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The supporting effect of pipe wing rib designed to achieve early contact between ground and steel arch tunnel support

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Abstract: In the construction of mountain tunnels, reaction forces of the legs of steel arch supports against the ground are often expected to support the ground being excavated. In these cases, a stress concentration occurs in the ground directly under the support legs. If the bearing capacity of the ground is insufficient or displacement is not effectively constrained, the local failure of the ground under the support legs or settlement of the tunnel supports due to large deformation could result. It is therefore necessary to reinforce the support legs to reduce settlement. As a means of reducing settlement, wing-ribbed steel arch supports are well used. In this study, with the aim of finding a way to quickly reduce the settlement of steel arch support legs, effectiveness of a new type of wing ribs to reinforce steel arch supports was investigated through laboratory testing.

1. Introduction

Measures to stabilize the legs of steel arch tunnel supports are taken mainly to prevent tunnel instability in cases where the bearing capacity of the supporting ground is insufficient and the ground is plasticized by the load of thesinking of the arch support legs and stress concentration. Widely used methods include enlarging the bearing area of tunnel support legs, forming a temporary invert for the upper half of the tunnel cross section by shotcreting, and increasing the bearing capacity by placing rock bolts or leg piles downward into the ground under the arch support legs. Conventional wing-ribbed steel arch supports (hereafter it is called as "conventional wing ribs") used as a means of stabilizing arch support legs transfer axial forces through the arch support ribs and increase the bending moment capacity of the base plate sections in order to increase the load-bearing capacity of steel arch supports by enlarging the bearing area of the arch support legs. Even in the case of conventional steel arch supports, however, a confining pressure from the shotcrete surrounding the tunnel supports should increase the bending moment capacity because the supports are structurally integrated with the shotcrete. Therefore, it should be possible to make effective use of the bearing capacity of the tunnel supports by devising reinforcing members that are capable of transferring large axial forces. The authors thought, however, that because of their structural characteristics, conventional wing ribs allow the occurrence of voids between the tunnel support and ground, even if the ground under the base plate is flattened meticulously, so that a certain amount of ground settlement occurs before axial forces are transferred.

The authors developed a steel arch support with a wing pipe (hereafter it is called as a "pipe wing rib") to quickly reduce the settlement of an arch support leg by enlarging the area of contact between the arch support and the ground and ensuring full contact with the ground so as to make fully effective use of steel arch supports. This study aims to determine the load-carrying capacity of the newly developed pipe wing rib system through laboratory test.

2. Development of the pipe wing rib system

Conventional wing ribs: problems and considerations

In a typical steel arch support with a conventional wing rib, a rib is installed on the outside of the support flange to enlarge the bearing area of the base plate and thereby increase the bearing capacity of the ground. Excavating the ground, however, following the contour of a rib of this type is very difficult, and, because of the peculiarity of shape, excavation itself is a dangerous task. Shotcreting is usually carried out with the aim of achieving integrity with the ground. Since, however, sprayed concrete does not reach the region under the base plate of the wing rib, voids and loose regions often occur between the wing rib and the ground, making it difficult to reduce settlement so as to achieve full contact between the rib and the ground. Thus, the problem is that the additional supporting effect

Photo 1. Pipe wing rib.

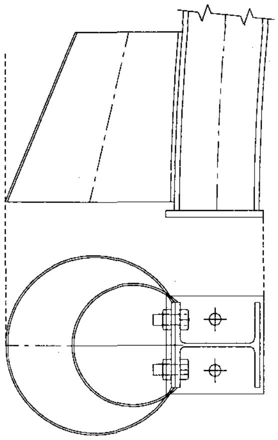

Figure 1. The shape of pipe wing rib..

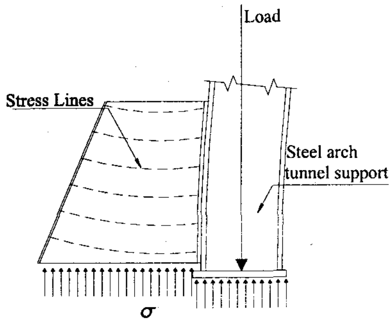

Figure 2. The mechanism of ground support.

of the wing rib cannot be expected immediately after the steel arch support is constructed, that is, when the stiffness of the steel arch support is most needed. It is possible to carefully flatten the excavated ground under the wing rib in order to prevent such a problem, but doing so would make the excavation even more dangerous.

