Reduction effect evaluation of reinforced concrete vibration isolation unit on ground vibration around Shinkansen viaducts

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1. INTRODUCTION

With the rapid development of high-speed railway, people have enjoyed the benefits of high-speed railway in developed regions in the world. However, it often brings annoyances to the residents alongside and malfunctions to vibration-sensitive equipment housed in the nearby buildings[1]. For the complex train-bridge-ground interaction problem, one of the most feasible methods is through in situ tests[2]. The theoretical and numerical methods are very difficult but more convenient to predict and simulate the ground vibration before or during the operation[3-4]. Simultaneously, it is necessary to take measures to reduce the excessive vibration to protect vibration-sensitive areas. The vibration reduction methods are divided into three groups: vibration reduction methods in source; in propagation path and in receiver. To select the suitable mitigation measure may depend on several factors and not just consider the cost and feasibility of implementation. For instance, Hara *et al.*[5] developed a new method rigidly connecting cantilever girders to reduce the vertical ground vibration by using the equivalent moving force. Yoshida and Seki[6] studied the influence of the change in rigidity of viaducts caused by viaduct columns with steel jackets or concrete block walls on the ground vibration. For the barriers, there are some previous works[3, 7] related to open/in-filled trenches and WIBs. The stiffer/softer in-filled materials are effective to reduce the ground vibration. Most of previous works are limited to the study of vibration isolation by single barrier, while few studies focused on the barrier utilized the advantages of both stiffer and softer materials.

Therefore, the reinforced concrete vibration isolation unit (RCVIU) as a new barrier is proposed to mitigate the ground vibration. The purpose of the present study is to evaluate the reduction effect of the RCVIU on the HST-induced ground vibration around Shinkansen viaducts. Applying a developed 3D numerical approach[8], the mitigation analysis considering the train-bridge interaction (TBI) is carried out to clarify the vibration screening efficiency of the RCVIU. The parametric influence of the RCVIU is also investigated.

2. ANALYTICAL MODELS

2.1 Shinkansen viaduct model

A typical reinforced concrete viaduct in the form of a rigid portal frame is adopted in **Fig. 1**. In Japan, it is widely applied for the high-speed railway. The analytical model is employed with three 24m length bridge blocks which are separated from each other and connected only by rail structure at adjacent ends in **Fig. 2**, in consideration of the connecting effect of rail structure and the influence of train's entering and leaving. Each block has three 6m length center spans and two 3m length cantilever girders, so called hanging parts, at each end. Both the viaduct and rail are modeled as 3D beam elements with six DOFs at each node. Double nodes defined as two independent nodes sharing the same coordinate are adopted to simulate the effect of ground springs at the pier bottoms and the elastic effect of the sleeper and ballast between the rail and the slab. Simulated track irregularities are also considered in both vertical and lateral directions[8]. Rayleigh damping is adopted for the structural model and the damping constant 3% is assumed for the first and second modes of the structure according to the past field test results.

