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Abstract

The authors performed a research using test trucks for a three-lane prestressed concrete bridge with 37.47m span that vibrated greatly. As the results of the research, the bridge had the frequency of the 1st bending vibration (*ca*. 3.0Hz). And also, since the frequency and that of general vehicle's vibration (*ca*. 3.0Hz) is close, the bridge and vehicles had caused coupled vibration. Moreover it was clear that the bridge had vibrated greatly, only when the test truck had ran at the 2nd slow lane. Because vehicle's suspension spring vibration had been generated by the road roughness with long space period nearby the expansion joint of the 2nd slow lane. This paper describes the vibration characteristics of the prestressed concrete bridge coupled with the vehicle's vibration generated by the road roughness with long space period nearby the expansion joint. Besides, this study also examined the countermeasure to decrease the vibration by the dynamic response analysis due to running vehicle.

Introduction

General trucks with leaf suspension have frequencies *ca* 3 Hz (Kajikawa *et al*., 2004). Besides, the frequency of the 1st bending vibration of the bridge with the span length of 30m appears in 2.8-3.3Hz. Since the frequency of the bridge (2.8-3.3Hz) and the frequency of vehicles (leaf suspension spring: 3Hz) are close, the resonance is occurred.

The coupled vibration of the bridge and vehicles is not related only to the frequency of the bridge and the vehicles, but also to the spatial period of the road roughness. The truck's tire spring vibration (Fukada, 2006; Fukada *et al*., 2007) is affected by short spatial period as faulting. On the other hand, the road roughness of the long spatial period as 5-12m influences on the truck's leaf suspension spring vibration. Especially, the bridge greatly vibrates by resonating to the truck's vibration generated by the road roughness of that spatial period nearby the expansion joint.

This paper describes the vibration characteristics of the prestressed concrete bridge resonated to the vehicle's vibration generated by the road roughness with long space period nearby the expansion joint. Moreover this study examined the countermeasure to decrease the acceleration amplitude on the dynamic response analysis due to running vehicle.

Object Bridge

The object bridge was remodeled from concrete box culvert to the prestressed concrete girder bridge. This bridge is the post-tensioning T type simple girder bridge, which the span length is 37.47m, the effective width is 14.50m and skew is 67degree. The side view of the object bridge is shown in Figure 1.

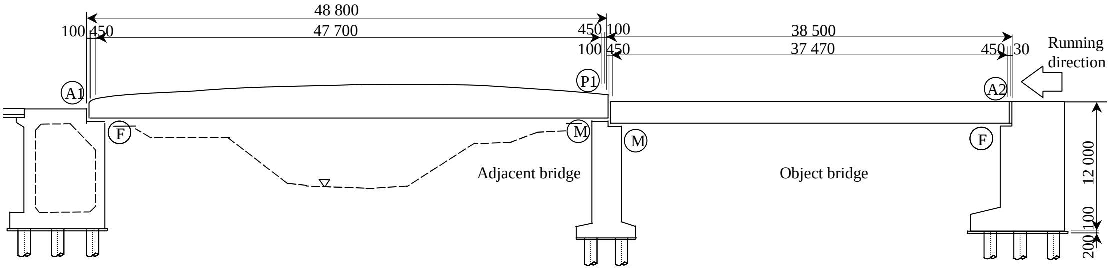
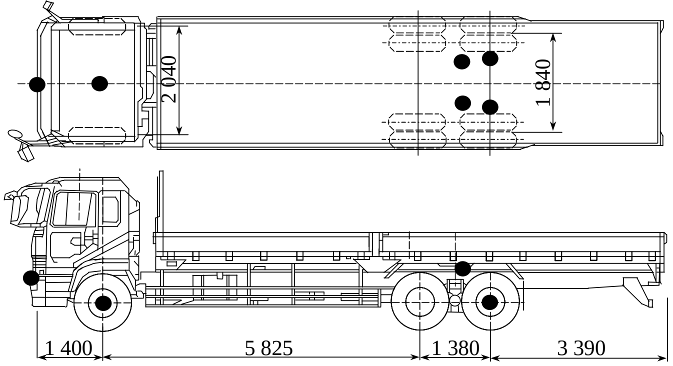


