Field pull-out tests on laterally installed small-diameter steel pipes with blades in embankment

Terrain essais d'arrachement sur installés latéralement de petit diamètre des tuyaux en acier avec des lames

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ABSTRACT: Demand for protection of embankments vulnerable to natural disasters is increasing in Japan. We have developed a method to strengthen existing embankments using laterally installed small-diameter steel pipes with blades. The pipes can be installed in any arbitrary direction using a small rig. Since the pipes are perforated, the pipes can act as drainage as well as reinforcement to protect slopes against relatively deep failure. In this study, field pull-out tests were conducted at three sites and in total seven pipes were tested. Test results reveal that the pipe whose outer diameter at the blade edge of 148-176 mm can provide pull-out resistance of 20-80 kN without softening in the resistance-displacement curve. Based on the test results, the predictive equation for the pull-out resistance of the reinforcing pipe is proposed by modifying the equation for the vertically installed steel pipe pile.

RÉSUMÉ : La demande de protection des digues vulnérables aux catastrophes naturelles augmente au Japon. Nous avons mis au point une méthode pour renforcer les digues existantes en utilisant de petits diamètres de tuyaux en acier installés latéralement avec des lames. Les tuyaux peuvent être installés dans toute direction arbitraire en utilisant une petite plate-forme. Étant donné que les tuyaux sont perforés, les tuyaux peuvent servir de drainage ainsi que le renforcement de protéger les pentes contre l'échec relativement profonde. Dans cette étude, les tests de traction sur le terrain ont été menées sur trois sites et au total sept tuyaux ont été testés. Les résultats des tests montrent que le tuyau dont le diamètre extérieur au bord de la lame de 148-176 mm peut fournir une résistance à l'arrachement de 20-80 kN sans ramollissement dans la courbe de résistance-déplacement. Sur la base des résultats des tests, l'équation de prédiction de la résistance à l'arrachement du tube de renforcement est proposée en modifiant l'équation de la pile de tuyaux en acier installé verticalement.

KEYWORDS: pull-out test, pull-out resistance, laterally installed steel pipes with blades, existing embankments

1 INTRODUCTION

Major rainfall-induced failure mode of the slope is shallow failure. It is believed that deep-seated failure of the slope only occurs in the natural slope and such a failure does not occur in the embankment. However in Noto Peninsula Earthquake (JSCE and JGS, 2007) and Suruga Bay Earthquake (Saito and Torimoto, 2009), expressway embankments collapsed in the deep failure mode at several locations. Triger of the failure was earthquake, but it is said that infiltration before the earthquake has made the embankment vulnerable to the earthquake.

The authors (2016) have developed a slope stabilization method using small diameter perforated steel pipes with blades (see Fig. 1. Hereinafter, referred to as steel pipes.) The steel pipes are installed in lateral not only to reinforce the slope but also to provide drainage to the slope. Picture 1 shows the pipe installation using an air-powered torque wrench with guide, which allows the installation in the limited space. Most of the similar conventional methods can be applicable only to the shallow failure, while massive reinforcement is required for the deep-seated failure. Our method is expected to apply to the relatively deep failure because of its large pull-out resistance.

The objective of this study is to evaluate the pull-out resistance of the small diameter steel pipes installed in the existing embankments laterally. Tests were conducted at three sites and in total seven pipes were tested. Based on the test results, the predictive equation for the pull-out resistance of the reinforcing pipe is proposed by modifying the equation for the vertically installed steel pipe pile.

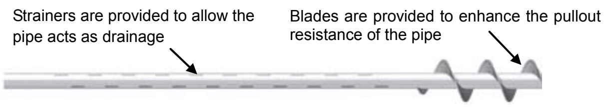


Figure 1. Perforated steel pipe with blades.

Picture 1. Installation of pipe using torque wrench.

Table 1. Predictive equation for vertically installed steel pipe pile with blades (JSCE, 2013)

Maximum surface resistance of single pile R_f	$R_f=\{\Sigma(f_{ci}\cdot L_{ci})+\Sigma(f_{si}\cdot L_{si})\}\cdot\pi\cdot D_w$ Clay : $f_{ci}=c_i$ c_i : Coheasion Sand : $f_{si}=5N_i+20$ N_i : SPT N-value L_{ci} : Thickness of clay layer L_{si} : Thickness of sand layer D_w : Blade outer diameter
Scope of application	Clay, Sand of more than SPT N-value 4 Blade outer diameter is 1.2-3.3 times of pipe outer diameter

2 POSSIBLE MECHANISM OF PULL-OUT RESISTANCE

2 .1 *Previous findings in pull-out resistance*

JSSMFE (1986) and RTRI (2007) indicated the evaluation method of the pull-out resistance of the reinforcement in the slope. Reinforcements in the Terre-Armee method are placed horizontally and their pull-out resistance is related to the effective overburden pressure (NHI, 2001). The pull-out resistance of the reinforcement of cut slope is typically evaluated by the effective overburden pressure and outer surface area of the reinforcement with correction factors for installation angle and confining pressure.