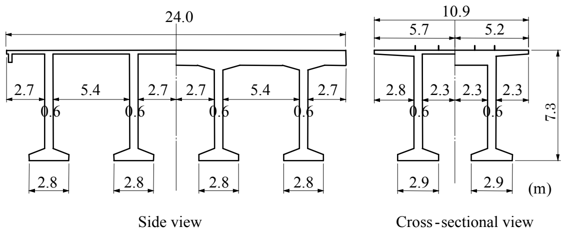

Fig. 1 Dimensions of Shinkansen viaducts

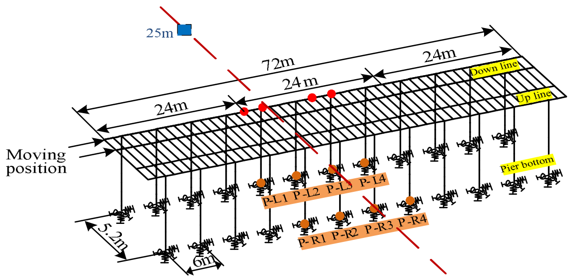

Fig. 2 Analytical model of Shinkansen viaducts

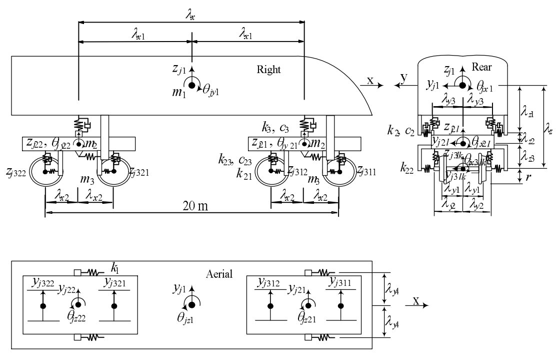

Fig. 3 High-speed train model

2.2 High-speed train model

High-speed train composed of sixteen cars is modeled as a complex multi-DOFs vibration system for each car without the coupling device in **Fig. 3**. Each car is treated as a car body, two bogies and four wheelsets regarded as rigid components, and connected by two groups of spring-dashpot suspension devices. To simplify the analysis but retain its accuracy, some assumptions are considered as follows: the train is running on a straight line at a constant speed; the wheelsets remain in full rigid contact with the rail; the uniform train model is used to describe all of train carriages. This HST model can reflect the vibration responses in both vertical and lateral directions.

2.3 Substructure and site model

Substructure model including one footing and seven piles for one structural set is adopted in **Fig. 4**. Site model mainly comprised three strata separated at depths of 6.8m and 17.2m is established by the thin layer element method in **Fig. 5**. The properties of substructure as well as site model are shown in **Table 1** and **Table 2**, respectively. The velocity of S-wave in the first stratum is 80m/s, from which the site condition can be considered as relatively inferior. The damping constant is assumed to be 5% according to the field tests. To simplify the analyses, the actual footing is approximated as a rectangular parallelepiped divided into 36 solid elements according to the conversion of volume. Upper footing surface is set to lie 0.26m under the ground surface. The piles are modeled as 3D beam elements and connected vertically to the footing. The ends of beam elements are established at soil layer interfaces. Site model is divided further into 21 thin layer elements. The layer elements are established down to a depth of 18.8m, to which the substructure model is embedded. The sizes of solid elements and the maximum thickness of each layer meet the criterion that they must be less than $1/5\lambda_s$ in the corresponding layer[9], where λ_s is the shortest S-wave wavelength in that layer. The program then automatically adds some extra layer elements and the viscous boundary at the base to simulate the effect of half space.

Table 1 Properties of substructure model

Parameters	Footing	Piles Type 1	Piles Type 2
Unit mass (t/m^3)	2.5	2.5	2.5
Cross-section area A (m^2)		0.058	0.045
Young's modulus E (kN/m^2)	2.5E+7	3.50E+7	3.50E+7
Moment of inertia I (m^4)		6.22E-4	3.50E-4
Poisson's ratio ν	0.2	0.2	0.2
Damping constant	5%	5%	5%

Table 2 Properties of site model

Parameters	Depth of stratum (m) 0–6.8	6.8–17.2	17.2–
Unit mass (t/m^3)	1.6	1.8	2.0
Shear modulus G (kN/m^2)	1.04E+4	6.63E+4	2.50E+5
Poisson's ratio ν	0.49	0.49	0.49
S wave velocity Vs (m/s)	80	190	350
Damping constant	5%	5%	5%