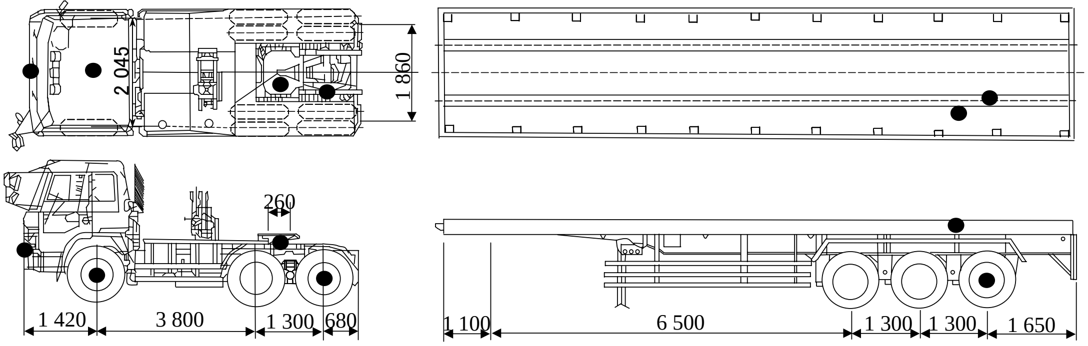
Figure 1. Object bridge.

Examination

The running tests using two types test trucks were curried out in order to grasp the dynamic response characteristics. The test trucks are the 3-axle truck with 245kN weight and semi-trailer truck with 421kN weight as shown in Figure 2.



(a) Test trucks (3-axle truck)



(b) Test trucks (semi-trailer truck)

Figure 2. Measurement points of test trucks.

The running speed of the test trucks is 80 km/h. The 3-axle test truck ran at the fast lane, 1st slow lane and 2nd slow lane respectively (Figure 3). The semi-trailer test truck ran at

1st slow lane and 2nd slow lane respectively (Figure 3) considering the running speed and traffic stream.

The measurement items are (1) Dynamic increment factor (dynamic amplification factor) measured by strain of girders, (2) Acceleration amplitude, (3) Characteristics (frequency and damping) of the bridge and (4) Characteristics of the test trucks. The measurement points of the test trucks and the object bridge are shown in Figure 2 and Figure 3, respectively.

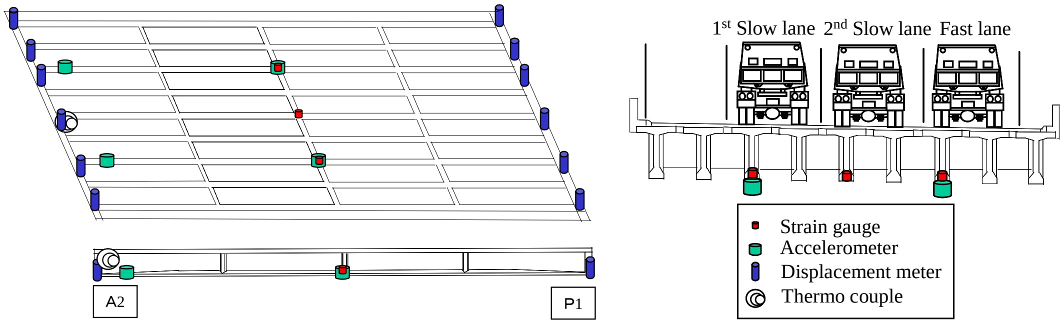
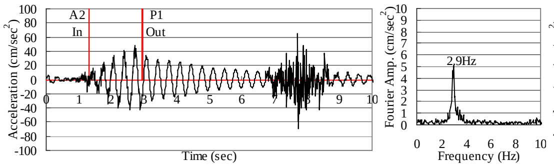


Figure 3. Measurement points of the object bridge.

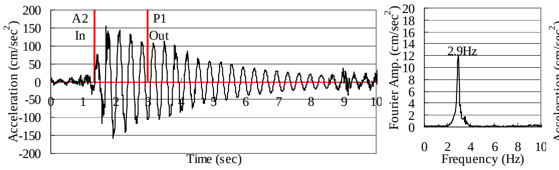
Results of the running test

Dynamic response

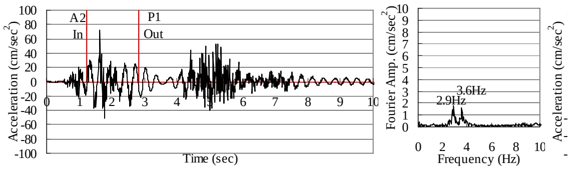
When the 3-axle test truck ran at each lane in 80km/h, the acceleration wave and spectrum of the bridge are shown in Figure 4. And also, the acceleration wave and spectrum of the 3-axle truck are shown in Figure 5. Here, the two pulse waves represented in the acceleration wave are shown the times as test truck's running position of A2 or P1.



