Development and Application of Aseismic Reinforcement Method for Railway Earth Retaining Structures

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Earth retaining structures, such as bridge abutments and retaining walls, are constructed at the boundary of bridges or embankments. There are a variety of earth retaining structure failure modes, therefore in order to be able to ensure rational aseismic reinforcement, it is necessary to develop a range of different aseismic reinforcement methods adapted to the relevant earth retaining structure’s failure mode. Moreover, there are many cases where construction work is severely restricted due to various limitations, such as land boundaries, available space, and time available for construction work. Therefore, the authors propose an aseismic reinforcement method, which can both improve seismic performance of earth retaining structures and be carried out efficiently. This paper outlines this research and describes some examples of the practical application of the newly developed reinforcement method.

Keywords: earth retaining structure, aseismic reinforcement, soil reinforcement

1. Introduction

This paper presents the development and applications of aseismic countermeasures for earth retaining structures such as bridge abutments and retaining walls. In the 1995 Hyogo-ken Nanbu Earthquake, not only bridges and viaducts but also many earth retaining structures were severely damaged. In response to this, what is known as level 2 seismic motion is now considered in the Japanese railway design, and aseismic reinforcement of existing structures is being implemented to ensure the seismic performance of the railway structures. Aseismic reinforcement of bridges and viaducts, to prevent shear failure is now almost complete in Japan. Now, implementation of aseismic countermeasures for existing earth structures, earth retaining structures, and bridge foundations has begun.

Figure 1 shows conventional aseismic reinforcement methods applied to a bridge abutment: strut work, injection method with sheet pile shut-off work, and installation of ground anchors or soil reinforcement. Figure 2 illustrates a typical type of aseismic reinforcement method applied to a masonry wall by soil reinforcement with additional RC facing construction. However, carrying out these reinforcement methods requires occupying a large space in front of the structure during construction. In locations where space is limited, such as in urban areas, construction itself often becomes difficult due to site restrictions and the construction environment. Nevertheless, the vast number of existing earth retaining structures and structures requiring aseismic reinforcement in urban areas, means that there is strong demand for the development of an economical aseismic reinforcement method that can be applied even on sites subject to severe constraints.

This paper reports on the research, development and application of aseismic countermeasures for earth retaining structures that can not only secure performance against level 2 seismic motion but are also suitable for these restrictive construction conditions in urban areas.

2. Aseismic reinforcement of bridge abutments

Following massive earthquakes in Japan, many cases in of residual sliding and tilting displacement of the abutment and associated backfill settlement were observed. Residual displacement of the abutment and settlement of the backfill soil results in relative displacement between the abutment and the backfill. In the case of railway structures, this relative displacement causes a significant track irregularity, which has a direct impact on train running...
safety. Therefore, aseismic reinforcement work on existing bridge abutments has been carried out over the past few years. Especially in urban areas, there are many old conventional bridge abutments, which must be reinforced. However, conventional aseismic reinforcement would involve occupying the roads and tracks in front of the abutment, whilst work is carried out, as shown in Fig. 1. This makes aseismic reinforcement of bridge abutments in urban areas very difficult, and can drive up the cost of reinforcement work.

Therefore, the authors developed three different aseismic countermeasures that can reinforce existing bridge abutments effectively whilst minimizing occupation of the surrounding area. The proposed aseismic countermeasures are outlined below:

1) Aseismic reinforcement method by connecting the soil reinforcement and abutment;
2) Aseismic reinforcement method by ground improvement of backfill soil;
3) Steel girder/abutment/embankment integrated bridge (named as Nailed Reinforced Soil bridge abutment).

This chapter introduces an outline of the aseismic reinforcement methods and gives examples of their application.

2.1 Aseismic reinforcement by soil reinforcement

Figure 3 shows the outline of a proposed aseismic reinforcement method using the soil reinforcement. In the proposed method, the bridge abutment is connected with the reinforced soil retaining wall. The reinforced soil retaining wall is constructed by cutting the existing backfill embankment with the soil reinforcement installation. The abutment resistance against the seismic load increases by integrating the reinforced soil retaining wall and bridge abutment. This method is not only able to increase the stability of the abutment, but can also strengthen the backfill embankment and wing wall adjacent to the abutment, since the backfill embankment becomes a reinforced soil retaining wall, as schematically illustrated in Fig.3(a).

The reinforcement of the adjacent wing wall and backfill embankment can also contribute to reducing settlement of bridge abutment backfill.