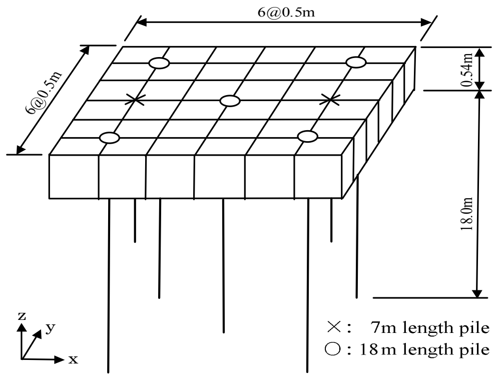

Fig. 4 Substructure model

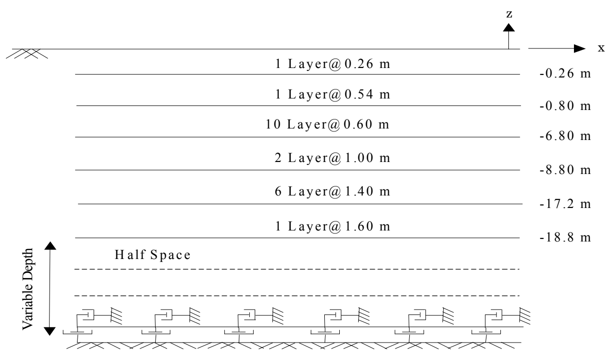

Fig. 5 Profiles of site model

3. ANALYTICAL APPROACH

In this study, the dynamic interactions between the train and bridge as well as between the foundation and ground are considered by the developed 3D numerical approach to solve the ground vibration problem. The entire train-bridge-ground interaction system is divided into two subsystems to simplify the modeling difficulty of the global system due to the extreme complexities of their interaction and the limit of the computational capacity. One is the train-bridge interaction system. Simulated track irregularities are considered as a part of system excitations. Through using Newmark's β method, the analytical program is developed to properly simulate the vibration responses of the viaducts and obtain the vibration reaction forces at the pier bottoms. The other one is the soil-structure interaction (SSI) system. Applying these vibration reaction forces as input excitation forces, the ground vibration around Shinkansen viaducts are simulated by using a general-purpose program SASSI2000[9]. The SSI problem is analyzed via a substructuring approach and by which the linear SSI problem is subdivided into a series of simpler sub-problems. Ground vibration of a certain observation point is obtained from the superposition of those engendered by each block with eight pile foundations. The vibration screening efficiency of the RCVIU is evaluated by the reduction VAL as follows.

$$\text{Reduction VAL [dB]} = \text{VAL}_1 - \text{VAL}_2$$

where, VAL_1 is the VAL of ground vibration without RCVIU, and VAL_2 is the VAL of ground vibration with RCVIU. The positive value represents the effective vibration reduction, while a negative value stands for the vibration amplification.

4. PROPOSED RCVIU

The RCVIU as a new barrier is proposed to reduce the HST -induced ground vibration around the viaducts as shown in **Fig. 6**. The relative location between the bridge pier and the RCVIU is shown in **Fig. 6a**. It is classified by the installation location. The measure nearby the vibration sources is referred to as an active isolation system, while it more in the proximity of the protected structures or areas is termed as a passive isolation system. According to the actual requirement of vibration reduction, the RCVIU can be designed in different locations, layers and shapes.

In this study, since Shinkansen viaducts are supported by the serried ranks of bridge piers, it isn't necessary to surround one by one of bridge piers with the RCVIUs to mitigate the ground vibration around the viaducts. Therefore, a double-layer RCVIU is installed at 5m to obstruct the transmission of the vibration energy from bridge piers as shown in **Fig. 6**. The properties of RCVIU are in **Table 3**. To simplify the analysis, the size of RCVIU is set as 72m×1.5m×4.4m; the size of each RC shell is set as 72m×0.5m×4.4m. It is modeled as 3D solid elements by using the computer program SASSI2000.

5. VIBRATION REDUCTION EVALUATION

The mitigation analysis with the RCVIU is performed at the operational speed of 270km/h. The benchmark model is run without any RCVIU to provide an appropriate reference for the comparison. The observation point lying on the line of P-R3 and P-L3 is located at 25m outward from Shinkansen viaducts in **Fig. 2**. The ground vibration is mostly contributed from 24 adjacent pile foundations of three bridge blocks. Considering the predominant frequency components of the external forces that are confirmed within 15Hz, the damping effect of the soil and the efficiency of the analysis, the highest frequency considered in this study is determined as 25Hz.

