap} \end{cases} \quad (2)$$

The *gap* being the initial spacing (here taken as the beam spacing width) and k as the pounding stiffness (taken as the axial stiffness of the beam) the energy loss in the pounding process was expressed with the damping c^2 :

$$c = 2\zeta \sqrt{\frac{km_1m_2}{m_1+m_2}}, \quad \zeta = \frac{-\ln r}{\sqrt{(\ln r)^2 + \pi^2}} \quad (3)$$

In the equation, ζ is the damping factor. For concrete, the coefficient of restitution r was taken as 0,65. m_1 and m_2 were respective beam mass at both ends of the pounding element.

To consider the influence of track on the seismic response of the bridge, a beam element with stiff connections was used to simulate a simply-supported beam. Vertical spring was established to simulate the vertical stiffness of the fastener. An elastic-plastic bar element was used to simulate the longitudinal resistance of the track, whereas the dynamic hysteresis curve of the bar element is shown in Fig. 2, in which r is the longitudinal resistance of the track and u is the track-bridge relative displacement.

Outside the bridge, the track together with 100 m of the embankment was simulated in order to reduce the influence of the boundary conditions^{9,10} and to accurately simulate the track-bridge interaction.¹¹ To simulate seismic excitation, besides establishing the large-mass element at the bottom of each pier and applying the longitudinal excitation, the large-mass element is established at the embankment support, applying the same excitation as the adjacent abutments.

Pot-rubber-bearing was adopted as the fixed bearing, simulated here as linear spring. The longitudinal movable

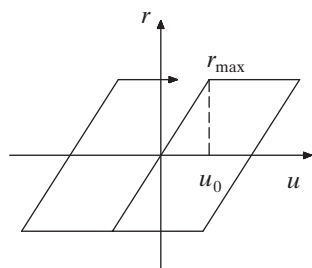


Fig. 2: Hysteresis of bar/spring element

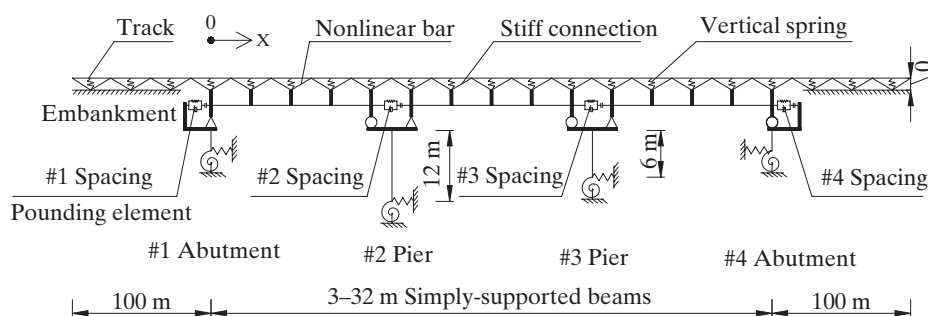


Fig. 3: Track-bridge interaction model

bearing was simulated as the elastic-plastic spring,¹² as per Fig. 2.

Pile foundation equivalent to the translational and rotational spring was applied to the pier bottom to simulate the pile-soil interaction. The nonlinear beam element was used to simulate the moment-curvature curve of the pier. The finite element model was established, and is shown in Fig. 3.

Project Description

The static arrangement of the bridge was three 32 m simply-supported beams. The deck width is 12 m, and the height is 3 m, as shown in Fig. 4.

The pier was round and hollow with pier cap plate thickness equal to 0,5 m, the height of abutments #1 and #4 equal 1 m, height of pier #2 and #3 equal 12 m, and that of pier #3 equal to 6 m. The spring stiffness of the pounding element was 1,9e3 MN/m, the damping 4,2e6 kg/s and the initial width of beam spacing 0,1 m. The pier and beam spacing is shown in Fig. 3.

