ASEISMATIC REINFORCEMENT OF VIADUCT FOUNDATIONS




Keiichi Nishiwaki*, Torajiro Fujiwara***, Akiyuki Watanabe**, Yasuo Watanabe***

In the current design of railway structures, we do not count the effect of soil resistance at the front of columns and concrete laid over the ground (hereinafter "foundation slab"), since it is difficult to assess the effect that the ground brings to structures in case of earthquakes.

We thought that adding foundation slabs to existing viaducts would be a simple aseismatic reinforcement method for viaduct foundations based on the appropriate consideration of the effect of soil resistance at the front of columns and the foundation slabs. Upon this assumption, we carried out centrifugal loading tests using downsized test models of a viaduct and a foundation slab.

The tests proved that surface ground and foundation slabs decrease the horizontal force of earthquakes to the foundation. Thus it was clear that setting a foundation slab could be an aseismatic reinforcement method for viaduct foundation.

Keywords: **Aseismatic reinforcement, Foundation, Foundation slab, Surface ground**

1 Introduction

Aseismatic reinforcement against large-scale earthquakes is ongoing in improvement of existing structures such as stations. Sometimes we decide aseismatic reinforcement of foundation is necessary after examination, but it is more difficult to take aseismatic measures for underground foundations than for upper structures. Usually we make reinforcement by means such as enlarging footings and increasing piles, but such reinforcement requires large-scale construction involving excavation and soil retaining that causes higher construction costs and longer construction period. Thus, simpler reinforcement is required.

In considering the underground resistance of structures, we can assume soil resistance at the parts shown in Fig. 1. In the current design of foundation of railway structures1), however, we only may count the resistance at the front of footings that are filled back in well. But if we could appropriately assess the effect of factors such as frontal resistance at the front surface of columns and the foundation slabs on the ground, we would be able to make more efficient reinforcement.

We therefore carried out centrifugal loading tests using a downsized test model. The purposes of the tests were to prove that surface ground and foundation slabs can be resistance elements against horizontal force in earthquakes, considering the damage to viaduct structures caused by past earthquakes, and to establish a simple reinforcement method for viaduct foundations. We will report the test results in this paper.

2 Instance where Surface Ground and Foundation Slab Functioned as Resistance Elements in Earthquakes

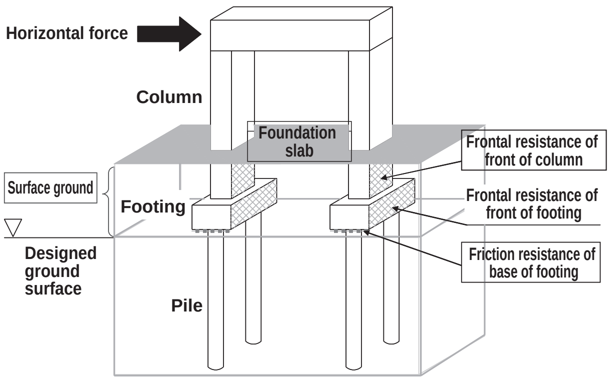

Fig.1: Model of Soil Resistance Points

At the Mid Niigata Prefecture Earthquake in October 2005, we faced an instance where shear failure occurred to the upper part of a rigid-frame viaduct that had been determined by quake resistance analysis not to be a type where shearing occurs first. That failure occurred because surface ground (filled back soil) and foundation slabs bound the middle part of the viaduct.

In this chapter, we will overview the damage to the No. 3 Wanatsu viaduct on the Joetsu Shinkansen line, which suffered shear failure in spite of the favorable analysis results in beforehand.

* TEKKEN Corporation (Previously at Frontier Service Development Laboratory)
** Frontier Service Development Laboratory, Research and Development Center of JR East Group *** Construction Engineering Center, Construction Dept.

2.1 Damage to No.3 Wanatsu Viaduct[2)]

The R2 frame of No. 3 Wanatsu viaduct is a one-layer rigid-frame viaduct with three spans and having a spread foundation. The columns were filled back with soil to half their height, approx. 4.0 m. The columns also had snow melting bases equipped with sprinkler units on the viaduct as shown in Fig. 2. A 15 cm-thick foundation slab (concrete slab on grade) was placed for the snow melting base and the slab was supported by piles so as not to carry the load of the base to the viaduct. These piles were steel pipe piles of 318.5 mm diameter and approx. 5.0 m long placed at approx. 3.5 m intervals longitudinally on the both sides of the track.

