Field pull-out experiments on flip-type ground anchors installed in a slope of cohesive soil, and verification of design method for pull-out resistance of the anchors by LEM and FEM.

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ABSTRACT

Due to the heavy rain caused by extreme weather related to climate change, the number of landslides in Japan is increasing on a decadal basis. As countermeasures against slope disasters, there is an increasing demand for convenient construction methods that can respond more quickly to small-scale sites and emergency measures for failed slopes. One of the effective countermeasures against it is flip-type ground anchors (flip anchors, hereafter). Flip anchors are directly pressed or driven into the ground and are pulled to open in the ground to obtain pull-out resistance without grouting. In this research, field pull-out experiments of actual flip anchors on a slope consisting of cohesive soil were conducted. To investigate the pull-out resistance of the anchors in the slope, three sizes of actual flip anchors were driven directly into the ground at 1.5 m or 2.0 m. Then the anchors were pulled by a hydraulic jack. As the results of the experiments, it was found that the flip anchor obtains pull-out resistance on slopes and is effective for slope reinforcement. The measured values were compared with calculated values by LEM and FEM. Calculated values qualitatively agreed well with the measured values.

Key words: *Anchor, Slope, Landslide, FEM, Pull-out*

1. Introduction

1.1. Flip type ground anchor

Anchors have been widely used for supporting structures on the ground and the water. Those anchors can be broadly divided into those used with grout and those not. There are 2 types of anchors among the anchors installed without grouting. One is pre-embedded in the ground, and another is driven or pressed directly into the ground. Flip anchors (**Fig. 1**) are kind of ground anchors that do not require grouting to obtain pull-out resistance. As shown in **Fig. 2**, flip anchors are driven or pressed directly into the ground. After being driven to the designed depth, the anchor head rotates and opens when pull-out force acts on the anchor.

Although the flip anchors have convenient workability, estimating the pull-out resistance depending on ground conditions is more difficult compared to general pre-embedded plate anchors, due to their above-mentioned specific resistance mechanism. A lot of previous research on pull-out capacity of the pre-embedded plate anchors were conducted so far, such as Majer (1955), Mors (1959), Balla (1961), Baker & Kondner (1966), Vesić (1971), Das & Seeley (1975), Merifield et al. (2006), Dickin & Laman (2007).

To estimate the pull-out strength of the plate anchors in sandy ground, the ground failure pattern above the anchor plate needs to be modeled. As shown in **Fig. 3**, it is known that ground failure pattern differs as the embedment depth of the anchor changes (Mayerhof, 1968). It can be expressed as the ratio of the length L or breadth

B of the anchor plate to the embedding depth. That certain depth dividing the failure pattern is called critical depth, and the depth is estimated by critical embedment ratio $(H/L)_{cr}$ or $(H/B)_{cr}$. For estimating the critical depth, Meyerhof (1968) proposed the values empirically related to friction angle ϕ of soils as shown in Table 1.

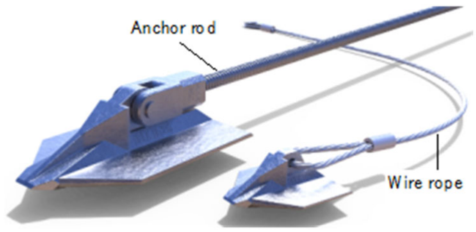
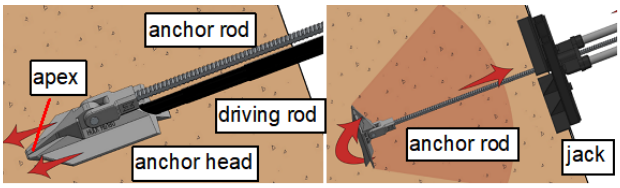


Fig. 1 Example of flip anchors (Anchoring Rope and Rigging Pty. Ltd., 2021)



(a) Installation stage (b) Pull-out stage

Fig. 2 Installation procedure of flip anchors (Anchoring Rope and Rigging Pty. Ltd., 2021)

