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Development of knock-off abutment for base isolated bridges

Y. Goto & T. Kikuchi
Technical Research Institute, Obayashi Co., Tokyo, Japan

Y. Ina
Civil Engineering Development Department, Obayashi Co., Tokyo, Japan

ABSTRACT : A knock-off abutment is one of the devices to absorb collisions between the base-isolated bridge girder and the abutment during major earthquakes. In this study, a new type of knock-off abutment to deal with conditions found in Japan, namely high seismicity and heavy highway traffic, was studied and confirmed their functionality through 1/2 model experiments. A design method which considers post-yield mechanism of knock-off device was proposed and a nonlinear numerical simulation analysis assured it to be applicable in actual use. A field study which applied this type of knock-off abutment to an actual base-isolated bridge also assured its practical utility.

1 INTRODUCTION

In Japan there is a probability of high magnitude earthquakes with prominent long-period wave constituents, which means that when adopting base-isolation design, it is necessary to prepare for large response displacement. Namely, one thing which must be considered when adopting base-isolation design for a highway bridge is the design of the parts connecting the base-isolated girders with the surrounding bridge abutments that will not be base isolated. One technique is the use of expansion joints that allow considerable allowance, but aside from the fact that this method requires large joint devices that might be difficult to install, would cause noise and vibration, would lose the stability of automobiles, and would tend to break often causing heavy traffic jams due to repair work.

Therefore, it is more rational to set the allowance of the expansion joints so they can handle medium and small earthquakes and at the same time design the bridge abutments so that when a serious earthquake occurs they will be only partially damaged by the collision, and absorb the impact so that the major structural parts such as the girders will not be destroyed.

As one example of this ingenuity, the knock-off device has actually been applied in New Zealand as shown in Figure 1. In this case, when the girder collides with the abutment, the knock-off element built on the abutment top detaches to the backfill earth, so structural damage to the abutment and girders from collision is avoided and repairs can made easily. However, Japan, which has more traffic than New Zealand and which is likely to experience an earthquake with a great magnitude causing response displacement large, needs to develop a new type of knock-off device, taking into consideration both the concept developed in New Zealand (Lanigan (1981)) and the domestic circumstances of Japan.

This study consisted of producing knock-off models of a scale 1/2 that of the actual structures including backfill earth as well as asphalt pavement, performing tests on them under both static and dynamic loads, analyzing the results with numerical methods and proposing a design method for knock-off abutments. Moreover, a field study which applied a set of knock-off devices to an actual bridge was also included.

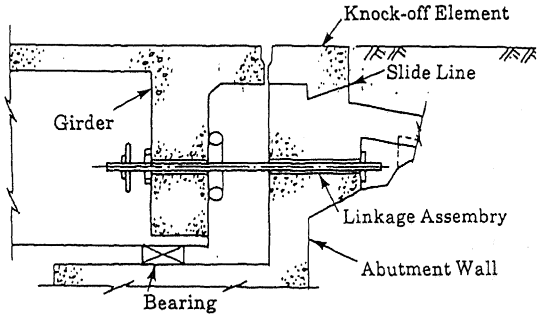


Fig. 1 Knock-off device
(Moonshine Bridge, M.W.D. of New Zealand)

2 EXPERIMENT

2.1 *Loading system*

A rough outline of the test device is shown in Figure 2. The bridge abutment ① and the backfill soil ② were loaded onto the test table ③ and then the girder ④ was fixed to the reaction wall. The test table was supported by a hydrostatic pressure bearing ⑤ and the actuator ⑥ caused it to slide in a lateral direction. From the static and dynamic motion of the test table caused by the actuator, the knock-off element ⑦ and girder could be made to collide. A load cell was installed in the tip of the girder to enable measurements of the reaction during collision.

2.2 *Model configuration*

The size of the models was 1/2 that of the actual structures and the knock-off element of each model was made of reinforced concrete with a depth of 2m, a width of 0.25m and a height of approximately 0.25m. The asphalt pavement model had the same strata as the actual structure and used asphalt pavement material with a layer thickness 1/2 that of the actual structure. Figure 3 shows details of the knock-off element and asphalt pavement model. The knock-off element models simulated cases in which the anchor dowel is present and others when it is not. In the New Zealand example, there is no anchor dowel, but when Japanese traffic conditions and expansion device installation conditions are considered it is thought that the anchor dowel becomes necessary. The steei bar section area for the anchor dowel was determined to be the section area that can resist the extraction force from the moment of overturn that is generated by wheel and brake loads.

