

CHARACTERISTICS OF WAVE PROPAGATION ON THE SOFT GROUND WITH NON-FLAT BASE -FROM THE VIEW POINT OF RAILWAY VEHICLE DYNAMIC BEHAVIOR-

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ABSTRACT :

In order to check the running safety of trains on structures, it is essential to take into account the characteristics of input earthquake motions. On the soft ground with a non-flat base, waves generate in a base slant area and propagate in the horizontal direction. The behavior of railway vehicle, therefore, is affected by the horizontally propagating waves. In this paper, we clarify the effects of these characteristics of wave propagations on the railway vehicle dynamic behavior. By the simulations, the following two characteristics were obtained: 1) the smaller shear wave velocity of soft surface layer becomes, the more cautions are necessary to secure the running safety of trains; 2) The running safety of vehicle running with high speed on the soft ground with a non-flat base is influenced by the amplification of the earthquake ground motion due to the basin effects rather than the difference of displacements between two adjacent piers.

KEYWORDS: Soft ground with non-flat base, horizontally propagating wave, vehicle dynamics behavior

1. INTRODUCTION

In seismic design for railway structures, it is necessary to secure the running safety of trains on structures. In order to check the effect of input earthquake motions on railway vehicles dynamic behaviors, shaking table tests using a full-scale carbody and numerical simulations have been conducted, and the results are effectively reflected in Japanese seismic design code [Railway Technical Research Institute, 2007]. These investigations have been conducted on the assumption that all railway viaducts are constructed on the horizontally layered ground. On the soft ground with a non-flat base, however, waves would be generated in a base slant area and propagate in the horizontal direction [Murono and Tanamura, 2001][Ishii and Ellis, 1970]. In order to discuss the running safety of vehicle on viaducts, therefore, it is important to clarify the effects of the horizontally propagating waves on the behavior of vehicle.

In this study, we investigated how these characteristics of wave propagations affect the railway vehicles dynamics behaviors by numerical simulations. We first grasped the characteristics of seismic ground behavior in the out-of-plane direction on the soft ground with a non-flat base by using 2D dynamic FEM analyses. Next we calculated seismic deformations of railway viaducts constructed on the soft ground with non-flat base. After that, we clarified how the horizontally propagating waves disturb the running safety of trains by calculating the folding angle, which is defined as the angle formed between neighboring slabs of viaduct due to the difference of displacements between two adjacent piers. Finally, we investigated the dynamics behavior of vehicles running on the railway structures on the soft ground with a non-flat base by using 'Vehicle Dynamics Simulator', which is the program developed by one of the authors.

2. DYNAMIC FEM ANALYSIS OF SOFT GROUND WITH NON-FLAT BASE

2.1. Analytical Method

To investigate how characteristics of wave propagation on the soft ground with a non-flat base have an effect on the behavior of vehicle, we conducted two-dimensional (2D) dynamic FEM analyses in the out-of-plane direction with simple ground models as shown in Fig. 1. We constructed models of soft ground with a non-flat base by altering the following two parameters: the inclination of bedrock, and the shear wave velocity of soft surface layer. The viscous boundary is assumed at the bottom of the ground model, and the isodisplacement boundary conditions are used on both sides of the model. The properties of the ground model are listed in Table 1. We conducted the non-linear analysis using the input ground motion as shown in Fig. 2, which is the Level-1 earthquake motion in Japanese seismic design code for railway structures.

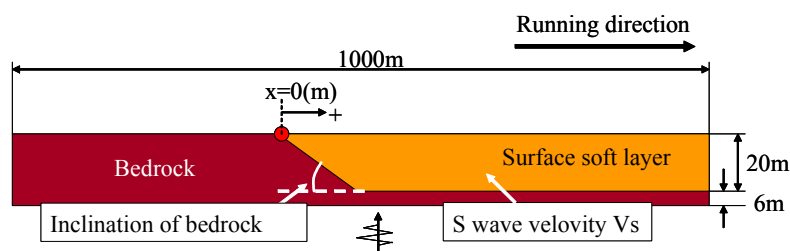


Figure 1 Ground model

Table 1 Properties of ground model

	Soft surface layer		Bedrock
Density (KN/m ³)	16		20
Damping factor h	0.01		0.01
S wave velocity Vs (m)	100	200	400
Impedance ratio	0.2	0.4	
(°)			
30	Case 1	Case 3	
90	Case 2		

