Investigation of bond strength on the surface of a mini-steel pipe with dimples

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ABSTRACT

Soil nailing has been used to reinforce an unstable ground such as slope stability and face bolting in bored tunnels. In these civil engineering projects, slender steel bars as reinforcement elements have been mainly used for axial tension load transfer. Alternatively, the use of steel tubular pipes is highlighted for constructability purposes and an extra bend/shear resistance of pipes. However, commercially available steel pipes have a smooth surface; thus, bond strength is not sufficient to resist pull-out tension loads. Therefore, the fabrication of, e.g., shear keys on the outer surface of a pipe is essential to obtain bond strength between the pipe and grout filling. Dimpled pipes, which have small depressions regularly arranged on the outer surface, that use an on-line depression-forming method have been developed to improve bond strength. This study presents a brief introduction of dimpled pipes; moreover, particular emphasis is given to the evaluation of high bond strength by pull-out tests and the associated mechanism.

Keywords: soil nailing, bond strength, pipe with dimples, confined effect

1 INTRODUCTION

In various civil engineering projects, soil nailing has been used to reinforce and strengthen an existing unstable ground by installing closely spaced reinforcing elements (“nails”) into it (e.g., Tei, 1993 and Byrne et al., 1996). Reinforcement elements are usually installed into predrilling holes and then grouted into place by a separated grout hose under pressure. By the mobilization of grout strength, a grout transfers load through friction or bond from reinforcement elements, leading to the stabilization of a ground. A typical application is to improve slope stability, in which a reinforcement bar is installed horizontally or sub-horizontally, by increased shear strength on potential sliding surfaces, as shown in the left of Figure 1 (e.g., Byrne et al., 1996). In addition, in recent years, a similar ground improvement technique is applied to bored tunnel construction in a soft ground (i.e., NATM). Ground treatment is undertaken within tunnels with open faces, as shown in the right of Figure 1, where a reinforcement element is made for soil ahead of the face by inserting to improve stability and to control ground movement (Mair, 1997).

Soil nailing works predominantly in axial tension loads by friction or bonding to surrounding soils; thus, slender reinforcement elements, mainly by steel bars, are used as nails. However, steel tubular pipes have been recently used for constructability purposes through a simultaneous installation process of a reinforcement pipe with drilling using a special drill rod in the pipe. Another benefit can be expected from the aspect of ground stability improvement. Soil nailing improves stability not only by increasing the normal force (and hence the shear strength of the soil itself) on potential sliding surfaces by tension load but also by providing additional shear strength from shear and bending resistances of reinforcement elements, as shown in Figure 2.

A commercially available steel pipe, which usually has a relatively smooth surface, has a problem in bond strength with grout materials for load transfer. The tensile strength, which is a predominant function even in steel pipes, of reinforcement elements should be adequate to provide the support force to stabilize the potential failure of soil blocks. Reinforcement elements must be embedded to a sufficient depth into a resistance zone to prevent pull-out failure, including failure by slip between a steel and grout. To obtain bond strength, on-bead shear keys are often fabricated on the outer surface of a steel pipe; otherwise, a very long pipe is essential. A new mini-steel pipe pile with dimples (in other words, depressions or dents) on the outer surface has been developed to improve bond strength between pipe surface and grout materials. In this study, a new pipe is briefly introduced and particular emphasis is given to the evaluation of bond strength by comparing the new pipe with normal undented steel pipes.
pipe surfaces as dimples. The on-line depression-forming process has made it possible to offer new pipe products with unique features without requiring secondary fabrication. A more detailed explanation of the on-line depression-forming method and the structural performance are presented by Taenaka et al. (2015).

![Fig. 4. Schematic of depression forming on a surface](image)

### 3 DISCRIPTION OF PULL-OUT TEST

In this study, pull-out tests of a pipe, as shown in Figure 5, were performed to evaluate bond strength between pipe surface and grout materials on the outer surface of a dimpled pipe.