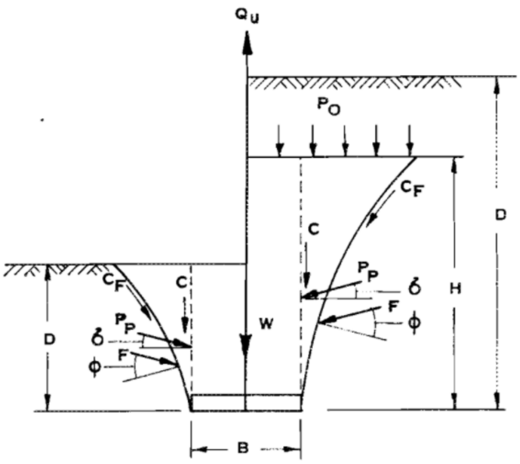


Fig. 3 Ground failure model associated with pull-out of plate anchors (Meyerhof & Adams, 1968)

Table 1. $(H/L)_{cr}$ depending on ϕ (Meyerhof & Adams, 1968).

ϕ	20°	25°	30°	35°	40°	45°	48°
$(H/L)_{cr}$	2.5	3	4	5	7	9	11

On the other hand, in clay, the estimation method is different from that in sand. In clay, Das (1980) presented a procedure for the estimation of the ultimate uplift capacity of shallow and deep anchors as **Eq. (1)**.

$$Q_0 = BL(\beta F_c c_u + \gamma H) \tag{1}$$

where Q_0 is the net ultimate capacity, *B* is the width of an anchor, *L* is the length of an anchor, $\beta = F_c/F_c^*$, F_c is breakout factor for a shallow anchor [$H/B < (H/B)_{cr}$], F_c^* is breakout factor for a deep anchor [$H/B \geq (H/B)_{cr}$], c_u is undrained shear strength of soil, γ is unit weight of soil, *H* is the embedment depth of the anchor.

On the other hand, there are few studies on flip anchors, such as Niroumand & Kassim (2013).

Although the number of studies is limited, flip anchors have a large number of field applications, mainly in Europe, the United States and Australia. Titi & Helwany (2007) reported investigations on approaches to resist surficial slope instability. The case of flip anchor was introduced as one of the construction methods that contribute to slope stability.

1.2. Objectives of this research

The authors have already proposed estimation methods for pull-out force of flip anchors in clay in horizontal grounds (Yoshida et al., 2021).

→ The estimated results were examined by comparing the calculated values with measured values from the field experiments in clayey ground. It can be useful for the design of future slope stabilization works using flip anchors.

2. Outline of the experiments

2.1. Experimental field

Fig. 4 shows the field of the experiments. The experimental field is in Toyama Pref. in Japan. The length of the slope was about 25 m, and the slope angle was about 30 degrees. The ground consisted of loose cohesive soils. Dynamic Cone Penetration Tests (DCPTs) were conducted in 2 locations on the ground above the slope. The results were converted to SPT-*N* values according to (Okada et al., (1992). As shown in **Fig. 5**, *N*-values of the ground were small in total. Especially, the *N*-values above the embedment depth (1.5 or 2.0 m) of the anchor were only about 3.

In this study, no other tests for getting soil characteristics were conducted considering the practical application of the flip anchors to actual sites. For the practical application, design methods to stabilize a slope with limited information of soil characteristics are required. In that case, the DCPT is useful to obtain the depth of unstable soil layers and stable soil layer.