When the steel pipe with blades is used as a vertical pile (JSCE, 2013) or as an anchor to prevent rotation of structures including retaining walls (FEMA, 2009), the evaluate methods of pull-out resistance of the steel pipe with blades have been proposed. However the pull-out resistance of the laterally installed steel pipe in the slope is not sufficiently examined.

The pull-out resistance of the steel pipe pile with blades is mobilized as the shearing resistance at the outer diameter of the blades provided that the disturbance of the surrounding soil is minimal during the installation. Table 1 shows the predictive equation for vertically installed steel pipe pile with blades (JSCE, 2013). The resistance is calculated by the strength of the soils multiplied by the outer surface area of the blades. (Hereinafter, this is called cylindrical surface area.) The strength is evaluated by the SPT N-value based on the field tests.

2 .2 *Possible mechanism of pull-out resistance*

Possible mechanisms in mobilization of the pull-out resistance of laterally installed steel pipe are schematically drawn in Fig. 2 based on the previous findings. The steel pipe with blades has the bladed section either in full-length of the pipe (Hereinafter, this is called the pipe with full-length blades.) or only around the tip portion (Hereinafter, this is called the pipe with tip portion blades). In the former shearing resistance at the cylindrical surface at the outer diameter of the blade is expected, while the skin friction at the non-bladed section and the bearing resistance at the end of the bladed section, i.e., at the boundary between bladed and non-bladed section, are also expected in the latter. Through the pull-out tests, contributions of the resistance mobilized other than the bladed section were examined.

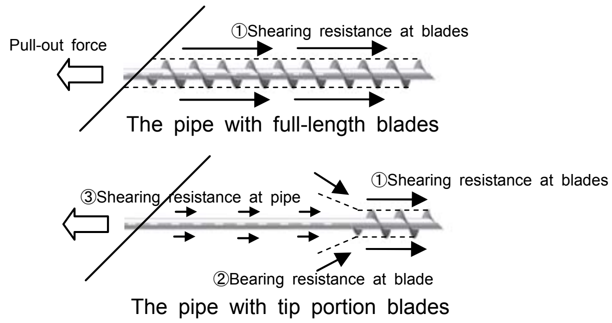


Figure 2. Possible mobilization of pull-out resistance of steel pipe with blades.

3 PULL-OUT TESTS ON ACTUAL EMBANKMENTS

3 .1 *Experiments outline*

In total seven pull-out tests on actual embankments were carried out at three different sites. Table 2 summarizes the conditions of each test and the maximum pull-out resistance obtained. The specifications of the tested pipes are as follows: the pipe outer diameter is 48.6-76.3 mm; the width of blade is 50 mm; the outer diameter at the blade edge is 148-176 mm; the pipe length is 2-5 m; and the bladed section is either in full-length of the pipe or only around the tip portion. Figure 3 shows the slope shape and the installation points of steel pipes at each test site. Typically, the steel pipes were installed at an elevation angle of 0-5 degrees, but one steel pipe was installed vertically at Site A to examine the difference between the horizontal steel pipes and vertical steel pipe pile. The spacing between the pipes was more than 1 m (5 times the blade outer diameter) to avoid interaction of the adjacent two pipes.

Picture 2 shows typical setup for the pull-out test. In the test, the pipe was conducted by pulling the steel bar connected to the pipe using a center-hole-jack. The loading sequences are as follows: at Site A, step-by-step loading and unloading (hold time of each step was 30 minutes); at Site B, step-by-step loading (hold time of each step was 5 minutes); and at Site C, nearly continuous loading (hold time of each step was just 2 minutes).

Table 2. Test conditions and maximum pull-out resistance obtained.