5.1 Time history and Fourier spectrum

As shown in **Fig. 7**, the amplitudes of time history become small after the RCVIU is installed at 5m. For the vertical and lateral direction, the maximum value respectively decreases 42.9% and 30.8% in the case of RCVIU. As shown in **Fig. 8**, their predominant frequency components are same but their amplitudes are different in both vertical and lateral directions. It is shown that the vibration responses in the low frequency band such as 9.0Hz and 12.0Hz are apparently reduced by the RCVIU. In particular, the lateral Fourier amplitudes in the high frequency band such as 18.0Hz and 24.0Hz are amplified a little due to the installation of RCVIU. The higher frequency components are integral multiples of the primary frequency component 3.0Hz depending on the train speed 270km/h in relation to the car length 25m. It is obvious that the vertical vibration responses are larger than the lateral ones. That is because the vertical vibration is mainly determined by train loads but the lateral vibration is caused by lateral irregularity.

5.2 Vibration acceleration level

As shown in **Fig. 9**, the vibration acceleration level (VAL) comparatively varies with propagation distance and vibration frequency in both vertical and lateral directions in the case of installing RCVIU or not. It is indicated that the lateral VAL is much smaller than the vertical VAL for each site position and vibration frequency. The VAL is attenuated with the increase of propagation distance for the overall trend in both vertical and lateral directions. After the RCVIU is installed at 5m, the VAL is amplified between the bridge pier and RCVIU and the

Table 3 Properties of RCVIU

Parameters	RC shell	In-filled material
Unit mass (t/m^3)	2.5	1.1
Young's modulus (kN/m^2)	3.30E+7	2.85E+3
Poisson's ratio	0.20	0.42
Damping constant	5%	30%