#### 3.1 Test methodology

This section presents the experimental equipment and conditions in the pull-out tests. It has been reported that the control of the radial confinement of a reinforcement element is very important to link the laboratory test and field as steel pipe and the soil ground (e.g., Hyett et al., 1992). They have explained this point in detail and proposed the modified test equipment in consideration of confined conditions. Furthermore, Takahashi et al. (2010) have conducted pull-out tests of the fabricated shear-key pipes for the stabilization of a tunnel face using an appropriately designed pipe as a confining medium. To simulate the same confinement condition (i.e., radial stiffness of the surrounding soils) as a field condition, a polyvinyl chloride (PVC) pipe was used in this study. The radial stiffness ($K_{r,p}$) of the PVC pipe can be calculated from the thick-wall cylinder theory by the equation as follows:

$$K_{r,p} = \frac{2E_p}{(1+\nu_p)} \left\{ \frac{d_i^2-d_o^2}{d_i[(1-2\nu_p)d_i^2+d_o^2]} \right\},$$  \hspace{1cm} (1)

where $E_p$ and $\nu_p$ are the Young’s modulus and Poisson ratio of the PVC material, respectively, and $d_i$ and $d_o$ are the inner and outer diameters of the PVC pipe, respectively. On the other hand, the radial stiffness of surrounding soils around reinforcement elements can be expressed by the cavity expansion (contraction) theory (e.g., Johnston et al., 1987 Airey et al., 1992 and White, 2005) given by
solidification time

Table 1 Test cases for the pull-out test

| Test ID  | Diameter (mm) | Thickness (mm) | Length (mm) | Number of dimples in circumference direction | Number of dimples in longitudinal direction | Unconfined compressive strength (MPa) |
|----------|---------------|----------------|-------------|-----------------------------------------------|-------------------------------------------|-------------------------------------|
| DP-6-1   | 76.3          | 4.5            | 500 (~6.6D) | 6                                             | 9                                         | 25.3                                |
| DP-6-2   | 76.3          | 4.5            | 500 (~6.6D) | 6                                             | 9                                         | 17.0                                |
| DP-6-3   | 76.3          | 4.5            | 500 (~6.6D) | 6                                             | 9                                         | 16.4                                |
| DP-6-4   | 76.3          | 4.5            | 225 (~2.9D) | 6                                             | 4                                         | 22.4                                |
| DP-6-5   | 76.3          | 4.5            | 225 (~2.9D) | 6                                             | 4                                         | 28.0                                |
| DP-6-6   | 76.3          | 4.5            | 225 (~2.9D) | 6                                             | 4                                         | 38.0                                |
| DP-9-1   | 76.3          | 4.5            | 500 (~6.6D) | 9                                             | 9                                         | 21.3                                |
| DP-9-2   | 76.3          | 4.5            | 500 (~6.6D) | 9                                             | 9                                         | 20.7                                |
| DP-9-3   | 76.3          | 4.5            | 285 (~3.7D) | 9                                             | 5                                         | 11.4                                |
| DP-9-4   | 76.3          | 4.5            | 225 (~2.9D) | 9                                             | 4                                         | 19.2                                |
| DP-9-5   | 76.3          | 4.5            | 225 (~2.9D) | 9                                             | 4                                         | 27.9                                |
| DP-9-6   | 76.3          | 4.5            | 225 (~2.9D) | 9                                             | 4                                         | 29.8                                |
| NP-1     | 76.3          | 5.0            | 500 (~6.6D) | No dimple                                     | No dimple                                 | 14.8                                |
| NP-2     | 76.3          | 5.0            | 500 (~6.6D) | No dimple                                     | No dimple                                 | 29.8                                |

\[ K_{RS} = \frac{2E_S}{(1 + \nu_S)d_S} = \frac{4G_S}{d_S}, \]  

where \( E_S, G_S \), and \( \nu_S \) are the Young’s modulus, shear modulus (i.e., \( G_S = E_S/(1 + \nu_S) \)), and Poisson ratio of the soils, respectively, and \( d_S \) is the outer diameter of a grout. By linking the stiffness of the PVC pipe and soils based on parameters in a field, appropriate dimensions of the PVC pipe can be determined. Through this calculation, the PVC pipe was determined to be 140 mm in diameter and 7 mm in thickness, which means \( E_S = 440–460 \) MPa.

