# Numerical Evaluation on Reduction effect of Reinforcement Countermeasures on Train-Induced Ground Vibration around Shinkansen Viaducts


Hokkaido University ○Student Member Fatinnur Salsabeel ISKHANDAR
Hokkaido University Member Xingwen HE
Hokkaido University Fellow Member Toshiro HAYASHIKAWA
Hokkaido University Member Takashi MATSUMOTO
Kobe University Fellow Member Mitsuo KAWATANI


## 1. INTRODUCTION

Japan's high-speed railway system, the Shinkansen, serves a vital role in the transportation network connecting major cities. Since 1964, Shinkansen has contributed to the economic and social development in Japanese society. Up to this day, the transportation capacities of the high-speed railway system have been continually developed through the use of new train models and improved equipment. The high-speed railway's major path usually passed directly through over densely populated urban areas, where the railway structure is mainly comprises elevated bridges of reinforced concrete in the form of a portal rigid frame.

However, along with the further urbanization and development of more rapid transport facilities, there is rising public concern about the environmental problems caused by high-speed railways in modern Japan. The bridge vibration induced by running trains is propagated to the ambient ground via footing and pile structures, resulting in environmental problems related to ground vibration around the viaducts. These vibrations can influence precision instruments in hospital and laboratories, or people who are studying or resting in school, hospitals and residences[1)].

To cope with abovementioned environmental vibration problems, various recommendations for countermeasures to reduce vibration problems of the Shinkansen railway were proposed. Vibration regulation law legislated in 1976 was the first law concerning environmental problems in the world. Since then, various methods have been researched and implemented to reduce the vibrations. Generally, the vibration reduction methods are divided into three categories: reduction method in sources; propagation paths or receivers. Selecting suitable mitigation measures may depend on several factors including the cost and feasibility of implementation.

The purpose of this study is to propose effective countermeasures against excessive ground vibration around Shinkansen viaduct and evaluate their performance. For that purpose, three-dimensional (3D) dynamic analysis is used as an approach to simulate the train-induced ground vibration around Shinkansen viaducts. The effectiveness of proposed countermeasures are examined based on the numerical results.

## 2. NUMERICAL PROCEDURE

The dynamic interactions between the running train and viaduct as well as the foundation and ground are considered through three-dimensional dynamic numerical approach to simulate the ground vibration. However, it is difficult to model the entire train-bridge-ground interaction system as whole, because of their extreme complexities and limited computational capacities. Therefore, in the current stage of this research, the entire system is simplified by dividing the whole system into two sub-systems; the train-bridge interaction sub-system and ground-bridge interaction sub-system.

### 2.1 Train -Bridge Interaction

Dynamic responses of the high-speed railway viaducts under moving bullet trains are analyzed by considering the train-bridge interaction and a computer program is developed. The viaducts, including the rail structure are modeled as three-dimensional (3D) finite element bridge model. The dynamic differential equations the bridge are derived using modal analysis. Newmark's β step-by-step numerical integration method is applied to solve dynamic differential equations. The detailed formulation process of train-bridge interaction problem can be found in the reference[2)]. Dynamic reaction forces at the bottoms of the piers obtained from this analysis are used as input external excitations in ground vibration analysis.

### 2.2 Foundation -Ground Interaction

Ground vibrations around the viaducts of the high-speed railway are simulated using a general-purpose computer programmer named SASSI2000[3)] in which the previously obtained reaction forces at the bottoms of the piers is used as input dynamic forces. In this programme, the soil-structure interaction (SSI) problem is analyzed using a substructuring approach by which the linear soil-structure interaction is subdivided into a series of simple sub-problems. Each sub-problem is solved separately and the results are combined in the final step of the analysis to provide a complete solution using the principle of superposition.

## 3. NUMERICAL MODELS

### 3.1 Viaduct/Rail Model

A typical high-speed railway reinforced concrete viaduct in the form of a rigid portal frame is used in this analysis. One block of the bridge with 24m length is adopted as analytical model as shown in Figure 1. The block has three 6m length center spans and two 3m length cantilever girder at each end. Both the viaduct and the rail structure are modeled as three-dimension (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 the sleeper and ballast between the rail and the slab.