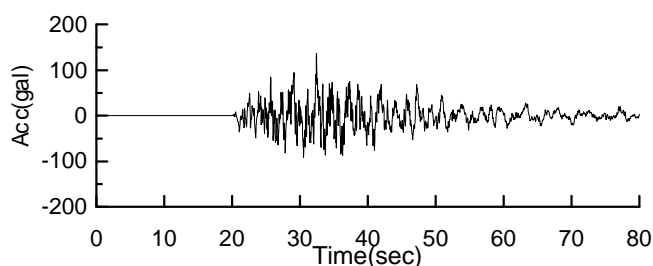


Figure 2 Input motion

2.2. Characteristic of wave propagation

Figure 3 shows the acceleration responses obtained by 2D FEM analysis for Case 1. We see that different waves arrive at each point on the soft ground with a non-flat base. This characteristic occurs because of ground irregularities. Next Fig. 4 shows snapshots of the acceleration for Case 1. We see that a wave generated in the base slant area propagates in the horizontal direction. These characteristics of wave propagation, which is termed as 'basin effects', causes the time lag of responses between two structures. To examine the running safety of trains, therefore, it is essential to take into account the basin effects. Finally in Fig. 5, the maximum accelerations on the ground surface for Case 1, Case 2 and Case 3 are compared. Around

the edge of the basin, the maximum accelerations become larger than those at the places remote from the edge of the basin due to horizontally propagating waves. Then the smaller shear wave velocity of soft surface layer becomes, the more remarkable this characteristic becomes. On the other hand, the inclination of bedrock does not much affect on the variation of the maximum acceleration.

According to the analysis in the out-of-plane direction of several studies, it has been shown that Love wave predominates as a horizontally propagating wave [Akiyama, 1993]. In Fig. 6, the phase velocities of Love waves on the horizontally layered ground for Case 1 and Case 3 obtained by the method proposed by Haskell are compared [Haskell, 1953]. The smaller shear wave velocity of soft surface becomes, the smaller velocity of Love wave becomes. As the velocity of the horizontally propagating wave is related to the time delay of the responses of railway structures, it is important that we take into account the influence of the horizontally propagating waves on railway vehicle dynamic behavior to examine the running safety of trains on railway structures.