Development of the pipe wing rib system and its design concept

As shown in Figure 1 and Photo 1, the pipe used in a pipe wing rib is a truncated cone formed by a thin steel plate. This steel pipe is removable and can be bolted on, either directly or indirectly through a connector plate, to the flange plate or the web plate of a steel arch support leg according to the site conditions. Therefore, it does not need to have been welded in outdoor beforehand, as in the case of conventional wing ribs. The pipe wing rib is also designed so that early contact between the steel arch support and the ground can be achieved by shotcrete into the pipe.

As concrete is sprayed into the truncated-cone pipe of the pipe wing rib, the reaction force acting on the pipe wing rib turns into the reaction force resultant consisting of the reaction force acting on the steel arch support base plate and the reaction force in the cross section of the shotcrete placed across the underside of the pipe wing rib base plate. The reason for this is as follows. As shown in Figure 2, even before the concrete in the pipe wing rib hardens, the concrete is confined by the inside surface of the pipe so that loads from the ground are supported by the arch action of the concrete. Although the reaction force causes not only axial force but also bending moment and shear force, these forces are resisted by the shotcrete surrounding the pipe wing rib acting integrally with the pipe wing rib.

The installation of a pipe wing rib requires working space around the steel arch support leg, but the pipe wing rib is easy to install because there is no need to carefully flatten the ground surface. Pipe wing ribs are lightweight and easy to handle, and full contact with the ground and the required bearing area can be achieved by filling the pipe with shotcrete or fresh concrete. To verify the effectiveness of the pipe wing rib in reducing support leg settlement and increasing bearing load capacity, particularly under initial loads, a compression test was conducted under laboratory conditions.

3.Verification of the supporting effect

Test method

To verify the supporting effect of the pipe wing rib, a full-scale laboratory test was conducted using two types of wing ribs (conventional wing rib, pipe wing rib) as models of steel arch support as shown in Figure 3. For both types of wing ribs, an underside width of 650 mm was used. The pipe wing rib models were filled with either gravel (10 mm or smaller crushed stone) or pit sand (washed sand) as a substitute for shotcrete. The pipe wing rib consisted of a wing pipe formed by a 3.2 mm thick steel plate bolted on to steel arch support. The combined area of the underside of the pipe wing rib and the underside of the steel column was 2,172 cm^2. In the test, 10 mm or

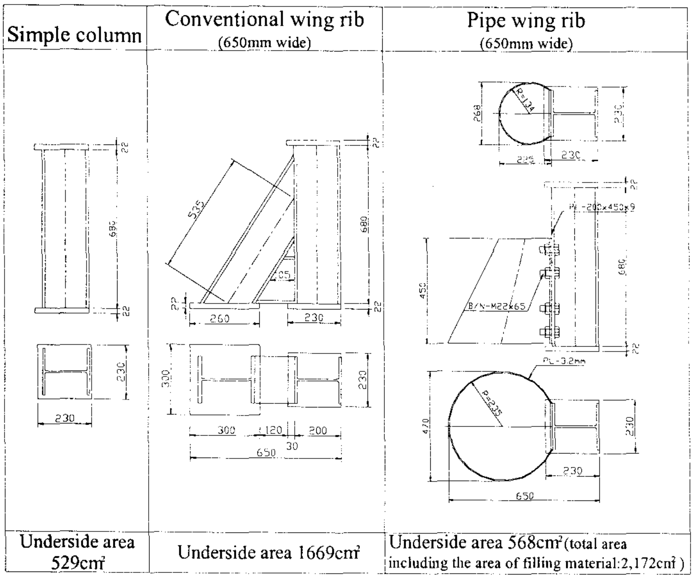

Figure 3. Three modek of steel arch support.

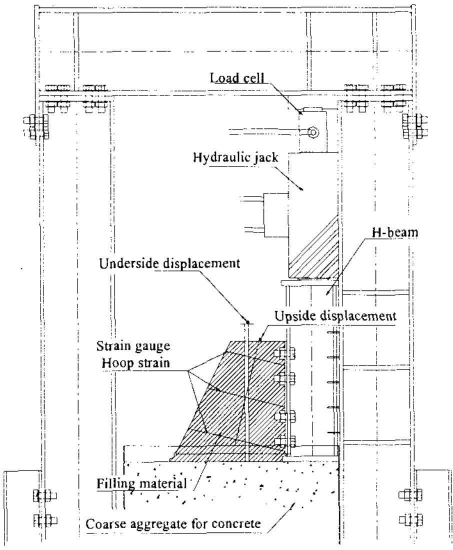

Figure 4. Compressoion test.