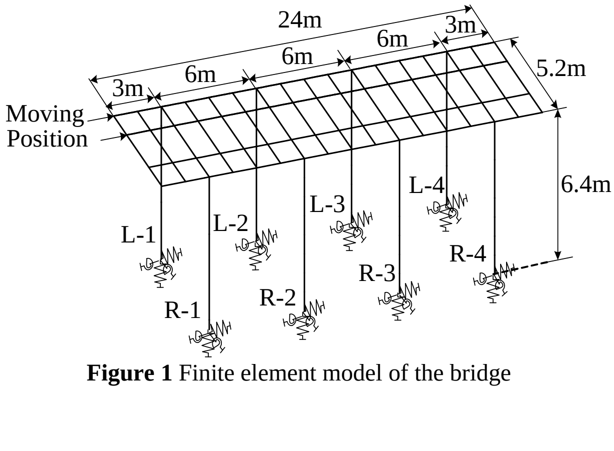


**Figure 1** Finite element model of the bridge

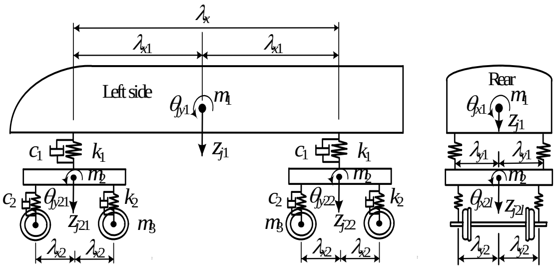


**Figure 2**  9 DOFs car model

**Table 1** Train Model variants

| Definition ($j^{th}$ car) | Variants |
|---|---|
| Bouncing of car body | $z_{j1}$ |
| Parallel hop of front bogie | $z_{j21}$ |
| Parallel hop of rear bogie | $z_{j22}$ |
| Rolling of car body | $\theta_{jx1}$ |
| Axle tramp of front bogie | $\theta_{jx21}$ |
| Axle tramp of rear bogie | $\theta_{jx22}$ |
| Pitching of car body | $\theta_{jy1}$ |
| Windup of front bogie | $\theta_{jy21}$ |
| Windup of rear bogie | $\theta_{jy22}$ |

**Table 2** Properties of substructure model

| Parameters | Footing | Piles Type | |
|---|---|---|---|
| | | 1 | 2 |
| Unit mass (t/m$^3$) | 2.5 | 2.5 | 2.5 |
| Cross-section A (m$^2$) | | 0.058 | 0.045 |
| Young 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 v | 0.2 | 0.2 | 0.2 |
| Damping constant | 5% | 5% | 5% |

**Table 3** Properties of ground 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$^s$) | 1.04E+4 | 6..63E+4 | 2.50E+5 |
| Poisson`s ratio v | 0.49 | 0.49 | 0.49 |
| S wave velocity Vs (m/s) | 80 | 190 | 350 |
| Damping constant | 5% | 5% | 5% |

### 3.2 Train Model

Each car of the train is modeled as a nine DOFs system as shown in Figure 2, and the variants used are given in Table 1. The train is composed of 16 cars according to the actual operational case and the train velocity is set to be 270km/h, referring to the actual operational speed. In this study, the DOFs of the car are limited to the ones that contribute to the vertical vibration of the bridge. The mass of whole-sets takes only a small proportion in the whole train system. Therefore, to simplify the analysis the wheel-set is assumed to remain in full rigid contact with the rail.

### 3.3 Sub-structure/Ground Model

The sub-structural model consists of the footing and pile structures of the viaducts. One footing and seven piles make up one structural set as modeled in Figure 3. The upper footing surface is set to lie 0.26m under the ground surface. Circles represent piles that are 18m long and crosses represent piles with 7m length. The piles are modeled as three-dimension (3D) beam elements and connected vertically to the footing. The ends of beam elements are established at soil layer interfaces. Properties of the footings and the piles are shown in Table 2. The ground comprises of three strata, separated at depths of 6.8m and 17.2m. Table 3 shows the properties of the ground model. The velocity of the S-wave in the first stratum is 80m/s, where the soil is considered relatively soft. The damping constant is 5% according to field test. For analysis, the ground model is divided further into 21 thin layer elements as shown in Figure 4. Layer elements are established down to the depth of 18.8m of which the structural model is embedded. The programme is then automatically adds some extra layer elements and the viscous boundary at the base to simulate the effect of half space.