Site, test case	Specification of test pipes	Max. resistance	Soil conditions
Site A（Sep.-Oct. 2012）			
KS176-LW4	STKM13A ϕ76.3×10t×4.0m Elevation 0 deg. D_w=176 mm L_w=3784 mm	35kN	Equivalent SPT N-value 7.1
KS176-LW2D90	STK400 ϕ76.3×4.2t×2.2m Vertically installed D_w=176 mm L_w=2112 mm	50kN	Equivalent SPT N-value 3.1
Site B（Apr.-May 2013）			
EB148-LW5	STK400 ϕ48.6×3.5t×5.0m Elevation 0 deg. D_w=148 mm L_w=5000 mm	110kN	Equivalent SPT N-value 4.1
EB148-LW2	STK400 ϕ48.6×3.5t×6.0m Elevation 0 deg. D_w=148 mm L_w=1800 mm	100kN	Equivalent SPT N-value 4.1
Site C（Sep.-Oct. 2014）			
KM176-LW2	STK400 ϕ76.3×4.2t×5.8m Elevation 5 deg. D_w=176 mm L_w=2112 mm	20kN	SPT N-value 9
KM176-LW1	STK400 ϕ76.3×4.2t×5.8m Elevation 5 deg. D_w=176 mm L_w=1056 mm	50kN	SPT N-value 9
KM176-LW0.5	STK400 ϕ76.3×4.2t×5.8m Elevation 5 deg. D_w=176 mm L_w=528 mm	19kN	SPT N-value 9

Spec. of pipe : Norm, outer diameter×thickness×length

D_w : Blade outer diameter L_w : Length of the blades section

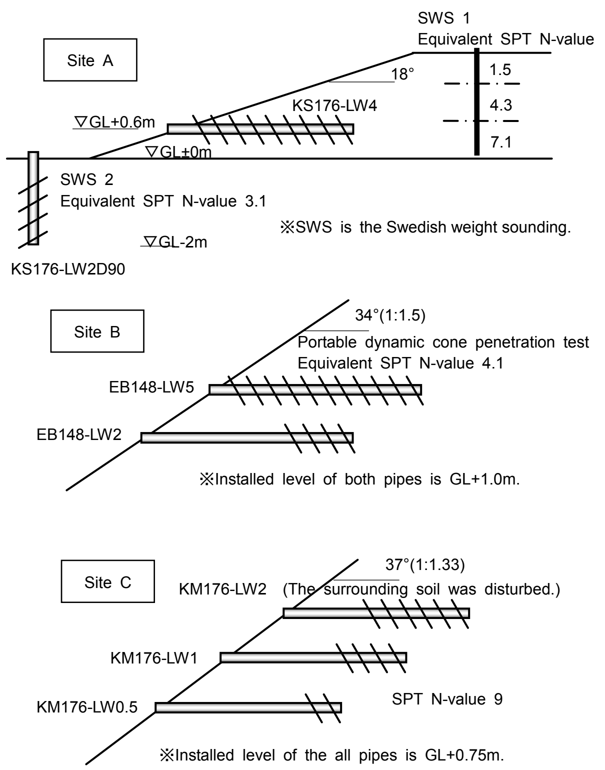
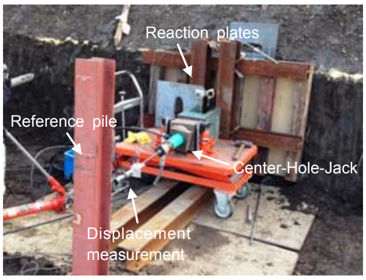
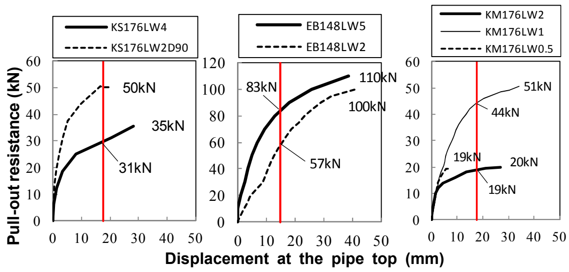


Figure 3. Slope shape and installation points of steel pipes at each site.



Picture 2. Typical setup for pull-out test.



(a) Site A (b) Site B (c) Site C

Figure 4. Pull-out resistance versus displacement at Sites A, B & C.

3 .2 *Results and discussions*

Figure 4 shows relationships between the pull-out resistance and displacement at each site. The vertical lines in these figures indicate the displacement of 10% of blade outer diameter.

At Site A (see Fig. 4(a)), the maximum resistance of KS176-LW4 is 0.7 times that of KS176-LW2D90, despite the cylindrical surface area of the former is two times that of the latter. The equivalent SPT N-value obtained by the Swedish weight sounding was 3 for the layer in which the vertical pipe was installed (KS176-LW2D90), while that was 7.1 at the depth in which the horizontal pipe was installed (KS176-LW4). This simple comparison of the SPT N-values contradict the pull-out resistance obtained, but the authors think that use of the latter SPT N-value may not be appropriate to estimate the strength of the soil near the horizontal pipe as the equivalent SPT N-value in the embankment was obtained by the sounding from the embankment top. Probably the SPT N-value near the horizontal pipe was nearly the same as that at the shallower portion of the embankment, i.e., the equivalent SPT N-value of 1.5. If this is the case, obtained results are reasonable.