The earthquake caused serious shear failure on the columns at the both ends of the viaduct and flexural cracks were predominant on the columns in the middle of the viaduct. Fig. 3 shows the damage of one of the columns with shear failure at the end of the viaduct. Those columns at the end were shorn off on the ground. Main reinforcement was bent greatly and shear reinforcement came off. Concrete buckled out from inside. The damage was so serious that we could not clearly determine the predominant damage direction. On the contrary, we only found some falling-off, slight blistering and flexural cracks of concrete on corners when we excavated the surface ground to survey the columns as shown in Fig. 4 and 5.

2.2 Horizontal Resistance of Surface Ground and Foundation Slabs

Based on the damage of columns and the underground survey results, we think that the reason why shear failure occurred to the viaduct not of the type where shearing occurs first was that the surface ground and the snow melting base (a foundation slab + piles) that is auxiliary equipment bound the horizontal displacement of the columns to the ground and the shearing span of columns became shorter.

In order to verify the phenomenon, we carried out the static non-linear analysis using two-dimensional FEM (Finite Element Method) modeling this viaduct. The analysis results showed that the horizontal force that the surface ground and the foundation slabs received at the time of shear failure of upper columns accounted for about a half of the total horizontal force. This means that the ground in front of columns and foundation slabs functioned as resistance elements against the horizontal force of the earthquake.

We think that the analysis of this instance of damage and the reproduction on the damage proved that surface ground, foundation slabs, and piles placed on the foundation slabs have major reduction effect on the horizontal force of the earthquake to structures.

3 Verification Test of Aseismatic Effect

Based on the instance mentioned in Chapter 2, we carried out verification tests to examine the horizontal resistance effect of surface ground and foundation slabs.

We will explain the detail and the result of the tests as follows.

3.1 Overview of Verification Test

3.1.1 Tested Structure and Ground Conditions

We conducted the tests using a centrifugal loading test device shown in Fig. 6. That device can reproduce the same stress that the actual structure receives to the downsized test model by adding arbitrary gravitational acceleration.

Fig. 7 shows the basic structure of the modeled viaduct and Fig. 8 shows a simplified illustration of the test. The scale of the test model is 1/50. As for the setting to the ground, we specified N = 5 for the assumed surface ground of filled back soil and the intermediate layer and N = 20 for the supporting ground. Controlling density by compaction, we made a model ground.

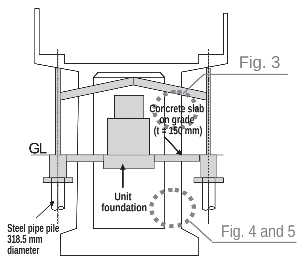

Fig.2: Model of Snow Melting Base

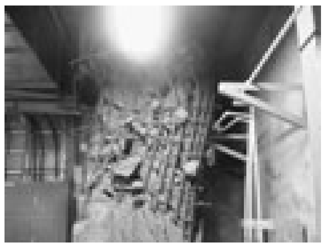

Fig.3: Damage to Column

Fig.4: Concrete Falling at Column Base

Fig.5: Flexural Crack at Column Base

3.1.2 Test Cases

Fig. 9 shows an illustration of the test cases. The purpose of this test was to examine the effect that the presence or absence of a surface ground or foundation slabs has on the earthquake horizontal force to foundation. We therefore made Case 1 without surface ground, Case 2 with surface ground only, and Case 3 with a foundation slab on the surface ground. In order to enhance reinforcement, we additionally made Case 4 with a foundation slab fixed with piles (hereinafter "foundation slab piles") with 50 mm-thick surface ground and 26 mm-thick earth cover from the upper surface of the footing to the upper surface of the foundation slab and Case 5 (36 mm-thick and 12mm-thick respectively). In total, we tested with five cases.

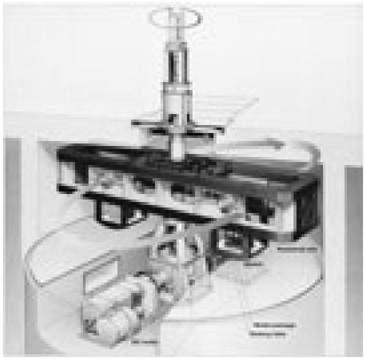

Fig.6: Centrifugal Loading Device

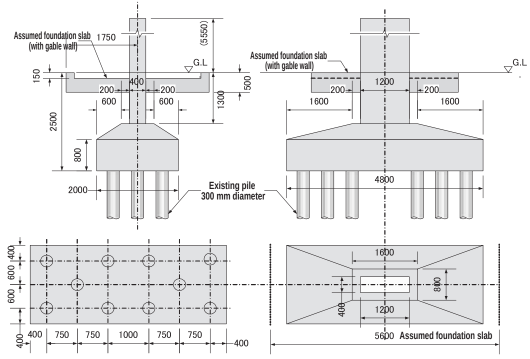

Fig.7: Modeled Viaduct Foundation (Original)