(a) 1st slow lane

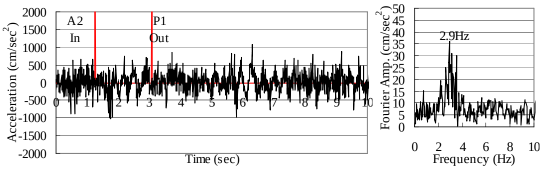


(b) 2nd slow lane

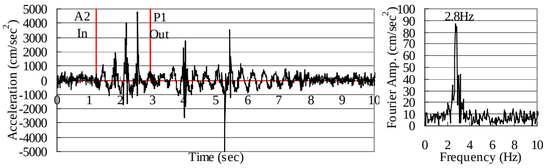


(c) Fast lane

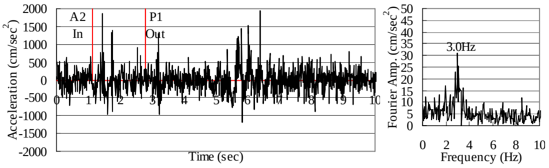
Figure 4. Acc. and spec. of the bridge.



(a) 1st slow lane



(b) 2nd slow lane



(c) Fast lane

Figure 5. Acc. and spec. of the 3-axle truck.

The acceleration amplitude in the mid span, when the 3-axle test truck ran at the 2nd slow lane in 80km/h, appeared the maximum (150 cm/sec^2). It is 3 or 4 times the acceleration amplitude when running in the fast lane or the 1st slow lane. Moreover the acceleration of the 3-axle test truck ran at the 2nd slow lane is becoming large gradually.

This study inferred the reason of the large vibration as follows.
(a) Resonated to the bending 1st vibration and test truck due to running in 2nd slow lane.
(b) Truck's vibration generated by road roughness with spatial period in 2nd slow lane.

Vibration characteristics

The acceleration spectrum obtained from the running tests proved that the object bridge had the bending 1st mode (2.9-3.0Hz) and torsion 1st mode (3.4-3.5Hz). The ordinary trucks with leaf suspension vibrate *ca* 3Hz. Therefore it is clear that the bridge resonates to the test truck, because of their close frequencies.

The frequencies and the modal damping of the bridge by the test vehicle running tests are shown in Table 1. The modal damping was computed using Eigensystem Realization Algorithm method (Juang *et al*., 1985).

	Bending 1st vibration				Torsion 1st vibration			
Running test case （Truck type，Lane）	Mid span (1st slow)		Mid span (fast lane)		Mid span (1st slow)		Mid span (fast lane)	
	Freq. (Hz)	Damp. (-)	Freq. (Hz)	Damp. (-)	Freq. (Hz)	Damp. (-)	Freq. (Hz)	Damp. (-)
3-axle truck, 1st slow	2.934	0.020	2.936	0.020	3.491	0.006	3.450	0.029
3-axle truck, 1st slow	2.962	0.026	2.931	0.027	3.556	0.014	3.473	0.017
3-axle truck, 2nd slow	2.907	0.019	2.906	0.019	3.436	0.039	3.422	0.014
3-axle truck, fast	2.885	0.016	2.846	0.036	3.496	0.013	3.446	0.050
Semi-trailer, 1st slow	2.907	0.024	2.876	0.023	3.456	0.022	3.621	0.029
Semi-trailer, 2nd slow	2.953	0.014	2.939	0.017	3.432	0.022	-	-
Semi-trailer, 2nd slow	2.983	0.038	2.955	0.038	-	-	-	-

Table 1. Vibration characteristics.

Dynamic increment factors and dynamic amplification factors

The dynamic increment factors (*DIF*) or the dynamic amplification factors (*DAF*) are defined as the ratio of the amplitudes of static and dynamic responses due to running vehicles. The *DIF* and the *DAF* were represented following equations.

The *DIF* and the *DAF* were calculated using strain data, when 3-axle truck or semi-trailer ran at each lane in 80 km/h. When 3-axle truck ran at 2nd slow lane, the *DIF* and the *DAF* were around 2 - 3 as shown in Table 2. When semi-trailer truck ran at 2nd slow lane, those were *ca* 1. These were much bigger than the response by test trucks running in other lane (fast lane and 1st slow lane).