Fig. 4 A field (slope) of the experiments

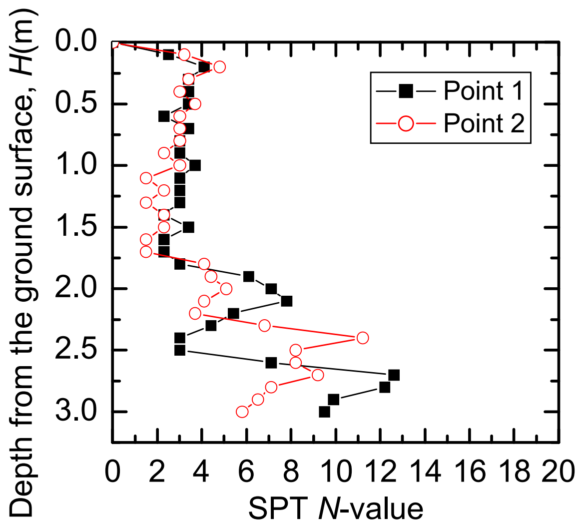


Fig. 5 Converted SPT *N*-values of the ground from DCPTs

2.2. Anchors used in the experiments

Three sizes of actual flip anchors were used for the field experiments (**Fig. 6**). The anchors were made from ductile iron. A steel rod having a diameter of 16 mm (for H110 anchor) and 25 mm (for HG100 & HG180 anchors) was connected to each anchor head for pulling the anchors. The length L and breadth B of the anchor are listed in **Table 2**. As shown in **Fig. 7**, to simplify the calculation, the B was modified as B_c to make the shape of the anchor rectangular having the same area A.

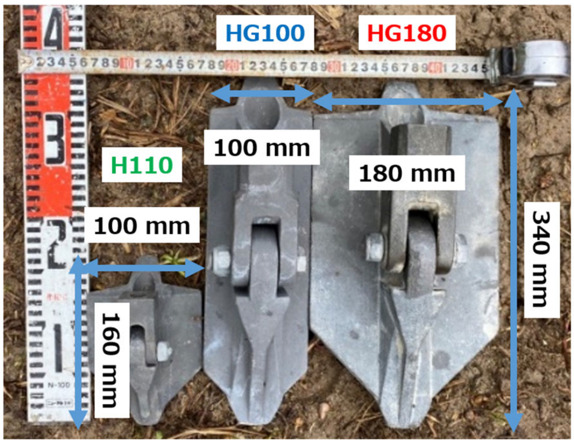


Fig. 6 Actual flip anchors used in the experiments

Table 2. Dimensions of flip anchors

Anchor type	L (m)	*B_c (m)	B (m)	A (m^2)
H110	0.160	0.079	0.110	0.013
HG100	0.340	0.088	0.100	0.030
HG180	0.340	0.143	0.180	0.049

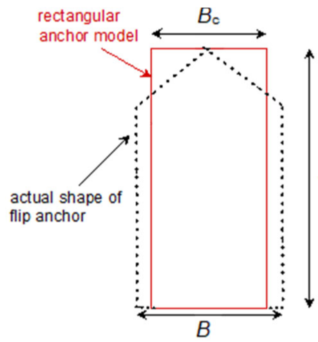


Fig. 7 Approximated shape of anchors for calculation

2.3. Experimental cases and procedures

Table 3 shows the experimental cases. A total of 6 cases of pull-out experiments were conducted on the slope.

Table 3. Experimental cases

Anchor type	Depth z (m)	
H110	1.5	2.0
HG100	1.5	2.0
HG180	1.5	2.0

All anchors were driven perpendicular to the slope with anchor head closed. The embedment depth of the anchor z was defined as the distance from the ground surface to the tail of the anchor (**Fig. 8**). The anchors were driven directly into the ground to the designed depth with a driving equipment (**Fig. 9**). It took about 2 minutes to install each anchor.

Fig. 10 shows equipment for the pull-out experiments. Anchor rods were pulled out by a hydraulic jack to measure pull-out force *F*. Pull-out displacement *w* was measured by an encoder. In the pull-out experiments, a bearing plate, having a diameter of 760 mm, was set on H-shaped steel beams, having a height of 150 mm and a width of 100 mm, to minimize the effect of reaction force on the ground. The distance of each H-shaped beam was 600 mm for H-anchors, and 800 mm for HG-anchors.