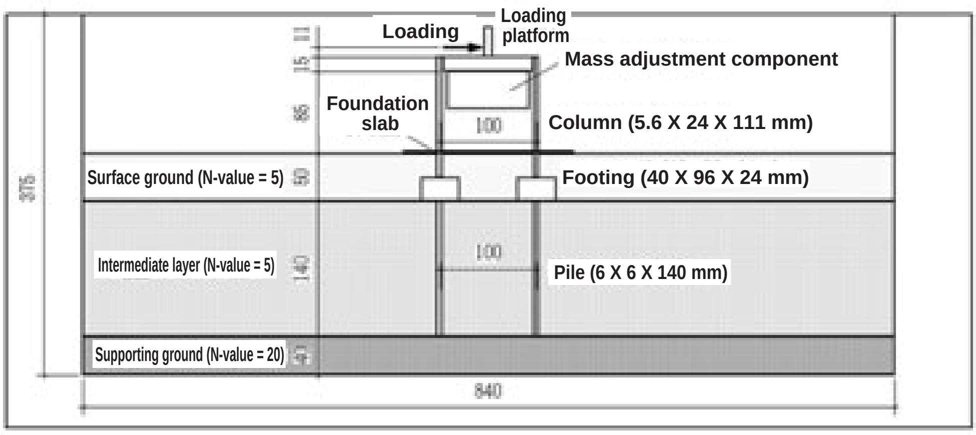

Fig.8: Simplified Illustration of Test

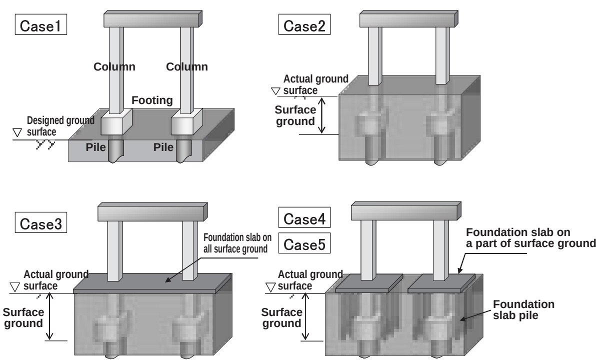

Fig.9: Illustration of Test Cases

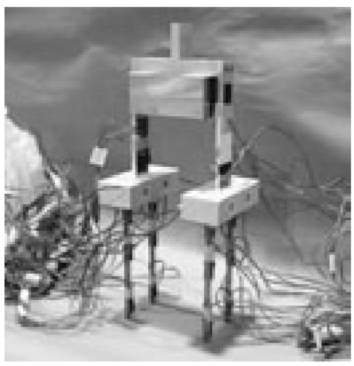

Fig.10: Appearance of Test Model

3.1.3 Test Model Data

We made test models of hard aluminum that mock a rigid-frame viaduct having the foundation structure shown in Fig. 7. Fig. 10 shows the appearance of the model. We specified the width of the components in the right-angle direction of loading to be 1/50 of the actual width of the components of the modeled viaduct, and the thickness of the components in the loading direction to make the bending rigidity of the components of the modeled viaduct and the test model equal to each other conforming to the law of similitude. Then, we converted five piles to be one pile based on the consideration of the effect of the pile group and placed the piles, while the modeled viaduct has pile groups of 10 piles per group for a footing.

Table 1 shows the data for each test model.

Foundation slab piles of Case 4 and 5 were assumed and modeled as BH (Boring Hole) piles or steel driving piles that are easy to place even under a viaduct of low overhead clearance.

3.1.4 Test Method

As shown in Fig. 8, we added static loading to a loading platform on the viaduct model at 0.03 mm/sec. horizontal displacement control. Tests were carried out in a centrifugal field of 50G created by a centrifugal loading device.

We measured the horizontal displacement of the loading point with a laser displacement meter to observe the deformation of the test model. And we measured the strain of the model with strain gauges attached to the columns and piles to understand the stress affecting upper structure and piles.

All the test results shown hereafter are the values of the test data converted into those for the actual structure.