The stress of the girder was calculated from maximum dynamic strain in each lane. The maximum dynamic strain in running test examination was 45.54 micro strains at the fast lane of girder, when 3-axle truck ran at 2nd slow lane. The stress of the girder was 1.41 N/mm^2. It is allowable level of stress in soundness, because the tolerance was 1.5 N/mm^2 in Japanese roadway bridge specification. However it should be examined the countermeasure to decrease the dynamic stress.

$$DIF\text{-}1 = y_{I,dy,max} / y_{st,max} \qquad (1)$$

Here, $y_{I,dy} = ABS(y_{dy} / y_{st})$ as shown in Figure 6.

$$DAF = y_{dy,max} / y_{st,max} \qquad (2)$$

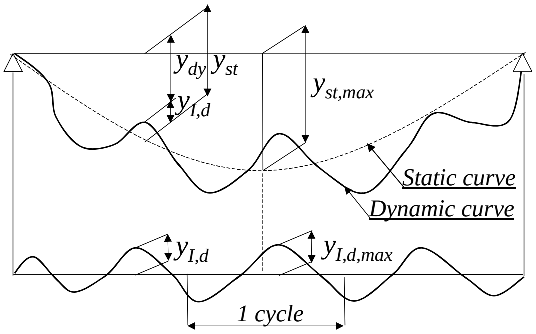


Figure 6. Outline of *DIF* and *DAF*.

	1st slow lane					2nd slow lane					Fast lane				
Running test case	$y_{st,max}$	$y_{I,dy,max}$	$y_{dy,max}$	*DIF-1*	*DAF-1*	$y_{st,max}$	$y_{I,dy,max}$	$y_{dy,max}$	*DIF-1*	*DAF-1*	$y_{st,max}$	$y_{I,dy,max}$	$y_{dy,max}$	*DIF-1*	*DAF-1*
3-axle truck, 1st slow	13.38	8.02	21.19	0.60	0.58	12.88	6.78	18.18	0.53	0.41	8.77	7.04	14.22	0.80	0.62
3-axle truck, 1st slow	13.59	6.59	19.12	0.48	0.41	13.30	5.78	19.07	0.43	0.43	8.87	6.74	14.22	0.76	0.62
3-axle truck, 2nd slow	11.83	26.97	41.79	2.28	2.53	12.15	34.72	38.33	2.86	2.16	15.99	31.11	45.54	1.94	1.85
3-axle truck, fast	6.03	6.07	11.15	1.01	0.85	13.20	4.76	17.78	0.36	0.35	18.12	8.22	25.66	0.45	0.42
Semi-trailer, 1st slow	21.98	14.81	31.90	0.67	0.45	21.35	10.15	30.22	0.48	0.42	14.35	10.59	24.69	0.74	0.72
Semi-trailer, 2nd slow	19.11	21.12	35.58	1.11	0.86	19.93	22.96	41.68	1.15	1.09	24.76	23.61	44.21	0.95	0.79
Semi-trailer, 2nd slow	18.96	19.66	33.87	1.04	0.79	20.00	21.13	40.06	1.06	1.00	24.93	22.34	43.61	0.90	0.75

Table 2. *DIF* and *DAF*.

Measurement of road roughness

The road roughness of the object bridge was measured in order to grasp the road profile of each running lane. The road roughness of the 1st slow lane and the fast lane was measured by the 8m-profile-meter. And also that of the 2nd slow lane was measured by the road-measuring car, because of the difficulty of the regulation of traffic. The measured road roughness of each lane was shown in Figure 7.

The road roughness of the fast lane was smaller than those of other lanes. The road roughness with spatial period as sin curve (about 10m) was appeared in 2nd slow lane nearby A2 expansion joint. Especially, amplitude of the roughness in A2 expansion joint of the lane was 40 mm (peak to peak).