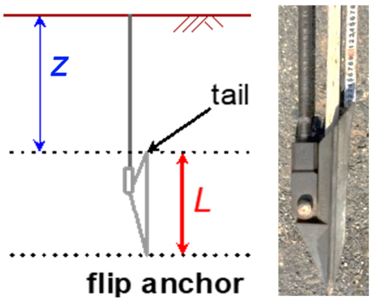


Fig. 8 Definition of embedment depth *z*

Fig. 9 A driving equipment for the installation of anchors

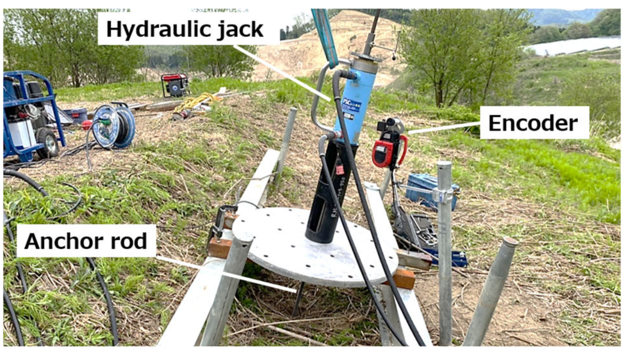


Fig. 10 Equipment for pulling the flip anchors

3. Results of the experiments

Figs. 11 and 12 show pull-out force *F* vs. pull-out displacement *w*. *F* of larger anchors got larger at the same *z*. *F* got larger when installed deeper ($z = 2.0$ m) than *F* in $z = 1.5$ m. This trend is the same as the results of the vertical pull-out experiments in horizontal grounds (Yoshida, 2021). For flip anchors, depending on the ground conditions, the amount of *w* which is about the same, or 1.5 times of *L* is needed to make the anchor head open in the ground based on the former research of authors. Thus, *F* started to rise at about that value of *w* for each anchor. This time, for the convenience of the experiments, *z* was small for the anchors in clayey ground conditions. If the embedment depth after the anchor opened was larger under this ground condition, *F* would have taken the constant value after the peak value. Or, because it was not completely a clay soil, it might also be influenced by sandy soil partly included. Generally speaking, it was found that the anchor can obtain pull-out resistance even if installed shallowly on a slope made of loose cohesive soil.

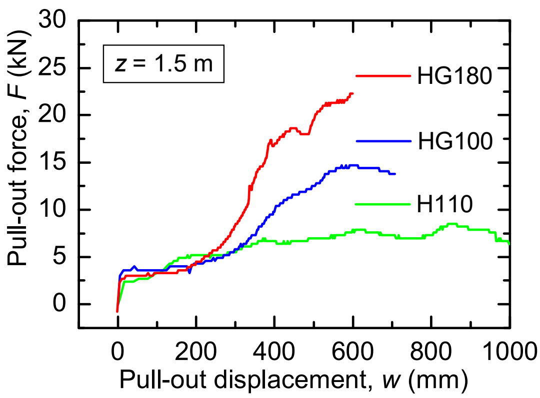


Fig. 11 *F* vs. *w* of each anchor at $z = 1.5$ m

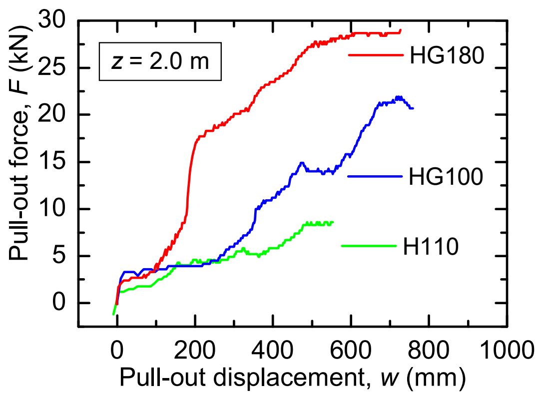


Fig. 12 *F* vs. *w* of each anchor at $z = 2.0$ m

4. Estimation of pull-out resistance of flip anchors by LEM

4.1. Calculation procedure of maximum pull-out force F_{max} in clay

To estimate pull-out resistance of pre-embedded plate anchors in clay by Limit Equilibrium Method (LEM), the calculation method was proposed as in Section 1.1.