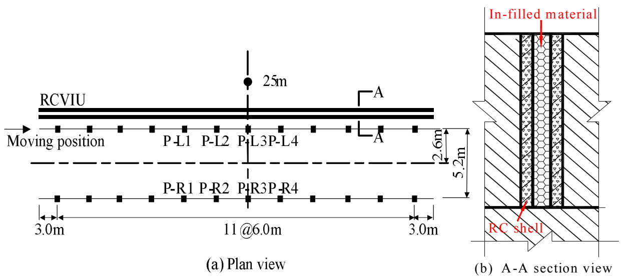

Fig. 6 Depiction of the RCVIU

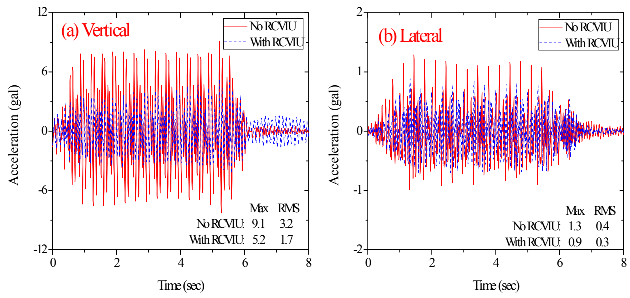

Fig. 7 Comparison of time histories of ground vibration

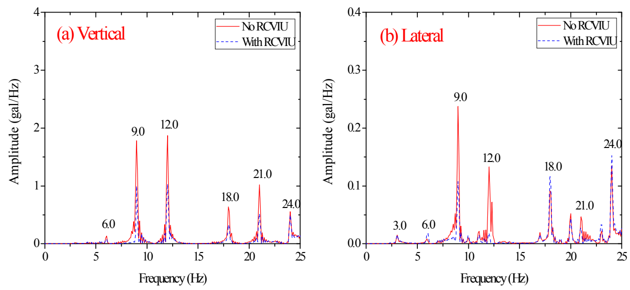

Fig. 8 Comparison of Fourier spectra of ground vibration

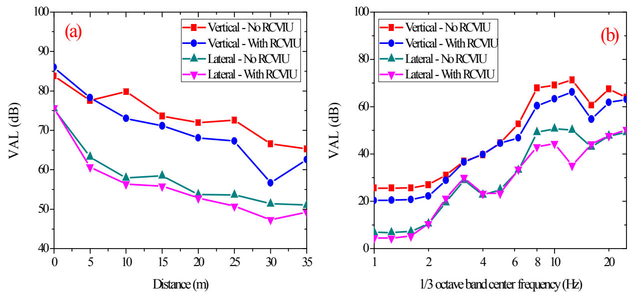

Fig. 9 Comparison of the VAL of ground vibration

amplified influence is weakened especially around 10m in the vertical direction. That is because the RCVIU can limit most of energies of the vibration waves in the region of bridge piers and then mitigate the ground vibration outward the RCVIU. At 25m, the vertical and lateral VAL respectively decreases 5.31dB and 2.88dB. In the vertical direction, it is 67.27dB at 25m which is less than the threshold of 70dB. About vibration frequency, the vertical and lateral VAL respectively decreases 7.55dB at 8Hz and 15.02dB at 12.5Hz. But the lateral VAL is amplified at some vibration frequencies.

5.3 Parametric influence of the RCVIU

Based on above analyses, the vertical VAL is employed to discuss the parametric influence of the RCVIU on the ground vibration. The effects of geometrical and material properties of RCVIU are investigated from vibration frequency as shown in **Fig. 10**. In particular, it is difficult to reduce the ground vibration around the primary frequency component by using the RCVIU. For the effect of depth and width, it is indicated that the increase of depth and width can effectively enhance the performance of RCVIU for most of vibration frequencies. For the effect of location, the vibration source isolation with RCVIU is the most effective measure to reduce the ground vibration around the viaducts except the RCVIU is installed at the amplified area 10m. For the effect of in-filled material, it is shown that the barrier with the stiffer material is more effective but the barrier with rubber can reduce some ground vibration around the primary frequency component. Therefore, the geometrical and material properties of RCVIU should be adjusted according to the actual requirement of engineering.

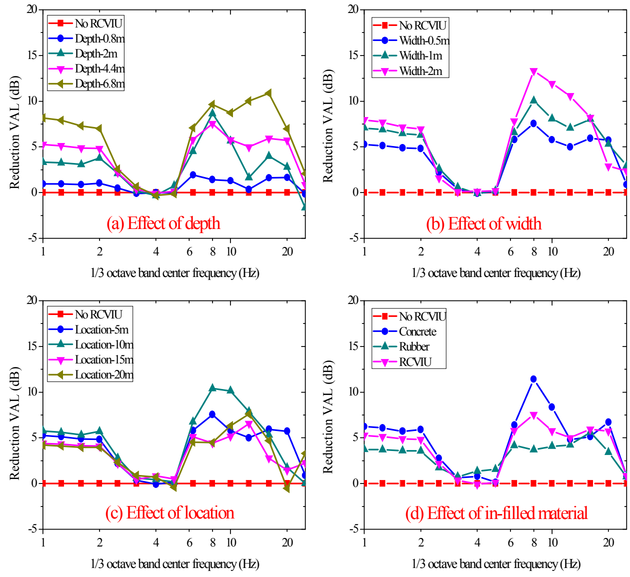

Fig. 10 Parametric influence of the RCVIU on the reduction VAL in the vertical direction

6. CONCLUSIONS

In this study, applying the proposed RCVIU as the new mitigation measure, the HST-induced ground vibration around Shinkansen viaducts is comparatively investigated for the vibration characteristic and vibration screening efficiency by developed 3D numerical approach considering the TBI and the SSI. Ground vibration is attenuated along with increasing the propagation distance in the near field. It is obvious that the vibration influence in the vertical direction is much more serious than that in the lateral direction. The higher frequency components are integral multiples of the primary frequency component depending on the train speed in relation to the car length. In the case of RCVIU, the vibration intensity reduces a lot except around the primary frequency component but the predominant frequency components have no variation. The factors such as depth, width, location and in-filled material can influence the performance of the RCVIU to isolate the ground vibration. At the same time, it can be easily designed in different locations, layers and shapes to effectively mitigate the HST-induced ground vibration in both vertical and lateral directions. The RCVIU that considered as the active isolation system will be more effective to diminish the ground vibration, construction scope and environmental damage.

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