The longitudinal stiffness of the fixed-pot-bearing was taken as 100 MN/m, the horizontal initial stiffness of the longitudinal movable bearing u_0 equal to 5,3 MN/m and the critical displacement as 9,3 mm. The rotational spring stiffness at the pier bottom was $5,3 \times 10^3$ MN-m/rad and the horizontal spring stiffness 28,2 MN/m.

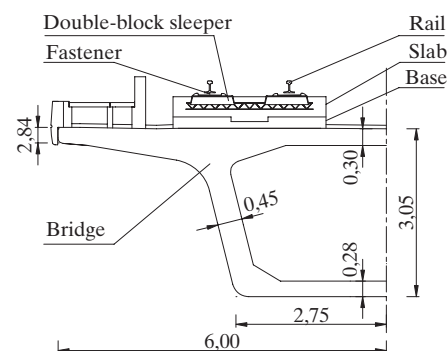


Fig. 4: Beam cross-section (unit: m)

A double unballasted track was laid on the bridge and the rail was of CHN60 (equivalent to UIC60). The longitudinal resistance of the track was taken according to Eq. (4).¹³ The vertical stiffness of the track structure was taken as 60 MN/m. The two-stage dead load was 130 kN/m.

$$r_{\text{Unballasted Track}} = \begin{cases} 24u & u \leq u_0 = 2 \text{ mm} \\ 48 & u > u_0 = 2 \text{ mm} \end{cases} \quad (4)$$

Rayleigh damping was adopted for the system damping; the damping factor h was taken as 0,05 and the coefficients α and β were taken according to Eq (5):

$$\alpha = 2h \frac{w_1 w_2}{w_1 + w_2}, \quad \beta = 2h \frac{1}{w_1 + w_2} \quad (5)$$

W_1 and W_2 were the first frequency and the frequency making the maximum contribution to the longitudinal modes.

The Mander model was adopted for the concrete of pier, the unconstrained concrete peak stress was taken as 34 MPa and the ultimate strain as 0,004. The reinforcement was HRB335, the sectional reinforcement ratio of pier-bottom plastic hinge zone was 0,004, the longitudinal main reinforcement ratio was 0,03¹⁴ and the pier-bottom axis force was 97,06 MN. Based on the above material model, the pier section moment-curvature was analyzed as shown in Fig. 5.

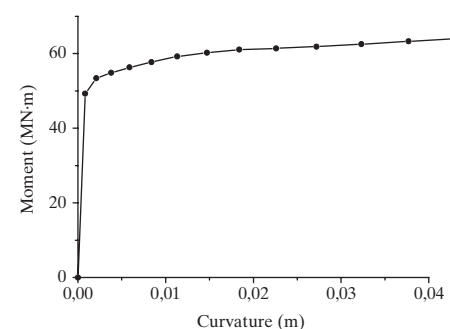


Fig. 5: Pier moment-curvature curve

According to Provisions in Ref. 15 the standard response spectrum was introduced into the SIMQKE_GR software developed at Berkeley, California University, to generate artificial accelerograms, with their response matching the standard response spectrum. Four artificial accelerograms were generated by the above method to act as the seismic excitation, with their characteristic periods shown in *Table 1*.

The acceleration peak value of each wave was adjusted to 0,3 g (design earthquake) and 0,57 g (high-level earthquake) based on reserving the spectrum characteristics of all seismic waves. Excitation was applied on the supports of the pier bottoms and on the embankment supports. While calculating the traveling wave effect, the difference in the input time was taken into account only at different supports, and the apparent velocity was calculated to be 500 m/s.

Influence of Track on Pounding Effect

Ignoring the track, the longitudinal uniform excitation and the pounding effect of beams under the traveling wave were analyzed, and the results are shown in *Table 2*.

As the spectral characteristics of the seismic waves were different, the pounding frequency and the pounding force were also quite different. With the increase of seismic intensity, the pounding effect was enhanced; under the traveling wave effect, the pounding effect was enhanced at the abutment of the movable bearing. In the following analysis, E4 of 0,57 g was taken as an example.