![Fig. 5. Setup for the pull-out test](image)

A test equipment similar to Takahashi et al. (2010) was prepared in this study. A test pile was placed at the center of a pipe as a confinement medium, and a grout material was cast inside the medium to surround the pipe. The bond strength was tested, as shown in Figure 5, by the downward pull-out test method wherein downward load was applied to the object pipe from the bottom end while a mold pipe (confining medium) and filling grout material were supported at the bottom.

### 3.2 Test cases

In this study, dimpled pipes with different dimple arrangements and normal pipes were used for bond strength testing. One type of dimpled pipes, i.e., a tubular pipe of 76.3 mm outer diameter and 4.5 mm thickness, has nine dimples in a circumferential direction at intervals of 25 mm in a longitudinal direction, whereas another type has six dimples in a circumferential direction at the same intervals. Note that the number of dimples in a longitudinal direction is a test parameter. Table 1 shows cases in this test program, where pull-out tests for 14 pipes, including two normal pipes, were performed.

![Fig. 6. Mobilized strength of a grout with solidification time](image)

Grout material for the test program was one of the materials used for the project to reinforce an open-face of a tunnel. Figure 6 shows unconfined compressive strength with solidification time for the materials. The results show the strong influence of solidification time on the strength in 24 h. Therefore, unconfined compressive tests were conducted for each pull-out test, listed in Table 1, covering a wide range of 10–30 MPa.
4 BOND STRENGTH

4.1 Test results

Figures 7 and 8 show load-displacement curves for pipes with no dimple, 6 dimples, and 9 dimples for weak and strong unconfined compressive strengths of grout materials, respectively, where load along the ordinate is bond strength per unit contact length to the grout materials. First, it is clear from both graphs that the bond strength of normal piles without depressions was extremely low; after hitting a peak load, the pipe/grout joint failure by sliding was observed. This suggests that it could be not proper for the load transfer between steel pipe and grout material, leading to little contribution to ground stability as nails.

Dimpled pipes exhibited extremely high bond strength; ultimate strength depended on the number of dimples on pipe surfaces and compressive strength of grout materials. Furthermore, ultimate bond strength was mobilized with displacement increase, staying very steady at a high level after the peak.

Figure 9 shows the relation between the unconfined compressive strength of a grout material of specimens described in Table 2 and the maximum bond strength per unit length obtained through the tests. Table 2 summarizes the test results. The maximum bond strength for two of the test cases, DP-9-1 and DP-9-2, could not be measured because the yield failure of pipes occurred first. This suggested that the 6.6D in the embedded length (D: outer diameter of a pipe) could be enough to avoid slip failure on the surface between pipe and grout material in case of dimpled pipe with nine in circumference direction.

The graph in Figure 9 proves clearly that the bond strength of dimpled pipes is far greater than that of normal pipes. It is also clear that the bond strength of normal pipes does not improve significantly as the strength of a grout material increases, whereas that of dimpled pipes increases from four to six times, by a simple comparison, that of normal pipes with an

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**Table 2 Test results**

| Test ID | Unconfined compressive strength (MPa) | Maximum bond strength (kN/m) | Additional resistance per one dimple (kN) |
|---------|---------------------------------------|------------------------------|------------------------------------------|
| DP-6-1  | 25.3                                  | 608.7                        | 4.29                                     |
| DP-6-2  | 17.0                                  | 585.4                        | 4.14                                     |
| DP-6-3  | 16.4                                  | 569.0                        | 4.00                                     |
| DP-6-4  | 22.4                                  | 764.4                        | 5.82                                     |
| DP-6-5  | 28.0                                  | 753.3                        | 5.67                                     |
| DP-6-6  | 38.0                                  | 848.9                        | 6.54                                     |
| DP-9-1  | 21.3                                  | 606.1 *                      | -                                        |
| DP-9-2  | 20.7                                  | 560.2 *                      | -                                        |
| DP-9-3  | 11.4                                  | 692.0                        | 3.54                                     |
| DP-9-4  | 19.2                                  | 869.8                        | 4.56                                     |
| DP-9-5  | 27.9                                  | 893.3                        | 4.66                                     |
| DP-9-6  | 29.8                                  | 876.4                        | 4.54                                     |
| NP-1    | 14.8                                  | 136.0                        | -                                        |
| NP-2    | 29.8                                  | 150.0                        | -                                        |

* DP-9-1 & DP-9-2 reached the pipe yield failure before the maximum bond strength was measured
increasing strength of a grout material. This strength improvement effect is larger than that obtained through another test using pipes to which protrusions were welded at intervals of 25.0 cm (four protrusions in every 1.0 m length) by Takahashi et al. (2010).