2.3 *Test cases*

Six knock-off models were produced and a total of 12 different experiments were performed under different conditions. The test cases are shown in Table 1. The sliding resistance of the knock-off element itself was examined in the experiments without backfill earth. In the dry sand test, it is easy to analyze the generative mechanism of the resistance when the knock-off element slides towards the backfill by using material with well known properties. The purpose of the experiments conducted without the anchor dowel was also to analyze the mechanism of resistance.

The purpose of the dynamic test was to study the effect of velocity when the knock-off element is pushed in to the backfill earth. The test velocity was set taking into consideration the normal earthquake response velocity of girders.

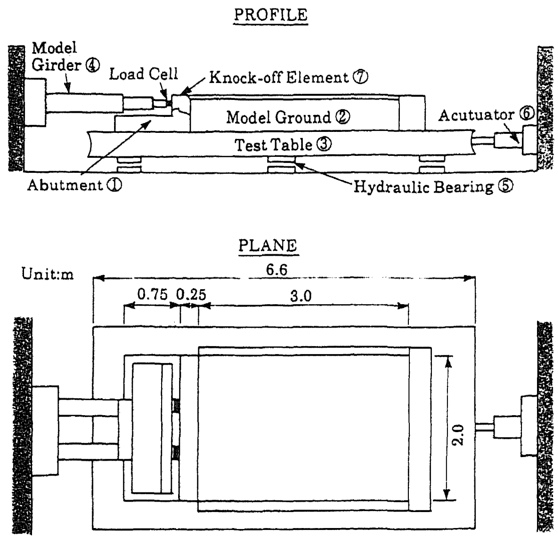


Fig. 2 Loading system

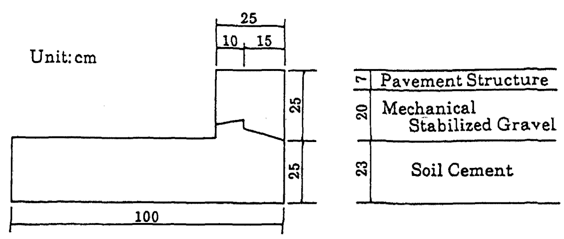


Fig. 3 Model of knock-off device and pavement

Table 1. Test cases

No.	Anchor dowel	Loading speed	Backfill
1	without	static	without
2	with	static	without
3	without	static	D. S.
4	without	10cm/sec	D. S.
5	without	15cm/sec	D. S.
6	without	20cm/sec	D. S.
7	without	static	A. P.
8	without	10cm/sec	A. P.
9	without	15cm/sec	A. P.
10	without	20cm/sec	A. P.
11	with	static	A. P.

D. S. : dry sand, A. P. : asphalt pavement

2.4 *Displacement - resistance relationship*

The relationship at collision between the sliding resistance force and the lateral displacement at the central position of the knock-off element is shown in Figures 4 - 6.

Figure 4 depicts a backfill of dry sand with no anchor dowel. The maximum resistances are between 13 - 16 kN and the effect of the knock-off velocity is small. On the other hand, Figure 5 shows the results when the backfill was asphalt pavement, also with no anchor dowel. In the case of asphalt pavement, the maximum resistances increase to be between 56 - 244 kN and the effect of the velocity becomes prominent. When the resistance reaches the maximum value, the displacement with dry sand of Fig. 4 is from 0.5 to 1cm, but is almost twice this amount with asphalt pavement of Figure 5. From these observations, it is understood that the effect of asphalt pavement on the knock-off device is great and that the effect of viscosity, a special property of asphalt, becomes dominant on the generative mechanism of the resistance.

Figure 6 compares the presence of the anchor dowel with the absence of it under the conditions of asphalt pavement. With the anchor dowel, the resistance increases substantially and the maximum displacement also increases, attaining a value of 4 cm. The anchor dowel, which did not break off even when the knock-off component started sliding, bore the majority of the resistance after sliding while causing post-yield expansion and extraction. These experiments in which the anchor dowel section area for the area of the knock-off sliding surface is 0.08% while that for the section area of asphalt pavement is 0.28%, reveal that resistance when this amount of anchor dowel is present is almost equivalent to that of asphalt pavement.