When considering the track, under the effect of four kinds of seismic waves, the pounding phenomenon did not occur between beams and between beam and abutment. This was because there was a nonlinear interaction between the bridge and the track: on one hand, the track enhanced longitudinal restraints of the bridge and reduced the longitudinal displacement of the beam; on the other hand, the seismic energy was consumed by the hysteresis of track-bridge connection element.

Figure 6 shows the influence of CWR on the #2 spacing and pier-bottom shear.

The study used $\Phi 40$ anchor rod (cross-sectional area 1256 mm²) as the beam connection device to be able to reduce 40% relative displacement and 56% pounding force.¹⁶ The double-track railway (four rails, and cross-sectional

area per rail 7745 mm²) laid on the bridge was equivalent to the beam connection device to enhance the integrity between beams and greatly reduce the relative displacement of beam ends, thereby reducing the probability of pounding and the collapse of the beam, and reducing the force in the pier.

Traveling Wave Effect

Because of the small span of the simply-supported beams, the traveling wave effect was usually not taken into consideration. In order to analyze the influence of the traveling wave effect on the track, the nonuniform excitation was applied to the track-bridge integral model in this paper, as shown in *Fig. 7*.

As the CWR could be regarded as an infinitely long beam, the track was more sensitive to the nonuniform excitation compared with the simply-supported beam. With the decrease of apparent wave velocity, the track stress increased quickly and the destabilization or the breaking appeared at the junction between beams. In addition, the pounding occurred between beams when the apparent wave velocity was smaller.

Thermal and Live Load Effect

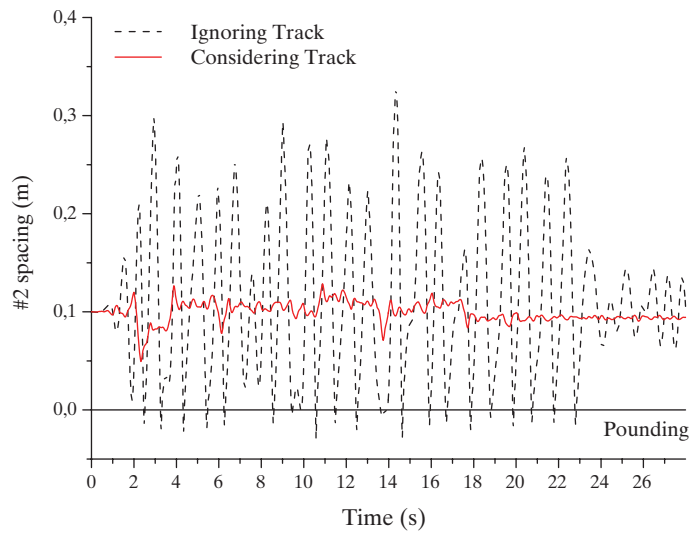
When the thermal effect and earthquake occurred simultaneously, the temperature force was calculated in accordance with beam temperature rise of 20°C.¹⁰ In the calculation of braking force, assuming that the train traveled into the bridge from #4

No.	Characteristic period(s)	Chinese Site type	Similar to Eurocode 8
E1	0,3	I	A-B
E2	0,4	II	C
E3	0,55	III	D
E4	0,75	IV	E