Figure 4(b) shows the test results at Site B. Although the cylindrical surface area of the bladed section for EB148-LW2 is 0.4 times that for EB148-LW5, the resistance for the former is 0.9 times that for the latter. If the pull-out resistance is governed mostly by the bladed section, the resistance for the former should have been much smaller. This fact indicates that the resistance mobilized other than the bladed section, especially the bearing resistance at the end of the bladed section, has contributed to increase the resistance in EB148-LW2.

Figure 4(c) shows the results at Site C. Although the cylindrical surface area of the bladed section for KM176-LW0.5 is 0.25 times that for KM176-LW2, the maximum resistance for both cases is almost the same. Here it has to be declared that the surrounding soil was disturbed during the installation of the pipe for KM176-LW2. Obviously this resulted in the smaller resistance in this case. Lesson learnt from this is that the installation of the pipe has to be made with great care.

Except KM176-LW0.5 in which unexpected accident did not allow us to give large pull-out displacement, no obvious softening is observed in the resistance-displacement curve even the pull-out displacement goes beyond 10% of the blade outer diameter in all the cases. This fact ensures the ductile behavior of the bladed pipe in the pull-out mode.

Table 3 summarizes the maximum pull-out resistance together with the unit effective resistance, which is defined as the resistance at the displacement of 10% of the blade outer diameter (Hereinafter, this is called effective resistance), divided by the cylindrical surface area of the bladed section.

4 EVALUATION OF PULL-OUT RESISTANCE

4 .1 *Comparison between measured and estimated resistances*

The effective resistance (resistance at a pull-out displacement of 10% of the blade outer diameter) in Table 3 is compared with the estimated value using the equation shown in Table 1. Figure 5 shows relationship between the measured effective resistance (Hereinafter, KM176-LW2 is excluded since the disturbance of the surrounding soil due to the pipe installation is serious.) and estimated values using the predictive equation for the pull-out resistance of the vertical steel pipe pile with blades. In the estimation, the frictional resistance for sand is used. Overall, the predictive equation seems to give reasonably conservative estimate, as long as reasonable SPT N-value is used. One exception is the estimation for KS176-LW4. As mentioned in the previous section, for this case, the SPT N-value obtained from the sounding from the embankment top (N = 7.1) overestimates the resistance, while that at the shallow depth of the embankment (N = 1.5) improves the estimation. This suggests that consideration of effective overburden pressure (or confining pressure) in the sloping ground is essential in the estimation of the effective resistance.

Table 3. Summary of maximum and unit effective resistances

Test case	Maximum resistance (kN)	Maximum displacement (mm)	Effective resistance※ (kN)	Cylindrical surface area $\pi \cdot D_w \cdot L_w$ (m^2)	Unit effective resistance (kN/m^2)
KS176-LW4	35	28	31	2.092	14.82
KS176-LW2D90	50	20	50	1.168	42.82
EB148-LW5	110	39	83	2.232	37.19
EB148-LW2	100	42	57	0.837	68.11
KM176-LW2	20	27	19	1.168	16.27
KM176-LW1	50	34	44	0.584	75.36
KM176-LW0.5	19	7	19	0.292	65.08

※Effective resistance : Load at displacement of blade diameter 10%

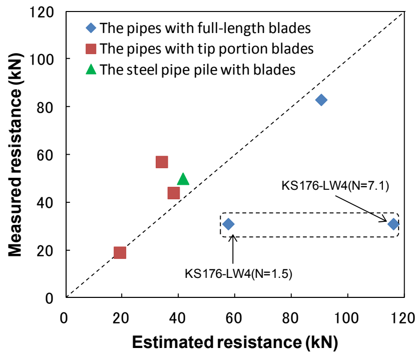


Figure 5. Comparison between measured and estimated resistances

To modify the predictive equation for the sloping ground, relationship between the effective pull-out resistance of the steel pipe and thickness of the covering soil at the middle of the bladed section, i.e., the average covering soil thickness, is examined. Figure 6 shows the relationship between the unit effective resistance and average covering soil thickness. Although the data points are scattered, it can be confirmed that the unit effective resistance is proportional to the average covering soil thickness.

Based on the confirmation in Fig. 6, the unit effective resistance τ is expressed as $\tau = K' \cdot \sigma_v \cdot \tan\phi$. Estimation of the coefficient of earth pressure K' is made using available data.