Using this calculation method as a reference, the authors proposed a method for calculating the pull-out force of flip anchors in clay (Yoshida et al., 2021). As an estimation method of pull-out resistance of flip anchors in clay, the interpretation method for T-bar penetration test is applied (**Fig. 13**). It is because pulling a flip anchor throughout clay is just reverse way of pushing T-bar into the clay (**Fig. 14**). In the T-bar test, the undrained shear strength of soil c_u value is estimated using **Eq. (2)** (Almeida et al., 2013) with the measured value of pressure p on the T-bar:

$$c_u = p/N_b \quad (2)$$

where N_b is the bearing factor of T-bar. N_b ranges from 8.5 to 12.5 for various types of clay with an average value of 10.5 (Low et al., 2010). In this field experiment, firstly unconfined compressive strength q_u is converted from N values as Eq. (3) according to Terzaghi & Peck (1967). Undrained shear strength c_u is derived from q_u as Eq. (4).

$$q_u = 12.5N \text{ (kPa)} \quad (3)$$

$$c_u = q_u/2 \quad (4)$$

It is assumed that p can be estimated using $N_b = 10.5$ as **Eq. (5)**:

$$p = N_b c_u \quad (5)$$

Fig. 13 T-bar penetration test (Almeida et al. 2013)

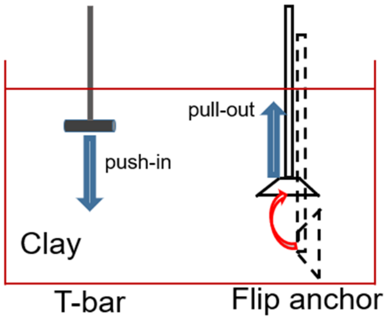


Fig. 14 Concept of reverse movement of T-bar and flip anchor

Thus, from the shear strength of the soil and the weight of the soil above the anchor, the pull-out force of flip anchors can be calculated by **Eq. (6)**.

$$F = pA + \gamma z \quad (6)$$

where F is pull-out force of anchors, p is pull-out pressure on anchor plate, A is projected area of anchor plate, γ is unit weight of the soil, z is embedment depth of an anchor plate.

4.2. Results of the calculation

Fig. 15 shows the comparison of measured maximum pull-out force F_{max} and calculated F_{max} by LEM for each z. While the measured values increased with the increase in z, the effect of increasing z was almost negligible in the calculated values. This could be because the proposed **Eq. (6)** only considers the impact of z on the weight of the soil mass. Even though there is a possibility of the ground loosening as the anchor is pulled closer to the surface, the experimental values being twice as high as the calculated values could be attributed to differences in the calculated c_u values converted from N values. c_u has the most significant effect on F_{max}. This time, the DCPTs were not conducted on the middle or lower points of the slope. Therefore, c_u was evaluated using the small N value of 3 from the measurements so as not to overestimate. Improving the measurement accuracy of c_u through more locations of DCPTs can enhance the accuracy of calculations made by the LEM.