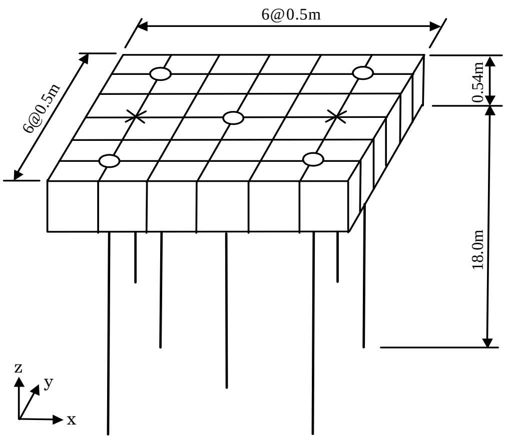


**Figure 3** Substructure model

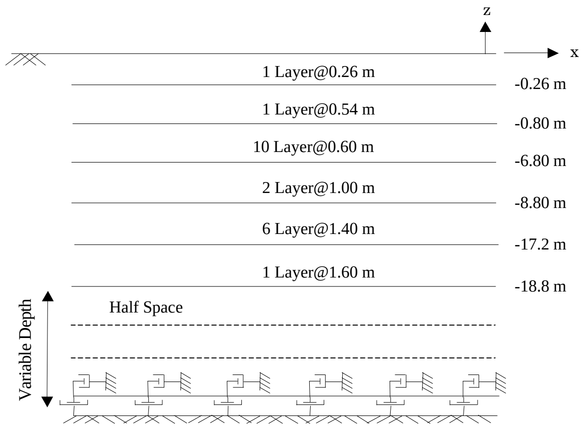


**Figure 4** Ground model with layer elements

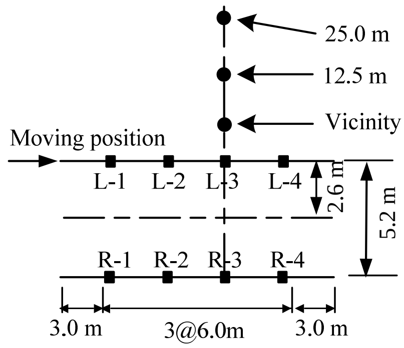


**Figure 5** Finite element model of the bridge

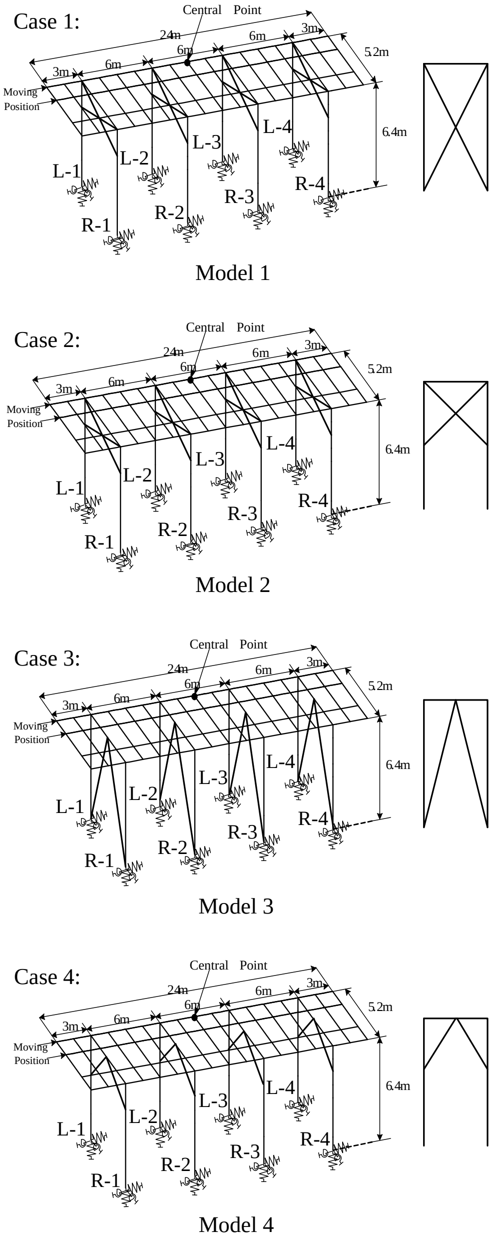


**Figure 6** Reinforced bridge models

### 3.4 Field measurements of ground vibration

Ground vibrations around the viaduct are measured at several ambient points which are at vicinity, 12.5m and 25.0m from the railways. Figure 5 shows the positions of the piers and the points of measurement. It consists of one block with 8 footings. Black rectangles in the figure indicate the footing positions. L and R denote the left and right sides of the bridge and each pier are labeled as 1 to 4 with respect to the running direction of the train. The distances between the centers of neighboring footings on each side are 6.0m and the central lines of the left and right footings are 5.2m.