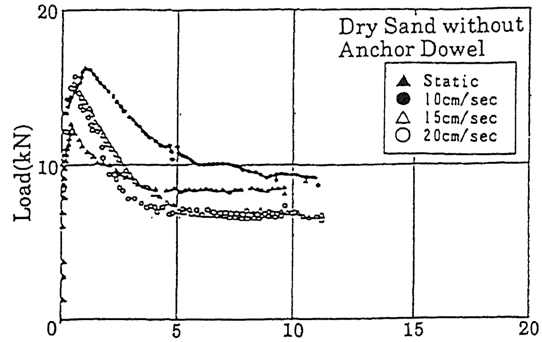


Fig. 4 Effect of loading speed (dry sand)

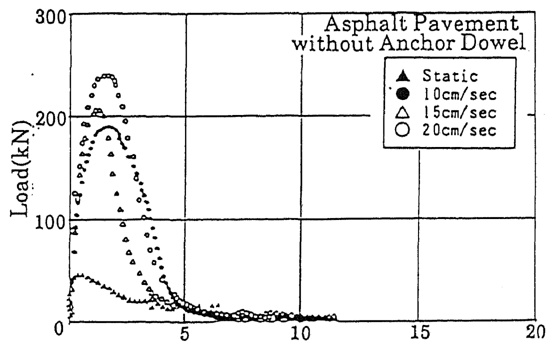


Fig. 5 Effect of loading speed (asphalt pavement)

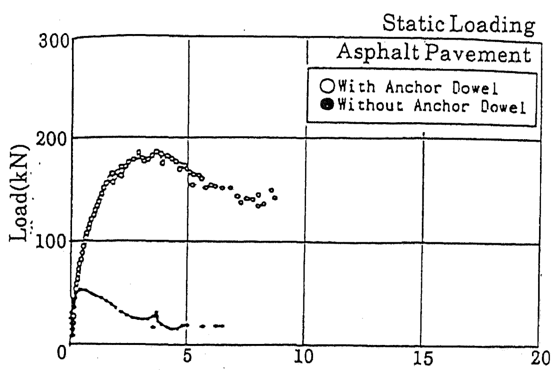


Fig. 6 Effect of anchor dowel

2.5 *Failure Mode*

The damage feature with dry sand backfill is shown in Figure 7. It is understood that a slip line appeared on the surface of the sand at a position 75 - 100cm from the end section of the knock-off device and the area rose up, causing slip failure when the backfill earth is subjected to passive earth pressure. The angle of inclination of the slip surface was 15 - 20 degrees. In the case of asphalt pavement as well (Figures 8 and 9), it was observed that the earth surface below the pavement caused slip failure. On the average, the inclination of that slip surface was 30 degrees.

Figure 8 and 9 show the damage features of the pavement surface when paved with asphalt. In the case of static load (Figure 8), the pavement surface in a vicinity of approximately 50cm from the knock-off device bent and caused damage. In the case of dynamic load(Figure 9), the pavement peeled up and the knock-off element crept under the pavement. These damage features were the same in each of the two cases of static load and the four cases of dynamic load. It is thought that the difference in the form of damage between static load and dynamic load depends on the effect of the visco-elastic property of asphalt.

Assuming that there may be high-speed run-away automobiles during or immediately following a major earthquake, it is desirable that the form of damage be as shown in Figure 9.