Table 1. Compression test patterns.

		Underside area	Filling material	Soil material
Pattern 1	Simple column	529cm^2	•	Aggregate (10mm or smaller)
Pattern 2	Conventional wing rib	1669cm^2		Aggregate (10mm or smaller)
Pattern 3	Pipe wing rib	568cm^2 (※2172cm^2)	Pit sand (washed sand)	Aggregate (10mm or smaller)
Pattern 4	Pipe wing rib	568cm^2 (※2172cm^2)	Aggregate (10mm or smaller)	Aggregate (10mm or smaller)

* Total underside area including the underside area of the filling material

smaller coarse aggregate for concrete was laid to simulate the ground, and the test specimen was placed directly on the aggregate. After the test specimen was placed, loads were applied by using a hydraulic jack so that axial force was directly applied to the steel arch support through a load cell. Loads were applied in 50 kN steps. Loading was continued for a total of eight minutes. The first measurement was taken after two minutes of loading, and the second and third measurements were taken three minutes and six minutes later, respectively. After confirming that settlement had converged after a total of eight minutes of loading as mentioned above, loads were applied from 0 to 500 kN. During the loading, stress in the thin steel plate (hoop stress), behavior of the filling material, and settling displacement were measured at 50 kN intervals for the pipe wing rib to test the functions of the pipe wing rib. For comparison with the pipe wing rib, settling displacement of the conventional wing rib was also measured.

Results of the comparative test

Figure 5 compares the amounts of settlement of the conventional wing rib model and the pipe wing rib models with the different types of filling materials, along with the loads applied to each model. As the figure clearly shows, the load applied to the pipe wing rib begins to increase at smaller amounts of settlement than the load applied to the conventional wing rib. This is thought to mean that in the case of the pipe wing rib, a condition equivalent to full contact with the surrounding ground occurs early to cause the reaction force of the support to occur. Comparison for the same amount of settlement reveals that the load-carrying capacities of the pipe wing rib filled with gravel, the pipe wing rib filled with pit sand, and the conventional wing rib are greater in that order. This result also indicates that the supporting effect of the gravel fill, which is less fluid than the sand fill, is greater than that of the sand fill.

As shown in Figure 3, the area of the steel base of the pipe wing rib is 568 cm^2, while the combined area of the steel base plates of the conventional wing rib is 1,669 cm^2. Thus, the area of steel at the base of the conventional

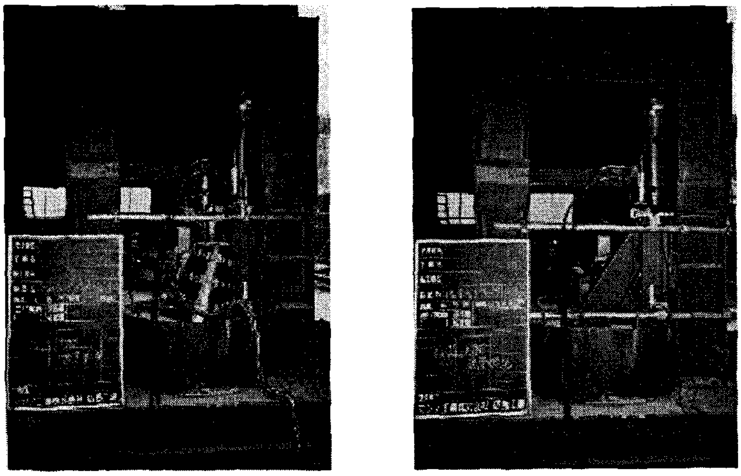

Photo 2. Compression test.

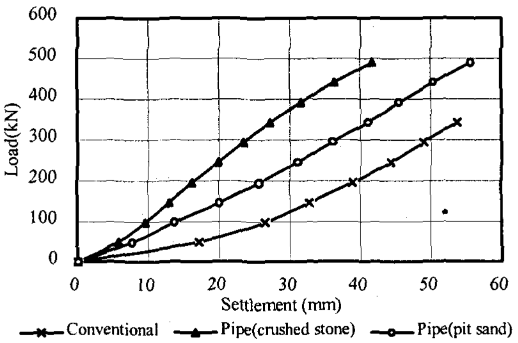

Figure 5. Relationship between settlement and bearing load.