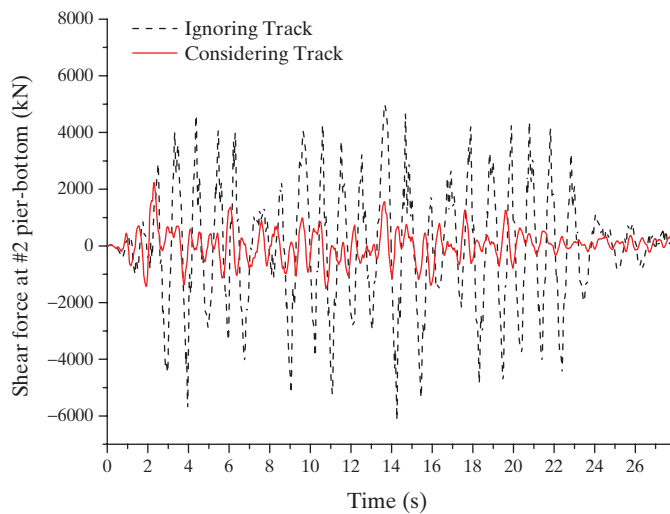
Table 1: Artificial wave characteristic

Artificial Wave	Spacing No.	Uniform Support Excitation				Traveling Wave Effect			
		0,3 g		0,57 g		0,3 g		0,57 g	
		Frequency	Force (MN)	Frequency	Force	Frequency	Force	Frequency	Force
E1	#1	—	—	—	—	—	—	—	—
	#2	—	—	2	13,6	—	—	3	23,3
	#3	—	—	5	45,4	—	—	5	31,9
	#4	—	—	—	—	—	—	—	—
E2	#1	—	—	—	—	—	—	—	—
	#2	—	—	5	41,1	—	—	6	47,2
	#3	2	30,4	6	64,7	1	7,2	6	53,3
	#4	—	—	—	—	—	—	1	—
E3	#1	—	—	1	—	—	—	2	20,2
	#2	3	28,8	14	73,1	3	37,1	14	98,8
	#3	5	25,3	15	69,8	4	44	13	97,6
	#4	—	—	4	20,7	—	—	6	29,4
E4	#1	—	—	2	16,2	—	—	4	11,7
	#2	7	46,1	22	90,9	6	35,8	14	121,8
	#3	8	35,3	19	97,7	5	37	13	57,6
	#4	—	—	6	30,3	—	—	26	42,6

Table 2: Pounding effect of beams (ignoring track)



(a) #2 spacing



(b) Shear force at #2 pier-bottom

Fig. 6: Structure response considering or ignoring track

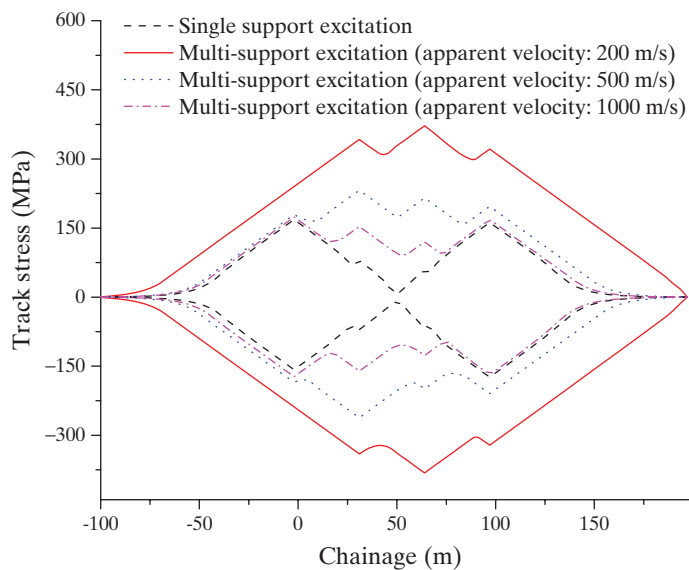


Fig. 7: Influence of apparent velocity on track stress (envelope)

abutment after 2S of the earthquake and started braking, the adhesion factor was taken as 0,164.¹⁵

In various cases, the longitudinal force of the track and beam-end spacing at #2 abutment are shown in Fig. 8.

It can be seen from Fig. 8 that, because of the smaller expansion length of the bridge, the influence of temperature on the longitudinal track force was not obvious, only making the beam-end spacing shorter by about 4 mm. However, during an earthquake, the track force would greatly increase owing to the train braking on the bridge. According to Code provisions,¹³ the breaking or instability of the track occurred at both abutments.

Taking into account that the train braking force increased with reducing train speed and reached its maximum at the completely stopping moment, the train should slow down as soon as possible and eventually stop on the embankment when an earthquake occurs.