### 3.5 Reinforcement countermeasures

In this study, the mitigation methods with reinforcement of piers are proposed in 4 different models as shown in Figure 6**.** Each case is simulated and their performance is analyzed. However, this paper only indicates analytical results of models 2 and 4, which indicate contrary tendencies.

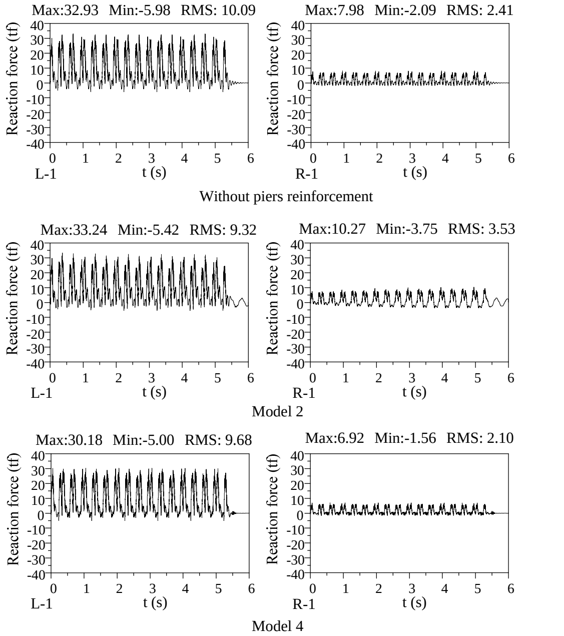


**Figure 7** Reaction forces at pier bottoms

## 4. ANALYTICAL RESULTS

### 4.1 Dynamic reaction forces at piers bottom

As shown in Figure 1, L-1 to L-4 and R-1 to R-4 indicate the piers on the left and right side of the bridge respectively with respect to the train running direction. The analytical results of reaction forces at the pier bottoms of L-1 and R-1 corresponding to models 2 and 4 are shown in Figure 7. Since the trains are assumed to run from the left sides of the viaducts, the dynamic reaction forces of the left side are much stronger than those on the right. Pier L-1 is located close to the cantilever part that is virtually a free end of the bridge. Excessive vibration response and shock effect of the wheels during the train entry induce pier L-1 to have larger ground reaction force than other piers. Figure 7 also shows that reaction force in case 2 is larger than that in case 4. This can be due to the increasing inertia forces of the reinforcement members and the change of structural dynamic characteristic.

### 4.2 Ground vibration responses

By applying the dynamic reaction forces obtained in the bridge vibration analysis at the 8 footings, the ground responses analysis is conducted using SASSI2000 program. Analytical results of Models 2 and 4 at the points of Vicinity, 12.5m and 25.0m (as indicated in Figure 5) in comparison to basic model (without reinforcement) are shown in Figure 8.

Ground vibration responses at vicinity is the largest followed by 12.5m and 25m distance from the railways. As the matter of fact, the ground vibrations response will become larger as it nearer to the source. It also can be seen that from Figure 8, the ground vibration responses for model 4 show positive feedback that ground vibration responses is greatly reduced. However, model 2 shows an opposite result. The reason can considered as that the input reaction force of model 2 is larger than those of other models, which resulted larger ground vibration response. This result indicates that it is important to carefully confirm the dynamic characteristics of the reinforced method rather than merely increasing stiffness of the structure.