Although this reinforcement has slightly less effect than multiple soil reinforcement, an alternative method is to conduct soil reinforcement at the top of the backfill embankment and connect it to the abutment with steel material (Fig. 3(b)).
The authors examined the effect of the reinforcement using tilting model test and shaking table model tests. The shaking table model test was conducted using a 1/8th scale model of the gravity type abutment. Figure 4 shows the situation after applying sinusoidal shaking with a maximum acceleration of 500 gals. The figure shows that the reinforcement significantly reduces both residual displacements of the bridge abutment and settlement of the backfill.

The authors also proposed a design method which follows the current design standard using a pseudo-static pushover analysis of the frame, with soil springs and a nonlinear response spectrum method. The trial calculation with the dimensions of the actual structure showed that the reinforcement effect was sufficient, even against Level 2 earthquake motion.

Applying the method to actual structures was considered, and a schematic view of the reinforcement plan is shown in Figs. 5 and 6. The target structures were an overpass and embankment straddling a railway track. This method was considered for application on this site since construction work from the front of the abutment can be significantly reduced, and both the abutment and the embankment can be simultaneously reinforced. The detailed design has now been completed, and adjustments are underway toward the start of construction.

2.2 Aseismic reinforcement by columns of soil improvement

Figure 7(a) is a schematic view of the aseismic reinforcement method achieved by constructing the columns of soil improvement in the backfill soil, which reduces the displacement of the bridge abutment and settlement of the backfill soil by reducing the earth pressure through the effect of soil improvement columns. Reinforcement work from the front of the abutment can be omitted since the soil improvement columns are created from the track surface.

Figure 7(b) shows another method which was proposed, to increase the reinforcement effect by connecting the abutment with the improved soil. However, this method requires construction from the front of the abutment.

The improved soil columns can be constructed by mechanical agitation or jet agitation using a low head machine with a height that does not hinder the overhead line. A preliminary stability analysis conducted for the bridge abutment supporting double tracks was used to determine the details for installing the soil improvement columns. As such, the columns were installed along the center and along the outside of each track; the soil improvement columns with a diameter of 800 mm were aligned evenly with a wrap length of 150 mm; the improved depth was almost the same as the height of the abutment; the strength was set to about 1 to 5 N/mm² depending on the quality of the backfill soil.

A series of reduced scale shaking table model tests verified the effect of the proposed aseismic countermeasure. Figure 8(a) shows the relationship between residual wall displacement and the maximum base acceleration, and Figure 8(b) shows the situation of the abutment and
backfill soil after the shaking. Detailed analysis of the interrelation between the abutment and improved column clarified the reinforcement mechanisms. The improved soil columns contribute to reducing the seismic earth pressure.
regardless of the connection between the abutment and soil column. Additionally, two different reinforcing effects are mobilized by the connection between the abutment and improved soil column. First, the connected improved soil column works effectively to increase resistance against the overturning of the bridge abutment. Second, horizontal resistance also increases thanks to the mobilization of frictional resistance between the improved soil column and backfill soil. Figure 8(b) shows that when the abutment and the improved soil were connected, even if the width of the improved soil is halved (Case 4), the improvement effect was the same or better as the case without the connection (Case 2). On the basis of the model test results, the authors proposed a design method based on the current seismic design method, as described in Section 2.1.

Figure 9 shows an application example of the method. In this example, the method is applied as aseismic reinforcement of the abutments supporting double tracks. Columnar improvement of soil is constructed to sandwich each track. Two lines of improved soil columns are constructed if the interval distance of the track is relatively large.

Since the line closure time between the last and first train of this section was only 3 hours, the shape of the improved soil column was changed from a circular shape with an improved diameter of φ800 mm, to a semicircular shape with an improved diameter of φ1400 mm, which results in shortening the construction time of the improved soil column.

2.3 Aseismic reinforcement by structural integration

Many existing old bridges are built using the conventional gravity type abutment and steel girder, which have to be reinforced or replaced. However, the replacement of existing bridges is time consuming and expensive, because of the need to install and remove temporary line girders and abutments. Therefore, the authors proposed an aseismic reinforcement methodology and life extension method which uses structural integration without replacing the existing bridges.

Soil reinforcement from the front side of the bridge abutment works by integrating the abutment with the backfill embankment. The reinforced concrete also unites the steel girder and abutment to extend the structural life and earthquake resistance of aged girders and abutments without replacing the steel girders (See Fig. 10).

By integrating the steel girders and the abutment, maintenance of the bearing can be omitted. The steel girder’s supporting condition changes from simple vertical support to multiple constraint conditions (i.e., vertical, hori-
The moment ion example of the proposed structure of steel girders and abutments behave as a rigid frame structure, in which passive resistance of the backfill soil on the opposite side of the abutment is also expected. Second, structural weakness of the bearings is eliminated. Third, frictional resistance mobilized by the soil reinforcement works to resist against seismic thrusts.