Arrangement of Track Expansion Device

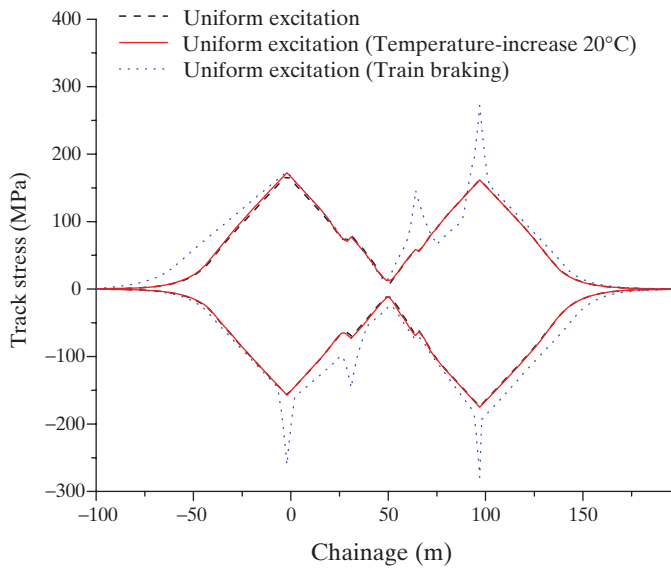
In some cases, when the track force, displacement and broken gap cannot meet the specification requirements, a track expansion device should be installed at the movable bearing of the bridge end. In order to analyze its influence on the abutment-beam pounding effect, it was assumed that the track expansion device was set at #4 abutment, in this study. The temperature load was calculated in accordance with the beam temperature reduction of 20°C and track temperature reduction of 40°C, as shown in Fig. 9.

The track is no longer continuous after setting the track expansion device (or the track fractures during winter); the longitudinal restraint on the beam reduces and the response of the beam displacement increases. The pounding takes place between the beam and the abutment near the expansion device and the force on the pier near the abutment is significantly increased.

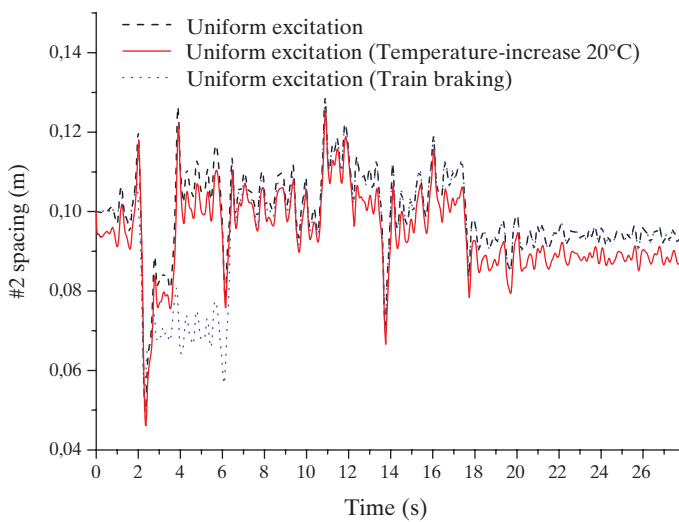
Therefore, it is recommended that the use of the expansion device is to be avoided under the premise to meet the specification requirements, or an automatic closure device and damper be used at the location of expansion joint to make the rail restore the continuity at the time of earthquake, which would greatly lower the seismic response of the bridge and the track.

Track Resistance Effect

In order to study the influence of track resistance on the pounding effect, the resistance values of ballasted track and



(a) Track stress (envelope)