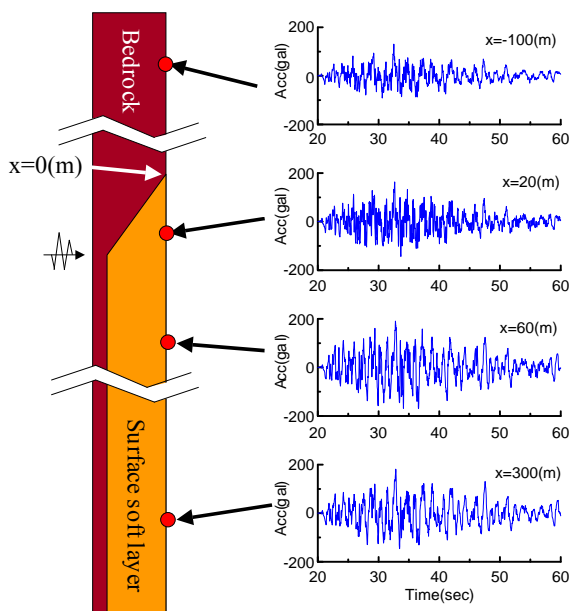


Figure 3 Acceleration response obtained by 2D-FEM analysis for Case 1

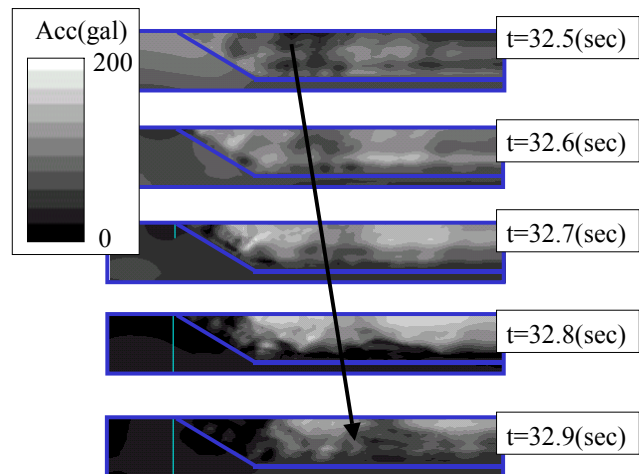


Figure 4 Snapshots of acceleration for Case 1

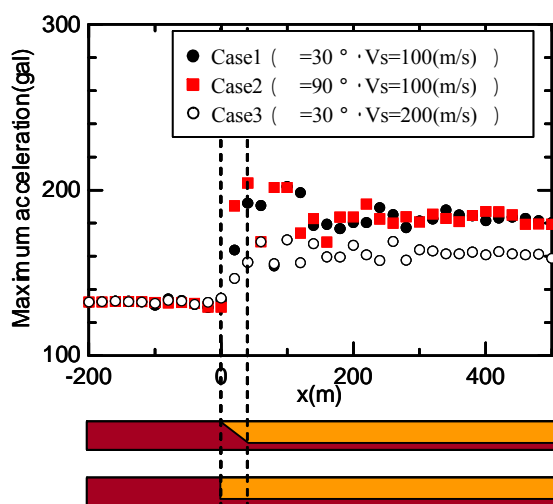


Figure 5 Influence of each parameter on the maximum acceleration

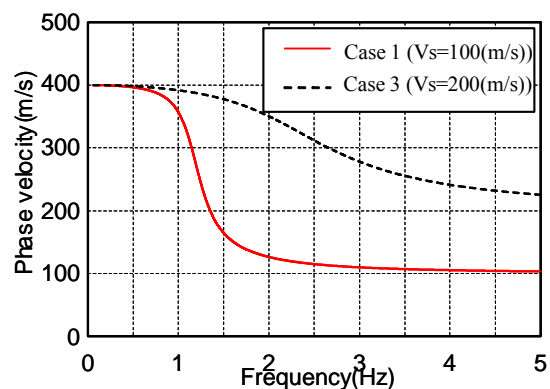


Figure 6 Phase Velocity of Love wave

3. INFLUENCE OF BASIN EFFECTS ON RESPONSE OF STRUCTURE

3.1. Calculation of response of railway viaduct

To examine the influences of basin effects on the responses of railway viaducts, we calculate the responses of one-degree-of-freedom piers based on the following conditions.

- (1) Piers are constructed at intervals of 20 meters on the soft ground with a non-flat base.
- (2) The natural periods of all piers are 0.8 (sec)
- (3) All piers are elastic, and their damping factors are 0.05.

Figure 7 shows the acceleration responses of piers for Case 1. We see that the response of each pier is quite different from each other due to the basin effects.

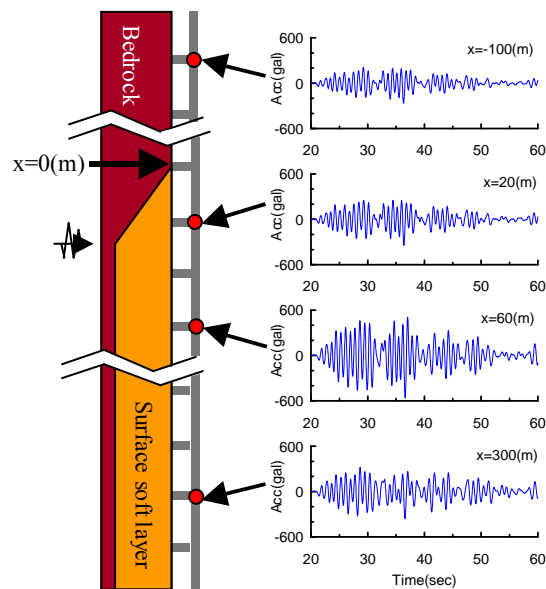


Figure 7 Acceleration responses of piers

3.2. Influence of basin effects on folding angle of railway viaduct

In Japanese seismic design code for railway structures, the maximum folding angle, which is defined by Eqn.3.1, is used to check the running safety of trains.

$$\theta' = \left\{ \frac{1}{S_1} (y_2(t) - y_1(t)) - \frac{1}{S_2} (y_3(t) - y_2(t)) \right\}_{\max} \quad (3.1)$$

where $y_1(t), y_2(t), y_3(t)$ express the displacement responses of piers, and S_1 and S_2 , the spans between adjacent piers as shown in Fig. 8.