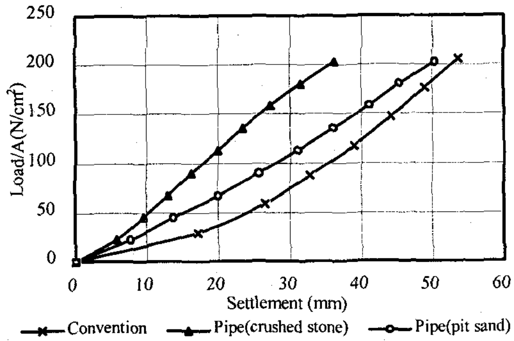

Figure 6. Relationship between settlement and stress in the loading plane.

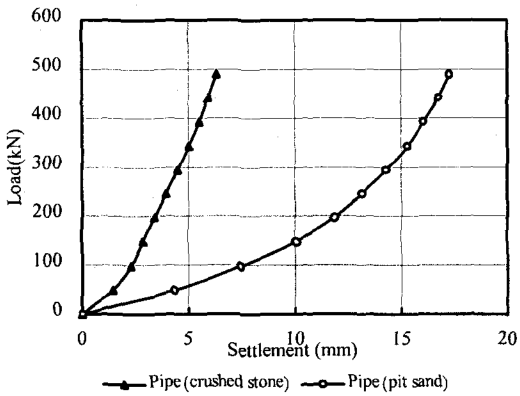

Figure 7. Relationship between settlement t and bearing load.

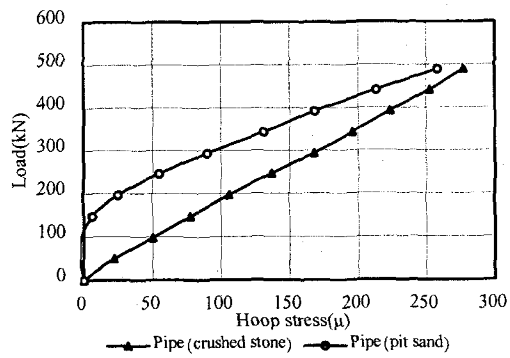

Figure 8. Relationship between hoop stress and bearing load.

wing rib is larger than that of the pipe wing rib by a factor of three, but the bearing capacity of the pipe wing rib is greater than that of the conventional wing rib. This is thought to be because the bearing area was increased by the effect of the sand or gravel fill confined by the pipe wing rib. Therefore, the sum of the area of the steel base plate

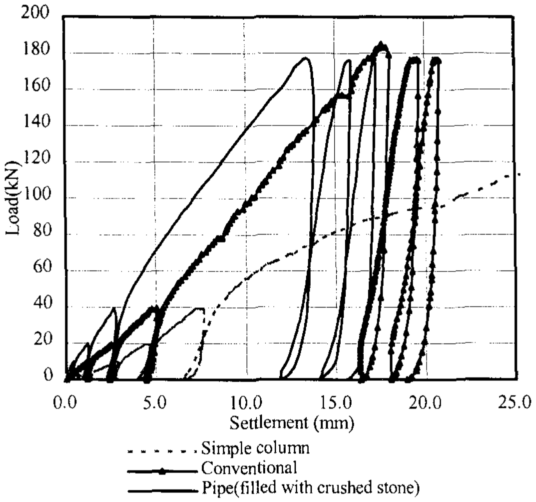

Figure 9. Comparison of settlement under initial loading (0–180 kN).

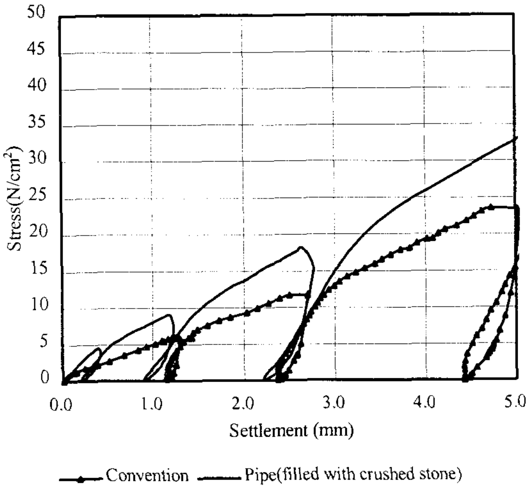

Figure 10. Comparison between settlement and underside stress.

and the area of the filling material (2,172 cm^2) was regarded as the bearing area of the pipe wing rib, and a comparison was made in terms of the bearing capacity (stress in the loading plane) per unit area of contact with the ground. Figure 6 shows the results of the comparison. As can be seen from this figure, the bearing capacities per unit area are roughly the same.