(b) #2 spacing

Fig. 8: Thermal effect and train braking

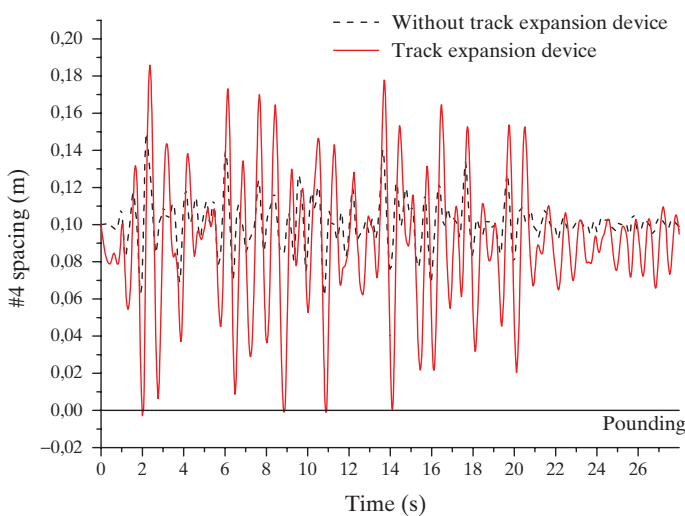


Fig. 9: Influence of expansion device on #4 spacing

small resistance fastener were chosen to be compared with the unballasted track.¹⁵ The value of the track resis-

tance is shown in Eq. (6). The variation of the #2 spacing, when using various resistance values, is shown in Fig. 10.

$$r_{\text{Small Resistance}} = \begin{cases} 26u & u \leq u_0 = 0,5 \text{ mm} \\ 13 & u > u_0 = 0,5 \text{ mm} \end{cases}$$

$$r_{\text{Ballasted Track}} = \begin{cases} 15u & u \leq u_0 = 2 \text{ mm} \\ 30 & u > u_0 = 2 \text{ mm} \end{cases} \quad (6)$$

With the reduction of the track resistance, the restricting effect of the track to the beam vanishes, resulting in an increase of the longitudinal displacement of the beam, which may cause pounding.

Protection Measures of Pounding

Taking a fastener of low resistance as an example, both the rubber bumper and beam connection device between beams were used to mitigate the pounding effect between beams, as well as between the beam and the abutment.

The rubber bumper is fixed on the beam body on one side to play the role of a buffer. The distance between the rubber bumper and the beam body on the other side was 20 mm, while bumper stiffness was taken to increase up to 1000 MN/m, as shown in Fig. 11.

Overall, the pounding force and the shear force at the pier bottom reduced with increase of stiffness in the rubber bumper. When the stiffness of rubber bumper was larger than 9×10^7 N/m, the pounding of beams was avoided.

The connection device was a steel anchor rod with a rubber insert, anchored at both ends of the beam. The rubber thickness is 20 mm, ignoring the stiffness of the rubber insert. The stiffness of steel bolt could be changed by changing its diameter, here the stiffness is taken as 10^{-4} to 10^{-2} times the beam stiffness for the comparison, and the results are shown in Fig. 12.

Both the pounding force and the pier-bottom force decreased with increasing stiffness of the beam connection device. When taken as 0,02 times of the beam stiffness, the pounding was avoided.

The rubber bumper and beam connection device could mitigate the pounding effect and the force in the pier bottom. The rubber bumper is easy to aging, and the beam connection