In this section, in order to clarify the effect of each parameter of the soft ground with a non-flat base on the running safety of trains, the maximum folding angles of railway viaducts are calculated based on the conditions shown in section 3.1. In Fig. 9, the maximum folding angles for Case 1, Case 2 and Case 3 are compared. First, the larger the inclination of bedrock becomes, the larger the maximum folding angle becomes also larger around the base slant area. For Case1 and Case 2, then, the maximum folding angle is much larger than those for Case 3. We can say, therefore, that the more caution is necessary in examining the running safety of trains on railway viaducts if the surface layer is relatively soft.

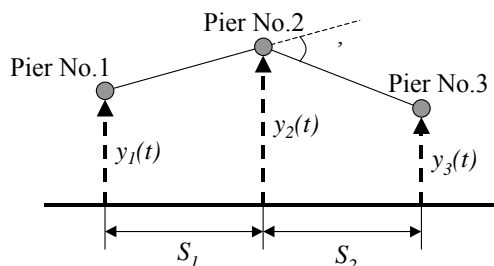


Figure 8 Calculation of folding angle of railway viaduct

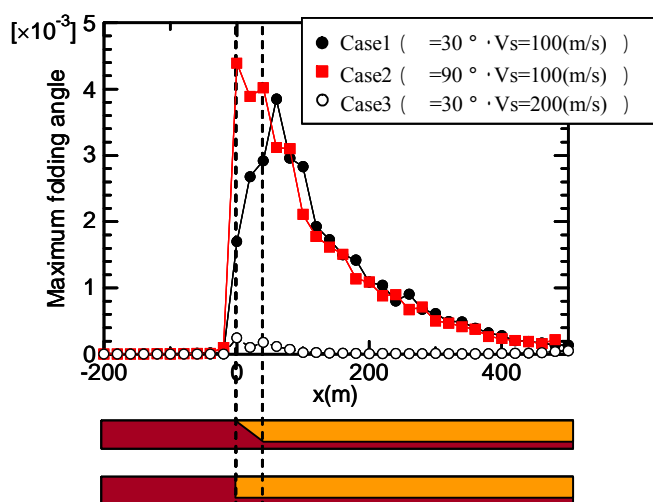


Figure 9 Influence of each parameter on the maximum folding angle

4. INFLUENCE OF BASIN EFFECTS ON RAILWAY VEHICLE DYNAMIC BEHAVIOR

4.1. Analytical Method

One of the authors has developed a simulation program, which is termed as 'VDS: Vehicle Dynamics Simulator', that investigates the dynamic behavior of railway vehicles during earthquake [Miyamoto et al, 2004]. In this study, we examine the influences of the basin effects on dynamic behavior of vehicle running on the soft ground with a non-flat base by using VDS.

4.1.1 Simulation model

Figure 10 shows a model of Shinkansen vehicle, which has a carbody, a truck and two wheelsets. Each model is connected with springs and dampers, and the number of degrees of the freedom of the whole model is 58.

4.1.2 Input vibration model

Figure 11 shows a model to input the vibration of railway viaducts into the wheel. We assume the spring and damper to support rail which correspond to those of a slab track. In this study, we take into account the input motions only at the right angles to rail.

4.1.3 Evaluation of safety limit

We use the relative displacement between a wheel and a rail as the indicator of the safety limit of running

vehicle. We judge that the vehicle derails in the case where the relative displacement exceeds 70 (mm) as shown in Fig. 12. In this study, we increase the amplitude of the input motion gradually, and investigate the running safety of trains by calculating RSL Power, which is the power of the input motion in the case where the relative displacement reaches 70 (mm).