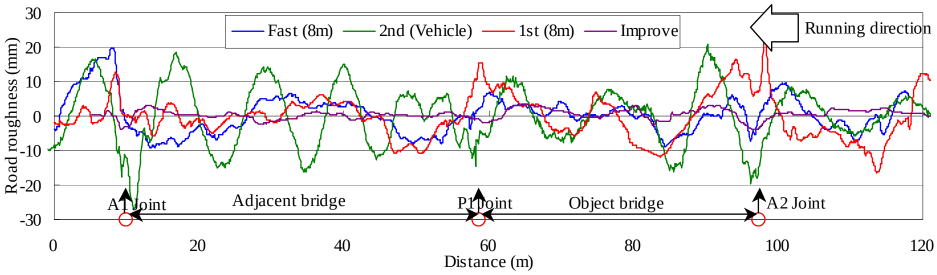


Figure 7. Measurement of the road roughness.

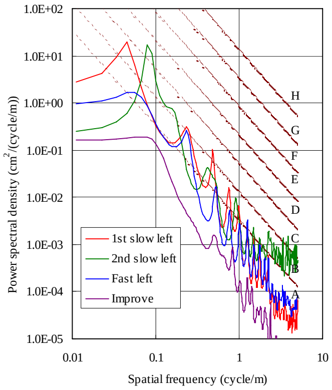


Figure 8. Power spectral densities with ISO 8608 estimation.

The power spectral densities by Maximum Entropy Method were simulated using measurement data of the road roughness as shown in Figure 8. And also, ISO 8608 estimation (ISO 8608, 1995) for road roughness was shown in same figure. From the power spectral densities with ISO 8608 estimation, the road roughness of the 2nd slow lane was estimated as class D road in the spatial frequency of 0.0785cycle/m (12.7m/cycle) and 0.0897cycle/m (11.1m/cycle).

From the calculation of the relationship between the vehicle speed, the spatial period and the loading time frequency by the vehicle and roughness using the one degree of system car model as shown in Figure 9 (Fukada, 2007), it was clear that the bridge with the roughness of the spatial period 10.0m/cycle are received vibration frequency 2.7Hz by the vehicle, when the vehicle ran in the speed of 100km/h (27.77m/sec) as shown in Table 3. Since the object bridge has the bending 1st vibration mode in 2.9-3.0Hz, if the vehicle ran in the speed of 100-110km/h, the bridge more resonates to vehicles than the results in the speed of 80km/h.

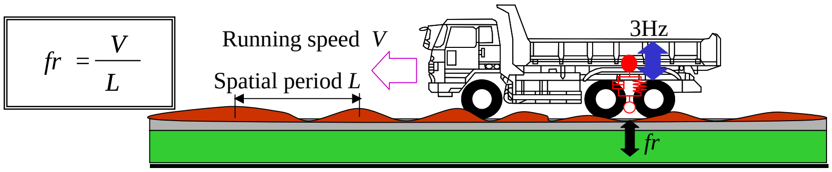


Figure 9. Loading time frequency by one-degree car model and roughness.

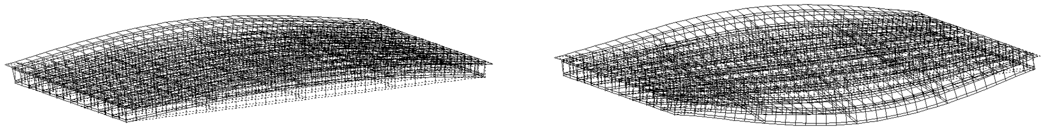
Running Speed (km/h)	Spatial period (m/cycle)							
	5	6	7	8	9	10	11	12
80	4.44	3.70	3.17	2.78	2.47	2.22	2.02	1.85
90	5.00	4.17	3.57	3.13	2.78	2.50	2.27	2.08
100	5.56	4.63	3.97	3.47	3.09	2.78	2.53	2.31
110	6.11	5.09	4.37	3.82	3.40	3.06	2.78	2.55

Table 3. Loading time frequency.

Simulation

Vibration characteristics

The frequencies of each vibration modes from the running test and Eigen-value analysis were shown in Figure 10. With comparison between the results of experiment and analysis, the validity of this bridge model was confirmed.



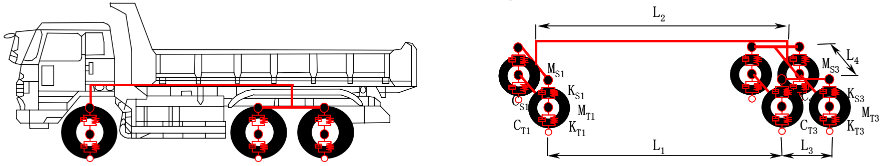
(a) Bending 1st mode
(Exp. 2.9-3.0Hz, Anal. 2.91Hz)

(b) Torsion 1st mode
(Exp. 3.4-3.6Hz, Anal. 3.44Hz)

Figure 10. Vibration mode.