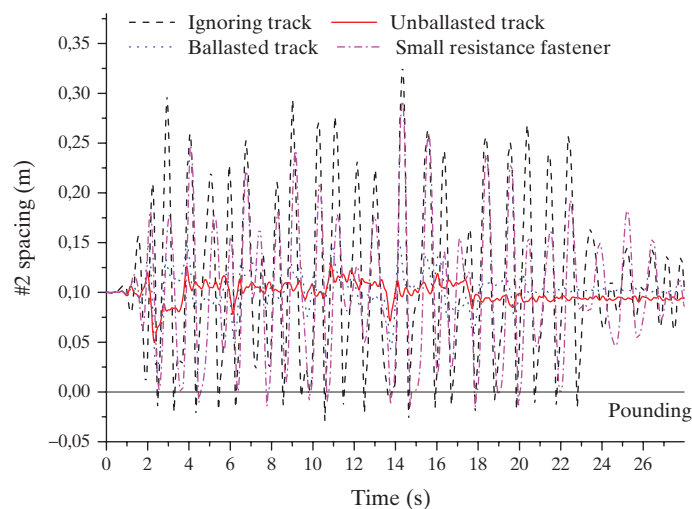


Fig. 10: Influence of track resistance on #2 spacing

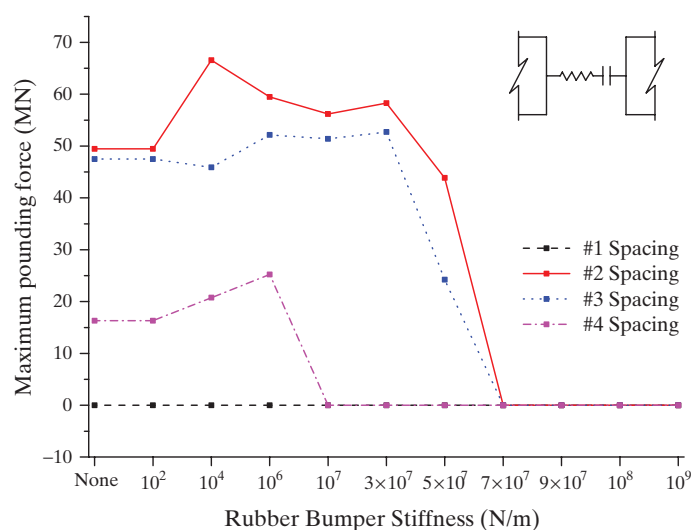


Fig. 11: Influence of buffer stiffness on pounding force

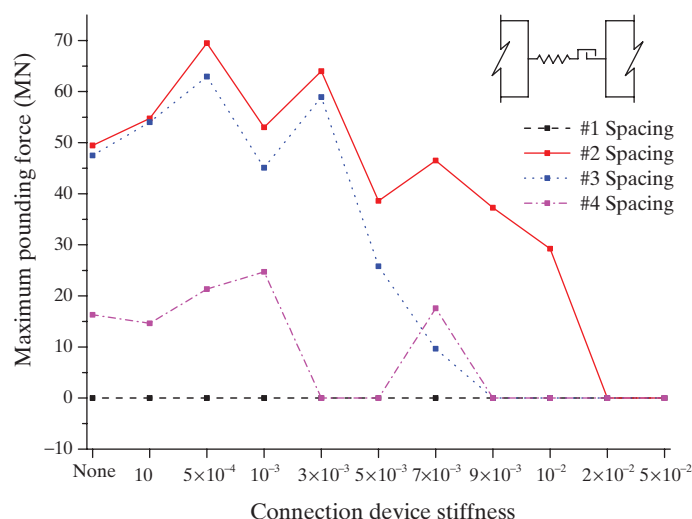


Fig. 12: Influence of connection device stiffness on pounding force

device prone to fatigue and corrosion. However, the beam connection device could reduce the pounding effect and the probability of the beam overtuning.

Therefore, the pounding prevention measures should be comprehensively selected according to the site environment and operation condition.

Conclusion

The pounding effect of simply-supported beams carrying high-speed railway, may occur between beams, and between the beam and the abutment. The pounding effect relates to the spectrum character of the seismic wave, and increases with increase of earthquake motion intensity. The track provides an additional longitudinal restraint for the bridge, and can greatly reduce the beam displacement, thereby mitigating the probability of pounding and collapse of beam, and reducing the force on the pier. When calculating the pounding effect of railway bridges, the influence of the track should be considered.

The track is extremely sensitive to the traveling wave effect. The longitudinal force of the track greatly increases with decrease of the apparent velocity and the pounding phenomenon may occur between the beams.

The temperature has the least influence on the dynamic response of the simply-supported beams. However, the train's braking greatly increases the force in the track and can make the track rupture or buckle at the abutment. Considering that the significant influence of a vertical earthquake on train-bridge interaction may cause train derailment, it is suggested that the train should brake as far as possible before going into the bridge at the time of earthquake.

The track expansion device makes the track structure discontinuous. Reducing the track constraint on the beam, the pounding can occur between the beams closer to it. The constraint of the track to the bridge decreases with the decrease of the track resistance. When a low resistance fastener is used, pounding effect may occur.

Both rubber bumper and beam connection device can mitigate the pounding effect and reduce the force in pier. The protection measures of pounding should be reasonably chosen according to local conditions.

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