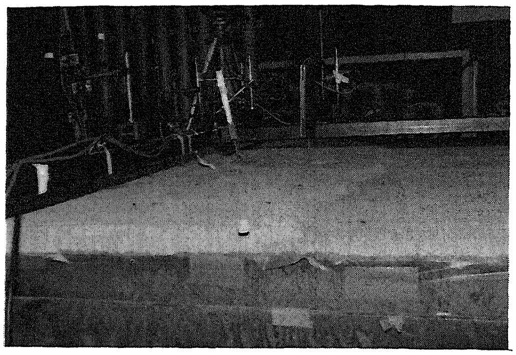


Fig. 7 Rise up of backfill sand

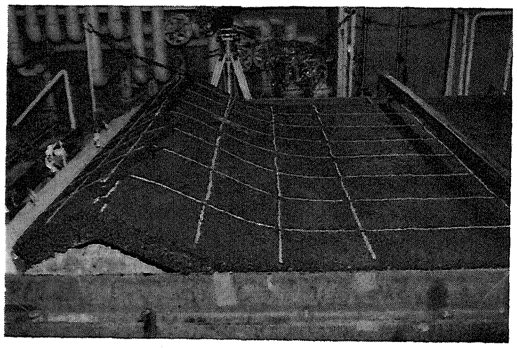


Fig. 8 Deformation by static load

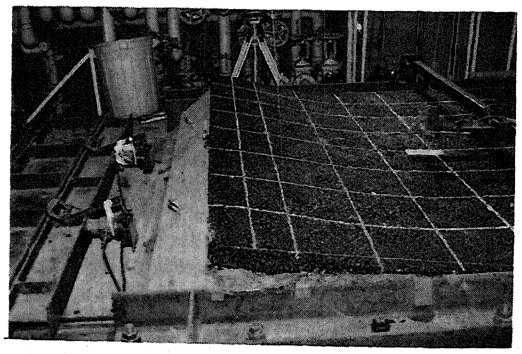


Fig. 9 Deformation by dynamic load

2.6 *Reparability*

Since major damage does not occur to the knock-off device when there is no anchor dowel, repair can be made by removing the damaged section of the pavement and repaving the area. Since the anchor dowel is not easily broken off when it is present, damage can occur in the concrete from the root insertion section of the anchor dowel and the concrete can peel. Then, it is necessary to improve the design method of the anchor dowel and the reinforcement of concrete around its root insertion.

3 NUMERICAL ANALYSIS

3.1 *Analysis by plastic equilibrium theory*

Resistance was calculated based on the plastic equilibrium theory in which friction and cohesion act on the slip surface in each boundaries considering the wedge-shaped soil block shown in Figure 10. It is assumed that cohesion also acts on the inside of the asphalt pavement. In addition, the ratio of rigidities between asphalt pavement and backfill gravel was taken into account. The material property values used in the analysis are shown in Table 2, and the results of this analysis are shown in Table 3. The results of static load test appear to be virtually analyzed, but there is a certain disparity with the analysis values from the values of the dynamic load test. It is understood that it is very important to correctly evaluate the dynamic material properties of asphalt pavement.

3.2 *FEM analysis*

Resistance was also calculated by FEM which can consider geometric and material non-linearities. Mohr-Coulomb's failure standard was used as the constitution equations of the backfill material and the pavement. Figure 11 shows a mesh of the model and an analyzed typical failure displacement. The load was applied statically from the left side boundary of the model. Relation between the calculated maximum resistance and the displacement is shown in Figure 12. The best fits of elastic modulus of asphalt to the experimental results are $2.0x10^5 kN/m^2$ for static loading and $4.7x10^5 kN/m^2$ for dynamic loading. Those values are reasonable when compared to the empirical material constant of asphalt pavement.

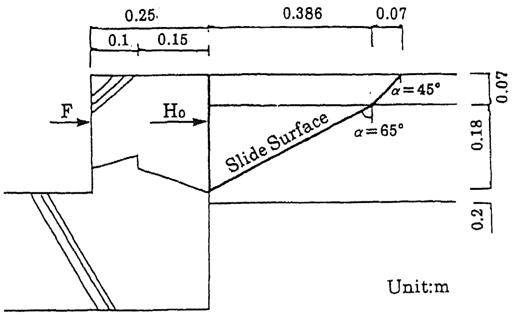


Fig. 10 Soil wedge model

Table 2. Material constants

	Concrete	Dry sand	Gravel	Asphalt pavement
Unit weight (Mg/m3)	24.	15.2	21.	10.3
Friction	–	41.8°	40.0°	0°
Cohesion (kPa)	–	0.	0.	1,200.

Table 3. Maximum resistant force

Model condition			Test	Analysis
Anchor	Backfill	Speed	(kN)	(kN)
without	without	static	1.2	1.2
without	dry sand	static	12.7	13.1
without	asphalt	static	55.7	47.8
without	asphalt	dynamic	190.-240.	343.
with	asphalt	static	190.	207.