Additional resistance per one dimple for each case is also shown in Table 2, which was calculated as follows: the difference between the maximum bond strength on dimple pipe and normal pipe was taken. The difference of bond strength was normalized by the number of dimples on the contact surface to a grout material, of which data were plotted against the unconfined compressive strength of a grout in Figure 10. A rough trend was observed that bond strength per dimple increases with an increase in the unconfined compressive strength of a grout. This rough trend from the test results are interpreted as exhibiting a parabolic relation between additional bond strength and unconfined compressive strength, although the scatter still remained, in particular, in the range of greater strength of the grout.

![Graph](image)

Fig. 10. Resistance of each dimple with a compressive strength of a grout in dimpled pipes

4.2 Discussion (failure modes)

The outer surface of dimpled pipes was observed after the bond strength test, as shown in Figure 11. It has been confirmed from the photo that grout materials filled dimples even though these were small seen in Figure 9. Therefore, the shear failure of grout materials on the face of dimples was a predominant failure to principally determine the bond strength of dimpled pipes, which brought about high bond strength. Another failure mode was observed in a block of a grout material, as shown in Figure 12, which was a radial crack along a longitudinal direction of the test pipe; such radial crack was not observed in normal pipes.

The failure mechanism of dimpled pipes are supposed from the failure patterns as follows: A linear response appears at the initial stage of a pull-out test, related to the axial stiffness of a pipe, elastic properties of a grout, and interface properties of the pipe surface and grout. The strength in this stage could be controlled mainly by the adhesion. Followed by the elastic behavior, the stress drop occurs as shown in Figure 7 and Figure 8, which could be a fracturing mechanism on the dimpled surface. This failure mode, shear failure on a dimpled surface, is schematically illustrated in the left of Figure 13 from observation in Figure 11. As pull-out displacement increases, the grout annulus was pushed aside by geometrical mismatch of failure surface between two, which means dilation behavior. Under the cavity stiffness of confining medium (here, PVC pipe), the radial fracturing breaks leading to radial cracks, as schematically illustrated in Figure 14. In parallel, the confined pressure increases by dilation on a dimple surface with pull-out displacement increasing. As a result, it reaches the ultimate bond strength under a given confining pressure by dilation.

![Image](image)

Fig. 11. Outer surface of a dimpled pipe after the pull-out test

![Image](image)

Fig. 12. Contact surface to the pipe surface in a grout material

As described in Chapter 2, the geometry of dimples on a pipe has been optimized through development. One of the most important parameters should be the depth to length ratio of a dimple. Suppose that the length of a dimple is very short, the shear failure of a grout could tend to occur along the pipe surface, as shown in the right in Figure 13. There is little confining pressure increase in such a case, although very small
dilation arises because of roughness on the crack surface. Hyett et al. (1992) reported from comparison tests between confining mediums that bond strength does not increase after drop when confined condition was not activated. Therefore, the optimization of the geometry of a dimple, as enough length to depth of dimple has been secured in the developed new dimpled pipes, is very important to improve bond strength by utilizing the confined effect.

**Fig. 13.** Schematic of failure patterns on a dimpled surface: left, observed failure pattern; right, assumed failure pattern when the dimple length is short.

**Fig. 14.** Schematic of radial cracks and radial movement due to dilation on the dimple surface

5 CONCLUSIONS

It is expected that steel pipes as reinforcement elements for soil nailing can bring advantages in constructability and an extra resistance in ground stability. Dimpled pipes have been developed focusing on the improvement of bond strength between the pipe surface and grout material. Regularly arranged dimples on the outer surface, which are very small, can tenaciously grip the filling grout. The bond strength of dimpled pipes is improved in an interaction with the confined effect presumably. This study presents that the bond strength of normal pipes does not improve significantly as the strength of a grout material increases, whereas that of dimpled pipes increases from four to six times, by a simple comparison, that of normal pipes with an increasing strength of a grout material.

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