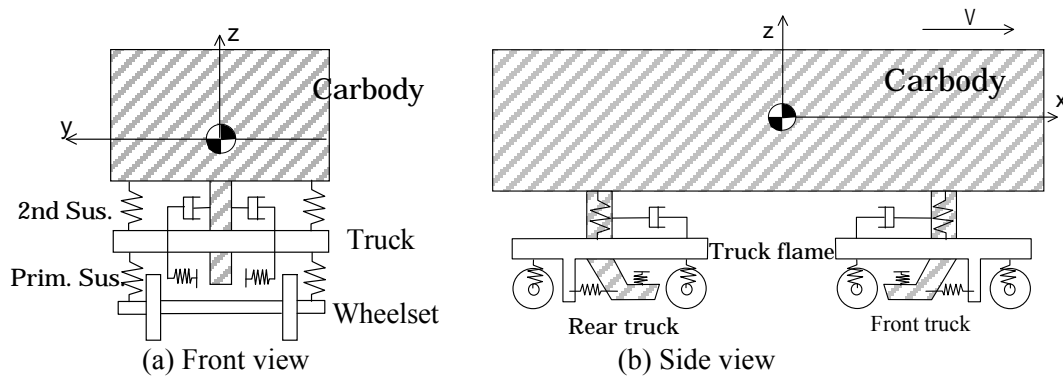


Figure 10 Simulation model of railway vehicle

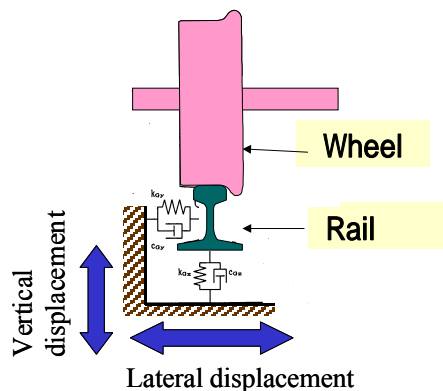


Figure 11 Vibration input model

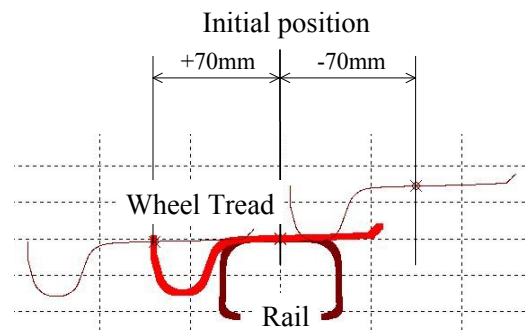


Figure 12 Evaluation of safety limit

4.2. Influence of response of railway viaduct on vehicle dynamic behavior

In this study, we investigate how the responses of railway viaduct affect the vehicle dynamic behavior by the following methods (shown in Fig. 13):

(Type (a)) Vibration at the point of X is inputted at all points uniformly.

(Type (b)) Vibration at each point is inputted separately by interpolating displacements at points between two piers.

Then we assume that the railway vehicle runs at speeds of 300 (km).

Figure 14 shows the RSL Power for Type (a). The horizontal axis expresses the point X where the input vibration is obtained. For Case 1 and Case 2, the value of RSL Power around the edge of the base slant area is smaller than that in the other area. This means that the earthquake ground motion obtained in the area has a severe effect on the running safety of trains. Next, for Case 3, the value of RSL Power is larger than that for Case 1 and Case 2. We can say, therefore, that the smaller the shear wave velocity of soft surface layer becomes, the more cautions should be taken in checking the running safety of railway vehicle, especially around the base slant area.