asphalt : Asphalt pavement with gravel bed

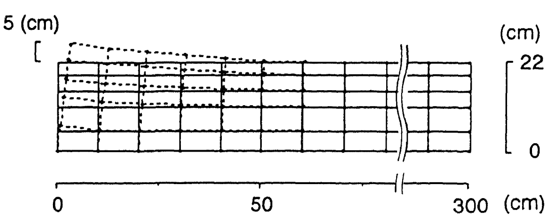


Fig. 11 FEM mesh and deformation pattern

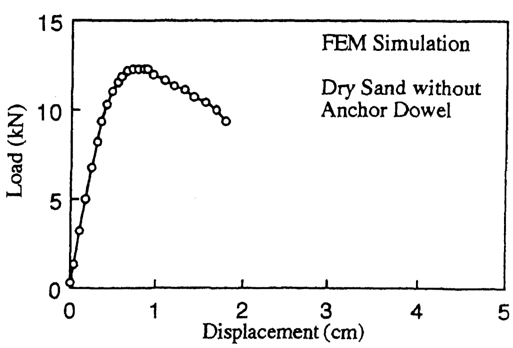


Fig. 12 Analyzed resistance and displacement

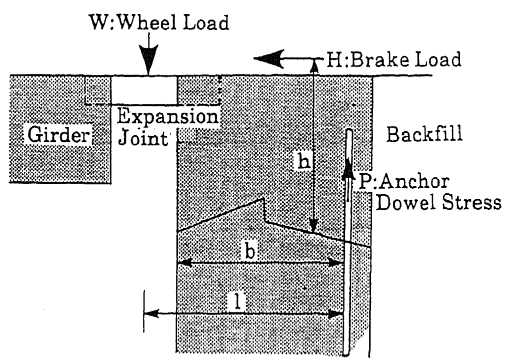
4 DESIGN METHOD

Summarizing the experiment and the analysis, a design procedure for knock-off device is proposed as follows :

(1) The necessary section area for the anchor dowel should be determined to be the section ares that can resist the extraction force from the moment of overturn that is generated by wheel and brake loads as shown in Figure 13.

(2) The resistance which can be calculated by the same plastic equilibrium theory as stated in foregoing 3.1 should be lower than either the bearing reaction force due to dead load or the force when the girder deck might fracture.

(3) Energy absorption due to the slide of knock-off element should be carefully estimated if its damping effect to the response amplitude of girder would be considered



$$P=\frac{Wl+Hh}{b}$$

Fig. 13 Design load of anchor dowel

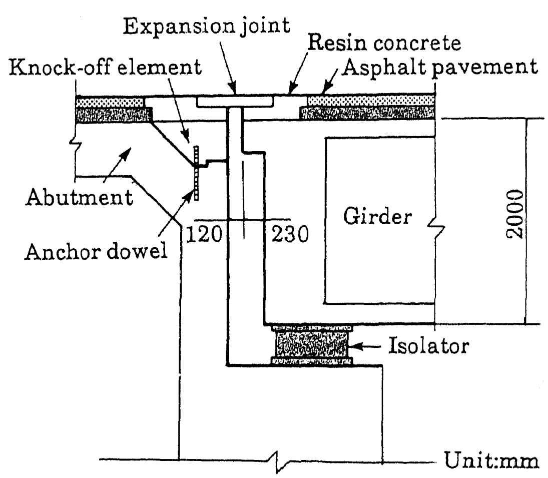


Fig. 14 Knock-off device applied to a bridge

5 FIELD STUDY

A set of this type of knock-off devices was applied to an actual base isolated bridge as shown in Figure 14. As the abutment of this bridge is a box culvert type, a full wedge type knock-off element was used. Strains in the anchor dowel due to the heavy wheel load were measured by the strain meters attached to the dowel. The measured strain was 10^{-5} at maximum and the stability of the knock-off device against heavy traffic load was assured.

6 CONCLUSION

(1) Resistance when the knock-off element slides toward the backfill can be analyzed by using the plastic equilibrium theory. The resistance mainly arises from asphalt pavement and anchor dowel. In particular, the asphalt pavement resistance with dynamic load reaches a level that is several times that of static load, and it is important to adequately estimate the rigidity and the strength of asphalt pavement.
(2) Backfill material of the knock-off element causes wedge-shaped slip damage. In the case of the static loading test, damage occurred when the surface of the asphalt pavement rose up and buckled, but in the case of the dynamic loading test, the asphalt peeled up and the knock-off element crept under it. Improvement of the design so that the knock-off element normally creeps under the pavement is desirable to insure the driving safety of automobiles during and immediately following an earthquake.
(3) Repair of damaged backfill material and pavement in a wedge is relatively easy. Design improvements on anchor dowel are needed because it damages the concrete at the point where it is attached.
(4) Non-linear FEM simulation well analyzes the experiment results. The cohesion of asphalt pavement was identified through the analysis as 1,200kPa and the elastic module were as 2.0×10^5 kN/m^2 for static loading and $4.7 \times 10^5 kN/m^2$ for dynamic loading.
(5) Field study showed that the strain in the anchor dowel when a heavy wheel load acts on the knock-off element is small enough and the design method proposed for anchor dowel assures the sufficient stability of the element against daily traffic loads.

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