Soil reinforcement from the front side of the bridge embankment. The reinforced concrete also unites the steel girder and abutment to extend the structural life of aged steel girders. Moreover, seismic performance is dramatically improved by structural integration based on three different mechanisms. First, the structure of steel girders and abutments behave as a rigid frame structure, in which passive resistance of the backfill soil on the opposite side of the abutment is also expected. Second, structural weakness of the bearings is eliminated. Third, frictional resistance mobilized by the soil reinforcement works to resist against seismic thrusts.

In the development of the method, model tests, member tests for corner reinforcement, and model tests for integrated reinforcement of abutments and backfill soil were conducted, and insight was gained into essential characteristics such as overall behavior and member behavior during an earthquake.

Figure 11 shows an application example of the proposed method. Initially, the bridge’s replacement was planned, but the proposed method was applied since the reduction of the construction cost and the construction period was expected. In the example, to improve the unreinforced abutment’s yield strength, steel bars were first inserted vertically into the abutment. Then anchors were placed from the abutment’s front to integrate the backfill soil and the abutment. Finally, the corners of the steel girder and abutment were integrated with reinforced concrete.

To check performance after construction, confirmation was obtained to ensure that the deflection generated at the girder with a passing train was reduced to 1/2 to 1/3 compared to before construction. Furthermore, it was confirmed that the noise level of passing trains also dropped.
3. Aseismic reinforcement of retaining wall

In Japan, there are more than 250,000 earth retaining walls along the railways, with masonry retaining walls making up the largest share. Masonry retaining walls were used as earth retaining walls before the development of concrete, and many cases of masonry retaining wall collapsing have been reported during large-scale earthquake. Masonry walls resist earth pressure by combining friction between each block and because the wall leans towards the backfill soil, though they are not physically joined. Therefore, if part of a block from the facing is dislodged, the wall tends to show catastrophic failure.

As illustrated in Fig. 2, ordinarily aseismic reinforcement of the masonry wall is achieved by combining the installation of soil reinforcement and constructing a rigid RC facing in front of the existing masonry retaining wall. However, many cases erecting a concrete wall is difficult because of limited construction space along the railway line. In addition, there are many obstacles, such as electric equipment that is difficult to remove and relocate on the masonry wall surface.

Therefore, as schematically illustrated in Fig. 12, a method has been proposed in which nets, wire nets, etc. are installed in front of the masonry wall, and soil reinforcements are installed to stabilize the backfill soil (net reinforcement method). The advantage of this method is that it does not require relocation of obstacles such as cables installed on the front of the retaining wall and that it does not require the construction of RC facing so that it can be installed in a narrow space. In addition, adopting injection-based soil reinforcement, provides a large resistance force with a small diameter and allows use of compact construction machines, thereby improving the workability of aseismic reinforcement.

The performance of this method was verified using shaking table model tests. Figure 13 shows the situation after the shaking in the model tests. In the case of no countermeasure, the blocks fell out, and the wall collapsed after shaking at 400 gals, whereas with reinforcement, the wall remained intact, albeit with a minor displacement, even after shaking at 800 gals. On the basis of these results, a design method was also proposed. Trial calculations confirmed that the general masonry retaining wall can be reinforced using the proposed method even against level 2 earthquake motion.

Figures 14 show examples of this aseismic reinforcement work to an existing masonry wall. In this case, the proposed method was applied for the reinforcement of an existing masonry wall with a height of about 7 m. An electronic cable was attached across the whole surface of the masonry wall, and it was difficult to build a RC wall. Soil reinforcements with a diameter of 110 mm were installed with horizontal and vertical spacing of 1 m. The net material used on the site was made of corrosion-resistant high-strength hardened steel wire considering the need for long-term durability and flame retardancy.

4. Summary

This report outlines seismic retrofitting methods for abutments and retaining walls that can be applied even in severely constrained conditions and describes examples applying the methods. Studies using model tests and numerical analysis were carried out for developing aseismic countermeasures. This research clarifies that the seismic performance of old existing structures can be effectively improved, even against massive earthquakes, by applying the proposed aseismic countermeasures. However, it is considered that the optimum reinforcement specifications need to be adjusted in accordance with the conditions of the existing structure. As a further study, the authors plan to collect and analyze application examples to develop optimized reinforcement specifications and a method to assist selection of the appropriate reinforcement method.

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