Dynamic response analysis

The dynamic response analysis (Fukada, 2007; Akiyama *et al*., 2007) using the direct integration method by Newmark's Beta method (Beta=1/4, *t*=0.005) considering the measured road roughness was performed. Damping is assumed to be Rayleigh damping. The 3-axle test truck was modeled as shown in Figure 11.



(a) Side view

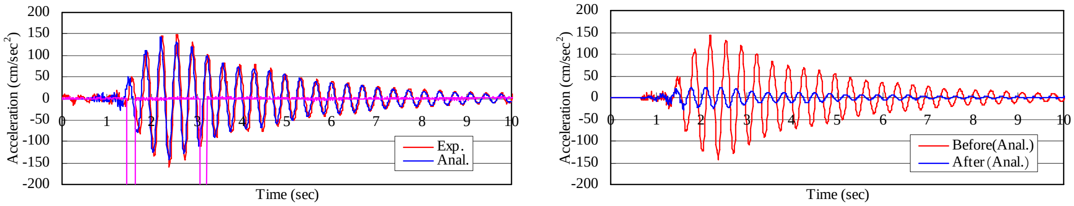
(b) Whole view

Figure 11. 3-axle test truck model.

The validity of the dynamic response analysis was examined by comparing the results of the acceleration in the running test and analysis. When the 3-axle test truck ran at the 2nd slow lane in 80km/h, acceleration wave of the experiment and analysis were shown in Figure 12(a). Here, the two pulse waves represented in the acceleration wave were shown at the moments when running positions are at A2 or P1. The validity of the dynamic response analysis was proved, since the analysis was similar to the experiment.

It investigated whether large vibration was dependent on the road roughness with spatial period. Then the pavement in the 2nd slow lane was improved on this simulation as shown in Figure 7. And also, the power spectral density of the improved roughness was simulated as shown in Figure 8. The amplitude of the roughness is very small in improved pavement. And then the spatial period of the improved pavement is not appeared in the area of the 0.1cycle/m.

When the 3-axle test truck ran at the 2nd slow lane in 80km/h, acceleration waves before and after improvement of the pavement were shown in Figure 12(b). Maximum amplitude of the acceleration was decreased to 81%. Therefore it is clear that the improvement of the pavement is effective in decreasing dynamic response of the object bridge.



(a) Exp. And Anal.

(b) Before and after improvement

Figure 12. Results of dynamic response analysis (Acceleration in the span 1/2).

Conclusions

The loading tests using test trucks were performed in order to grasp the vibration characteristics of the prestressed concrete bridge coupled with the vehicle’s vibration generated by the road roughness with long space period nearby the expansion joint. And also, this study examined the countermeasure to decrease the vibration by the dynamic response analysis due to running vehicle.

The conclusions acquired by this study are as follows.
(1) The object bridge had the bending 1st mode (2.9-3.0Hz) and torsion 1st mode (3.4-3.5Hz) from the acceleration spectrum obtained by the running tests.
(2) When the 3-axle test truck ran at the 2nd slow lane in 80km/h, the acceleration amplitude in the mid span appeared the maximum (150 cm/sec^2). It was 3 or 4 times the acceleration amplitude when that truck ran at the fast lane or the 1st slow lane.
(3) When the 3-axle test truck ran at each lane in 80km/h, maximum dynamic stress of each test was measured. The maximum dynamic stress of the girders was 1.41 N/mm^2. It is allowable level of stress in soundness, because the tolerance was 1.5 N/mm^2 in Japanese roadway bridge specifications.
(4) The dynamic response analysis due to running vehicles using measured road was performed. When the 3-axle test truck ran at the 2nd slow lane in 80km/h, acceleration waves of the analysis were similar to those of experiment. In particular, when the 3-axle test truck ran at the 2nd slow lane in 80km/h, bridge model vibrated greatly on the analysis similar to the experiment.
(5) It investigated whether large vibration was dependent on the road roughness with spatial period. Then the pavement in the 2nd slow lane was improved in this simulation as countermeasure. As the results of analysis, maximum amplitude of the acceleration was decreased 81%. Therefore it is clear that the improvement of the pavement is effective in decreasing dynamic response of the object bridge.

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