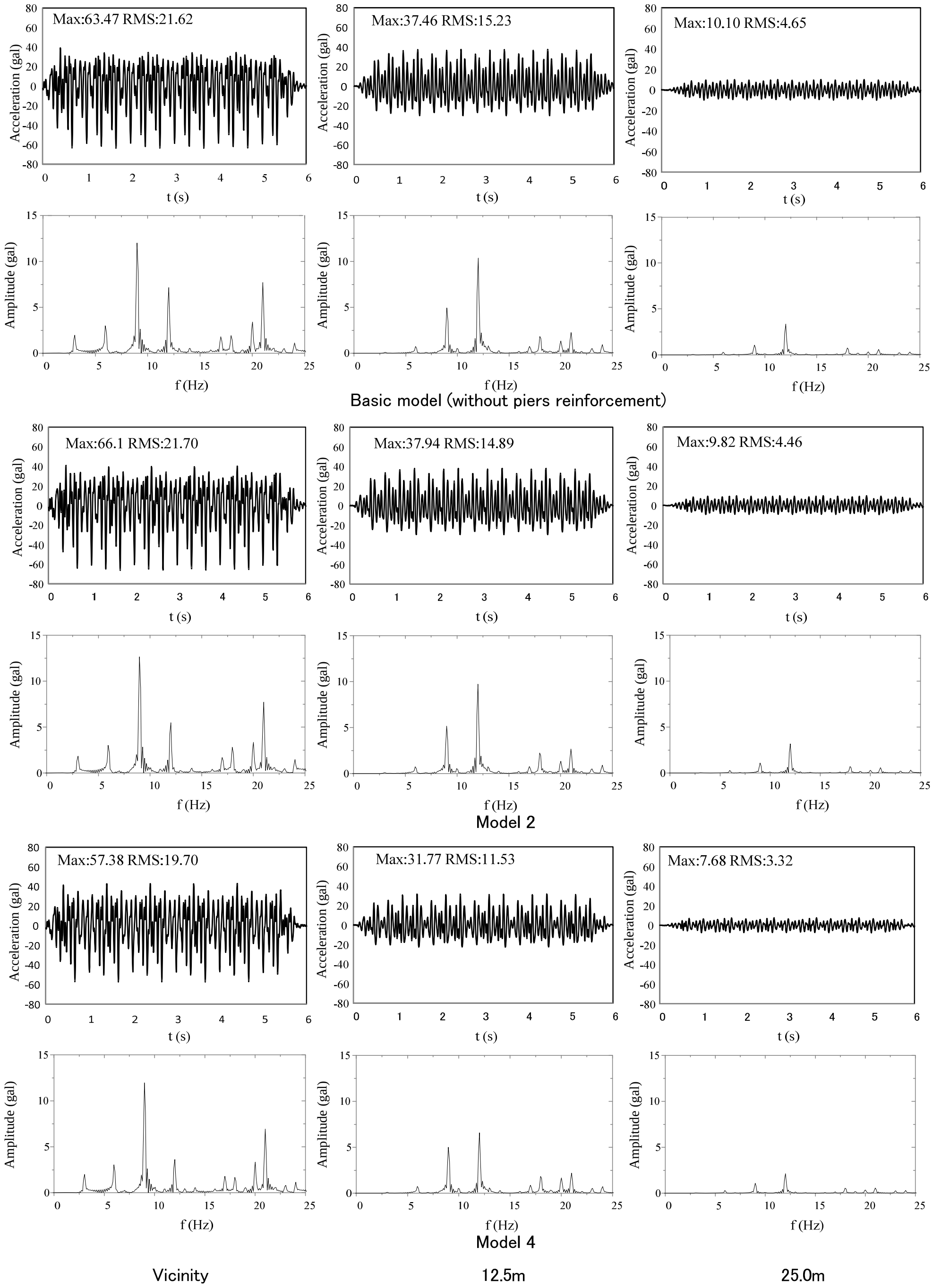


**Figure 7** Reaction forces at pier bottoms

## 5. Conclusions

In this study, employing the train-bridge interaction analysis program established by the authors, the dynamic reaction forces at pier bottoms of Shinkansen RC viaducts are simulated. Then using those reaction forces as input excitations, the ground vibration around Shinkansen viaducts is simulated and evaluated using a general program that can consider the sub-structure-ground dynamic interaction. Based on the numerical results, the effective reinforcement method is identified. At the same time, the phenomenon that similar reinforcement countermeasure can contrarily enlarge the ground vibration response is confirmed, which indicates the importance of examining the dynamic characteristics of proposed method using 3D dynamic analysis.

## References

1) Yokoshima, S. and Tamura, A: A study on factors constituting annoyance due to Shinkansen railways vibration. J. Archit. Plann. Environ. Eng., AIJ No526:1-7,1999
2) Xingwen He, Mitsuo Kawatani and Seiji Nishiyama: An analytical approach to train-induced site vibration around Shinkansen viaducts, Structure and Infrastructure Engineering, Vol. 6, No. 6, pp. 689–701, December 2010.
3) Lysmer, J., Ostadan, F. and Chin, C.C.: “SASSI2000 theoretical manual – A system for analysis of soil-structure interaction”, Academic Version, University of California, Berkeley, 1999.