3.2 Test Result

3.2.1 Relationship Between Loading and Displacement

Fig. 11 indicates the relationship between loading (P) and the horizontal displacement of the loading point (δ , hereinafter "displacement"). The relationship differed greatly with and without the surface ground and the foundation slab. As to the effect of the surface ground, the displacement of Case 2 (with the surface ground) fell to approx. 40% compared with that of Case 1 (without the surface ground) at the load P = 500 kN, and the displacement of Case 4 (with the thick surface ground) also fell to approx. 71% that of Case 5 (with the thin surface ground). Such decrease of the displacement depending on the surface ground and its thickness proves that the surface ground can be evaluated as the horizontal reaction force.

As to the effect of the foundation slab had on the relationship between loading and horizontal displacement, the displacement of Case 3 (with the foundation slab) at the load P = 500 kN fell approx. 14% compared that of Case 2. Moreover, we confirmed a 25% reduction over Case 2 in Case 4 with foundation slab piles. This showed that laying foundation slabs improve the horizontal resistance the ground bears.

3.2.2 Distribution of Bending Moment of Piles

Upon the measurement results with strain gauges attached to piles, we calculated curvatures using Formula (1) and bending moments at measured points using the Formula (2).

Curvature $k = (\varepsilon 1 - \varepsilon 2)/H*10^{-6}$ ... (1)

Bending moment $M = EIk$ ... (2)

Table.1: Test Model Data (Scale 1/50)

Case	Thickness of surface ground	Foundation slab (length in loading direction X width in right-angled direction of loading X thickness)	Foundation slab pile (diameter X length X number)
Case1	None	None	None
Case2	50mm	None	None
Case3		112 X 176 X 3.0 mm (slab on all ground)	None
Case4		72 X 70 X 4.8 mm per column (partially placed slab)	6 - 60 mm diameter - 6 piles per partially placed slab
Case5	36mm		

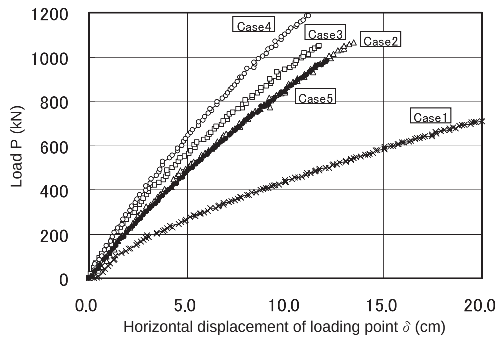

Fig.11: Relationship Between Load and Horizontal Displacement of Loading Point

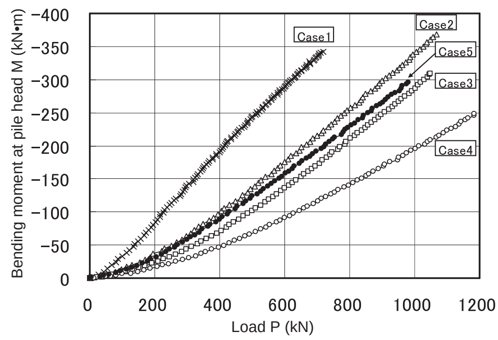

Fig.12: Relationship Between Load and Bending Moment at Pile Head

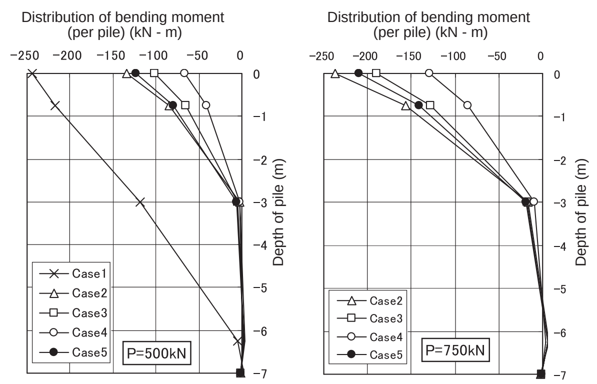

Fig.13: Distribution of Bending Moment (Left: P = 500kN, Right: P = 750kN)

In these formulae,

k : Curvature

ε 1 and ε 2: Strain values measured

H: Interval of strain gauges

E: Elastic coefficient

I: Geometric moment of inertia

Fig. 12 indicates the relationship between loads and bending moments at the pile head per pile of the modeled viaduct, and Fig. 13 illustrates the distribution of bending moments of each case at P = 500 kN and P = 750 kN. The values shown in Fig. 13 are average bending moments per pile of all four piles of the test model. Since Case 1 did not reach P = 750 kN, the distribution of bending moments at P = 750 kN in Fig. 13 includes no data of Case 1.