The angle of shearing resistance is estimated by ϕ=1.85・{N / (σ_v / 100 + 0.7) }$^{0.6}$ + 20, which is proposed by RTRI (2007). Figure 7 plots the estimated coefficient of earth pressure against the blade outer diameter normalized by the pipe diameter. (Hereinafter, this is called blade diameter ratio.) In this figure, not only the data obtained in this series of tests but also the data obtained from loading tests on vertical steel pipe pile with blade (JSCE, 2010). Ranges of the coefficients of earth pressure K' in Fig. 7 are (1) 1.2-3.7 (2.4 on average) for axial loading tests, (2) 1.5-4.1 (2.5 on average) for pull-out tests on vertical pipe piles, and (3) 2.2-3.1 (2.6 on average) for laterally installed steel pipes (in this series of tests).

The values are greater than the coefficient of earth pressure at rest and are equal to or smaller than that for the passive state and are comparable to the previous study on helical screw anchors (Ghaly & Hanna, 1992). From this figure, it can be also said that the coefficient of earth pressure does not change much with the blade diameter ratio and effect of the sloping ground cannot be seen. Thus, the constant value may be used irrespective of the blade diameter ratio and slope angle.

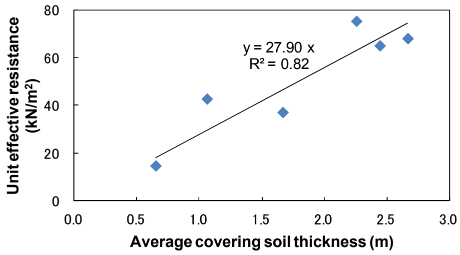


Figure 6. Unit effective resistance versus average covering soil thickness.

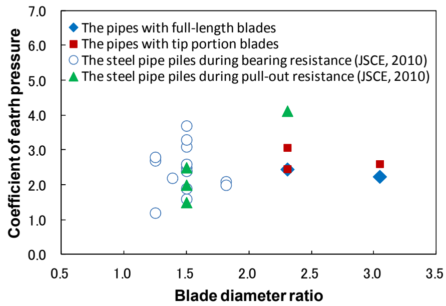


Figure 7. Coefficient of earth pressure versus blade diameter ratio.

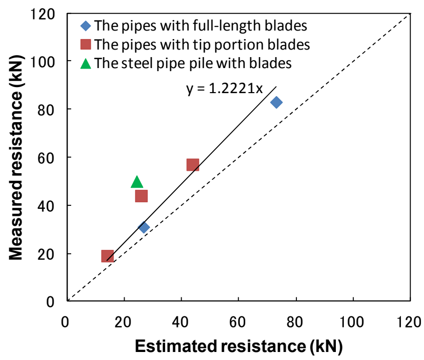


Figure 8. Comparison between measured and estimated resistances using proposed predictive equation.

4 .2 *Proposed predictive equation*

The predictive equation for the effective pull-out resistance of the horizontally installed steel pipe with blade is proposed based on the discussions above:

$$T_s = \pi \cdot D_w \cdot L_w \cdot K_s \cdot \sigma_v \cdot \tan\phi \qquad (1)$$

where T_s is the effective pull-out resistance (kN), D_w is the blade outer diameter (m), L_w is the length of the bladed section (m), K_s is the coefficient of earth pressure, σ_v is the average overburden pressure at the middle of the bladed section (kN/m^2), ϕ is the angle of shearing resistance of the soil (degrees).

Figure 8 shows the relationship between measured values and estimated values using the proposed predictive equation. In the estimation, the following assumptions are made: γ is 17 kN/m^2, ϕ is 30 degrees, K_s is 2.0. This K_s is equivalent to 1σ below the average of the coefficients of earth pressure (2.6) in Fig. 7. For better estimation, more test data may be needed.

5 CONCLUSIONS

In this study, to evaluate the pull-out resistance of the small diameter steel pipes installed in the existing embankments horizontally, field pull-out tests were conducted. Based on the test results, the predictive equation for the pull-out resistance of the reinforcing pipe is proposed by modifying the equation for the vertically installed steel pipe pile. Findings obtained from this study are as follows:

- The pull-out resistance of the laterally installed steel pipes, whose length is equal to or less than 5m, in actual embankments is ranging from 20 to 80 kN at a pull-out displacement of 10% of the blade outer diameter and no softening is observed in the resistance-displacement curves.
- Predictive equation for the pull-out resistance of horizontally installed steel pipe with blades is proposed.

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