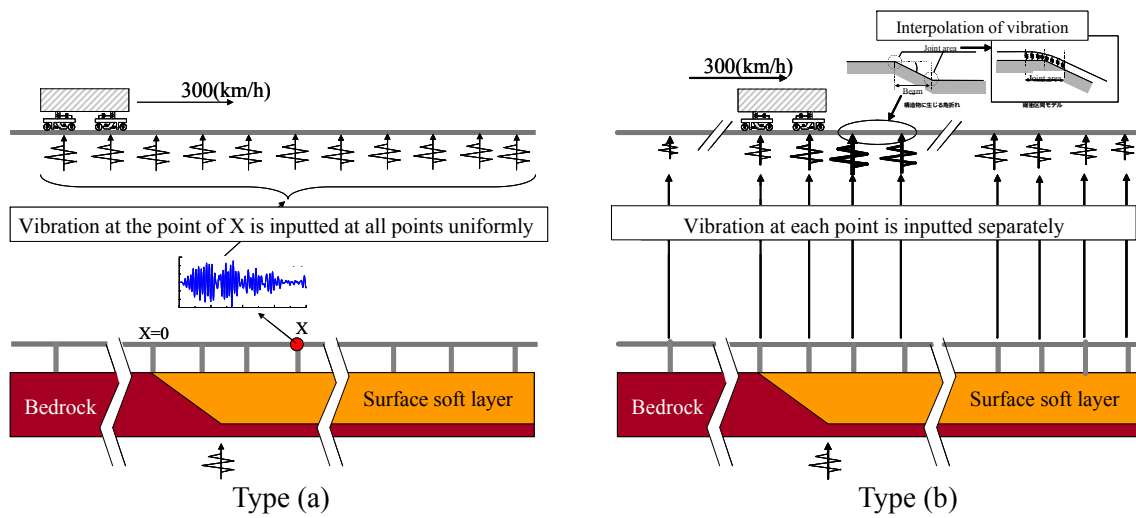


Figure 13 Method of numerical simulation

On the other hand, for Type (b), we calculated the heights of the maximum wheel lift by changing the passage timing of the railway vehicle. Figure 15 shows the results. The horizontal axis shows the occurrence point of the maximum wheel lift. We see that the occurrence point of the maximum wheel lift is far from the base slant area, where the maximum folding angle is relatively large as shown in Fig. 9. Comparing the results for Case 1 with those for Case 3, we can know that the wheel of vehicle can be lifted more as the surface layer becomes softer. Then comparison between the results for Case 1 and those for Case 2 shows that the inclination of bedrock has not so much effect on the heights of the maximum wheel lift. Finally, for the case that the largest height of the maximum wheel lift is obtained for Type (b), the RSL Power is about 2.55. This value is larger than that at the point on horizontally layered ground with surface soft layer for Type (a). This result indicates that the running safety of vehicle running with high speed on the soft ground with a non-flat base is influenced by the amplification of the earthquake ground motion due to the basin effects rather than the difference of displacements between two adjacent piers.

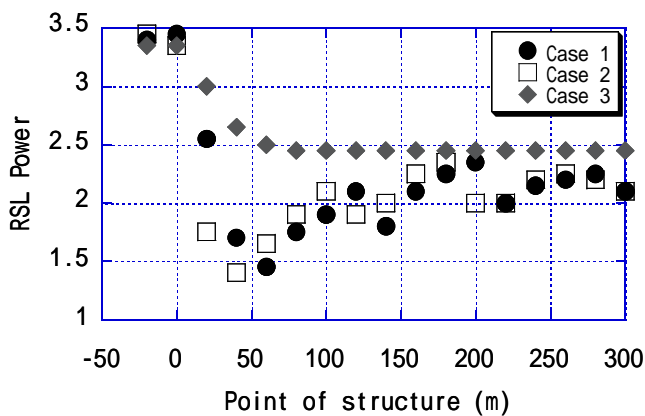


Figure 14 Running safety limits(RSL) power according to input wave at each point on a structure

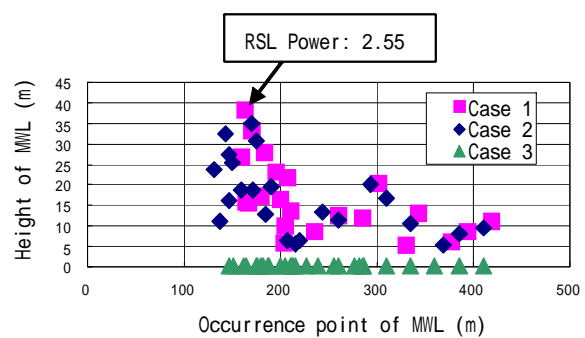


Figure 15 Maximum wheel lift at various passage timing

5. CONCLUSION

In this paper, we first investigated the characteristics of wave propagation on the soft ground with a non-flat base by 2D FEM dynamic analysis. Next we checked the effects of these characteristics of wave propagation on the railway vehicles dynamics behaviors by the numerical simulations. The results are as follows:

- 1) By the influence of the horizontally propagating waves generated in the base slant area, different waves

arrive at each point on the soft ground with a non-flat base. The horizontally propagating waves also affect the response of the railway viaduct.

- 2) The smaller the shear wave velocity of the soft surface layer becomes, the larger the variation of responses of railway viaducts becomes, and the larger the time delay of the responses between two piers becomes. It is necessary, therefore, to check carefully the running safety of trains on railway viaducts if the surface layer is relatively soft.
- 3) The running safety of vehicle running with high speed on the soft ground with a non-flat base is influenced by the amplification of the earthquake ground motion due to the basin effects rather than the difference of displacements between two adjacent piers.

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