The relationship between load and the consolidation displacement of the filling material shown in Figure 7 shows that the filling material in the pipe consolidates as the load increases, and that the degree of consolidation of the pit sand fill, which is more fluid than the crushed stone fill, is higher than that of the gravel fill. These results can be interpreted to mean that as shown in Figure 2, the filling material is confined by the inside surface of the pipe, and the arch action of the filling material occurs in the rib. This supports the above discussion. The relationship between hoop stress and load shown in Figure 8 also indicates that in the case of the gravel fill, hoop stress increases almost uniformly with load, while in the case of the pit sand fill, little stress acts on the pipe during the initial phase of loading as the applied load increases, indicating that the pit sand fill itself carries part of the applied load.

4. Comparison of effectiveness in reducing initial settlement

Test method

As clearly shown by the results of the supporting effect test mentioned earlier, because of the occurrence of voids and loose regions between the underside of the wing rib and the underlying ground, the settlement-reducing effect of the conventional wing rib cannot be expected until the underside of the rib comes into full contact with the ground. This reduces the effectiveness of the steel arch support at the early stages of excavation. So, a test was conducted to compare and verify the effectiveness of the conventional wing rib and the pipe wing rib in reducing initial settlement after excavation.

The loading apparatus used in the test was identical to the apparatus used in the test reported in Section 3.1. Three types of test specimens were used: an ordinary steel arch support (H-200×200×8×12), a conventional wing rib type support, and a pipe wing rib type support. The pipe of the pipe wing rib type support was filled with gravel (10 mm or smaller crushed stone) used as a substitute for shotcrete. After each test specimen was set up in the loading apparatus, loads were applied through a load cell by using a hydraulic jack, as shown in Figure 4, so that axial forces were applied directly to the H-beam. As loads were applied to the three types of test specimens, settling displacement was measured. Four stages of loading (0–10 kN, 0–20 kN, 0–40 kN, 0–180 kN) were performed in succession, and measurements were taken as the loading was carried out.

Test results

Figure 9 shows the test results for support leg settlement and loads applied for the different types of wing ribs. Figure 9 also shows the results for the simple column (without wing rib support). As the graph clearly shows, compared with the conventional wing rib, the pipe wing rib shows large loads for very small settlements, indicating high initial stiffness in a macroscopic sense. This indicates that stiffness of the steel arch support can be expected immediately after it is constructed. Thus, the test showed that the pipe wing rib is superior to the conventional wing rib built with H-beams in reducing settlement under initial loading conditions, a situation in which the effect of steel arch supports is needed most. Effectiveness of the pipe wing rib is also indicated by the fact that even greater settlements were observed in the simple-column (without wing rib support) case.

This indicates that while the pipe wing rib is in contact with the ground through the filling material, the conventional wing rib is not in contact with the ground because of voids and loose regions occurring between the wing rib and the ground that are not filled by shotcrete applied to structurally integrate the rib with the ground. Because of these voids and loose regions, the conventional wing rib settles until it comes into full contact with the ground.

Figure 10 shows the amounts of settling displacement converted to values corresponding to bearing stresses per unit area. As is clearly shown in the figure, the conventional wing rib and the pipe wing rib do not show significant differences in bearing stress per unit area of contact with the ground, showing similar settlement–stress relationships. Since the settlement–stress relationship is determined by the type of ground, the authors are thinking of conducting further tests using different soil materials in order to investigate their effects.

5. Conclusions

This paper has reported the results of loading tests conducted to verify the validity of the concept and effectiveness of a newly developed pipe wing rib system. The tests confirmed that the pipe wing rib increases the bearing area by the arch action of the filling material and is as effective as conventional wing ribs in supporting the ground during excavation. The tests also showed that the pipe wing rib is more effective than a typical conventional wing rib in reducing settlement under initial loading conditions because the pipe wing rib comes into contact with the ground immediately after installation.

As a next step, the authors are thinking of develop patterns of pipe wing ribs applicable to different bearing capacities of ground by analyzing the test results reported in this paper and measurement data collected at construction sites.

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