Comparing test cases excluding Case 5 (with surface ground of other thickness), the bending moment at the pile head at P = 500 kN was at the maximum with Case 1, and fell in the order of Case 2, 3, and 4. We found the same tendency at the increased load of P = 750 kN too; that is, the bending moment at the pile head fell from the value with Case 2 by 18% with Case 3 and by 46% with Case 4.

These results proved that with appropriate consideration of surface ground and foundation slabs we can decrease the bending moment to piles, and that fixing a foundation slab with piles etc. can further decrease such bending moment.

3.2.3 Distribution of Shear Force to Piles

We figured out the distribution of shear force to piles by differentiating bending moments of piles in the direction of depth. Fig. 14 shows the relationship between loads and shear force at the pile head, and Fig. 15 indicates the distribution of shear force for each case at P = 500 kN and P = 750 kN. The shear force here is the total of the shear forces to all piles.

The shear force of Case 2 at the pile head of P = 200 kN was lower than that of Case 1 by approx. 14%. This would be because the surface ground in front of piles and footings carried a part of the horizontal force.

Looking at the effect of the foundation slab, the shear force of Case 3 at the pile head of P = 750kN lowered from the shear force of Case 2 by approx. 22%. We assume this is because foundation slabs controlled deformation of the ground and that increased the horizontal force the surface ground carried.

The shear force of Case 4 at the pile head of P = 750kN fell greatly to approx. 55% of Case 2.

These results also lead us to the conclusion that surface ground and foundation slabs, and fixing foundation slab with piles too, have the effect in decreasing earthquake horizontal force transmitted to the foundation.

4 Conclusion

The instance of the damage of a viaduct in the Mid Niigata Prefecture Earthquake and this series of verification tests proved that foundation slabs could decrease the earthquake horizontal force carried to the viaduct foundation. We also confirmed that fixing foundation slabs with piles further decreases such horizontal force; hence, this method can be a simple reinforcement measure for viaduct foundations.

In order to develop this method into an actual reinforcement for viaduct foundation, we are now reviewing the design method too3).

We are planning to carry out experiments on the interference effect between footings and foundation slab piles when those piles are placed to make more appropriate evaluation of horizontal resistance of surface ground and foundation slabs. We will incorporate the experiment results in the design.

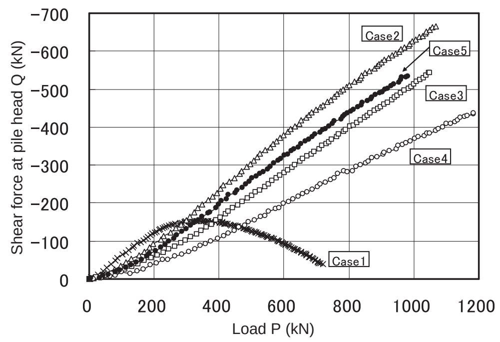

Fig.14: Relationship Between Load and Shear Force

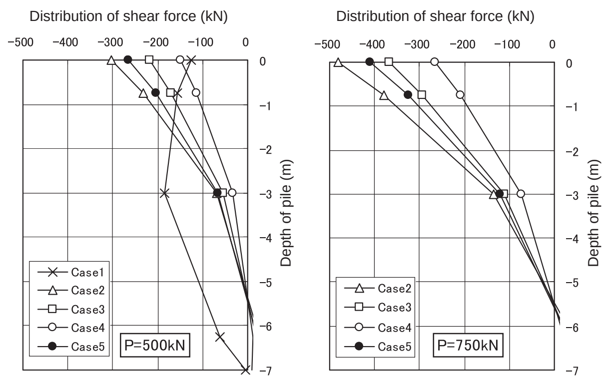

Fig.15: Distribution of Shear Force (Left: P = 500 kN, Right: P = 750 kN)

Reference:

1) Railway Technical Research Institute "Design Standard of Railway Structure and Commentary: Foundation and Structure Resistant Against Earth Pressure", Maruzen Publishing, June 2000
2) Torajiro Fujiwara, Takeshi Tsuyoshi, Ikuo Hagiwara, Hiroki Aoto "Consideration on Earthquake Damage of Railway Viaduct That Is Bound at Column Middle by Foundation", The 28th Japan Concrete Institute Annual Theses pp. 907 - 912, July 2006
3) Torajiro Fujiwara, Keiichi Nishiwaki, Yasuo Watanabe, Akiyuki Watanabe "Temporary Design of Aseismatic Reinforcement Using Foundation Slab", Structural Engineering Center of JR East SED No. 27, pp. 30 - 41, November 2006