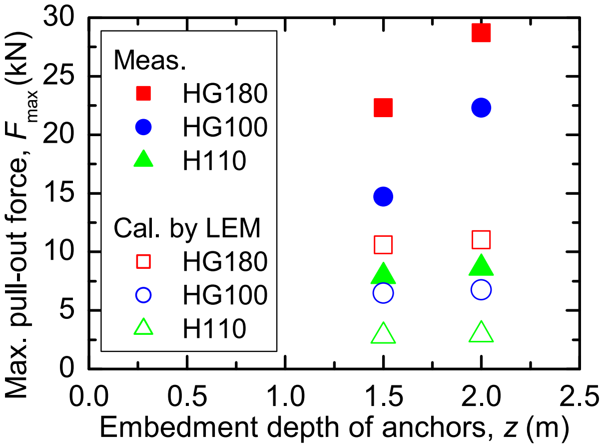


Fig. 15 Comparison of Measured & Calculated F_{max} by LEM

5. Estimation of pull-out resistance of flip anchors by FEM

5.1. Outline of the FEM analyses

F_{max} was also calculated by FEM. A software Plaxis 3D was used for the FEM analyses. As shown in **Fig. 16**, the ground with a height of 3.0 m, a slope length of 4.0 m, a slope angle of 30 degrees, and a width of 1.0 m was modelled with very fine mesh. The anchors were installed at the center of the width of the slope. In this analysis, the lower part of the slope does not significantly affect the analysis results because the anchors were installed near the shoulder of the slope, and z was only 2.0 m or less. Thus, to simplify the calculation, the length of the slope below the anchor was shortened maintaining the gradient of the slope. As the displacement boundary conditions, the horizontal displacements of the side surfaces and the vertical displacements of the bottom surface were fixed. The Mohr-Coulomb model was applied to the soil constitutive law. The parameters of the ground and material are shown in **Tables 4 and 5**. To make it more practical for disaster recovery and similar purposes, in this study, whether numerical calculations using parameters empirically converted from N values could be aligned with experimental values. Modulus of elasticity was calculated based on E = 500N + 6900 according to Public Works Research Institute (PWRI) in Japan. Empirically common values of initial void ratio and poisson's ratio were substituted for FEM analysis.

The FEM analyses were conducted according to the following procedure.

(a) Initial phase (Gravity loading): Anchor plates at each z were set with positive and negative interfaces in this phase.

(b) Pull-out phase: A forced displacement of approximately 160 mm (same as L of H110 anchor) was applied perpendicular to the slope as a simulation of pulling the anchor (**Fig. 17**).

Fig. 18 is a cross-section of the slope showing the total displacement when soil collapsed. **Table 6** shows the total displacement of the ground when the soil collapsed in the calculation. As shown in **Fig. 18**, the soil displacement associated with anchor pullout occurs locally deep in the slope soil. Whether the ground where the anchor is installed is sloped or horizontal may not significantly affect F_{max}, which will be investigated in future work.

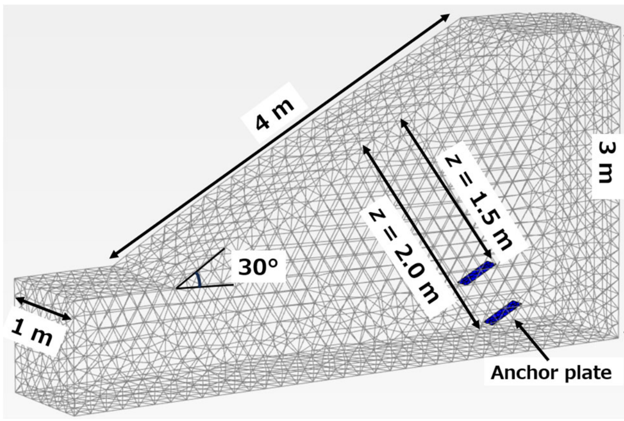


Fig. 16 Model ground (slope) for FEM analyses

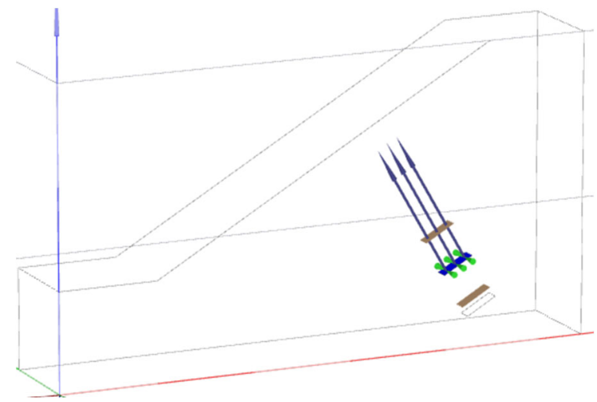


Fig. 17 Forced displacement of an anchor plate

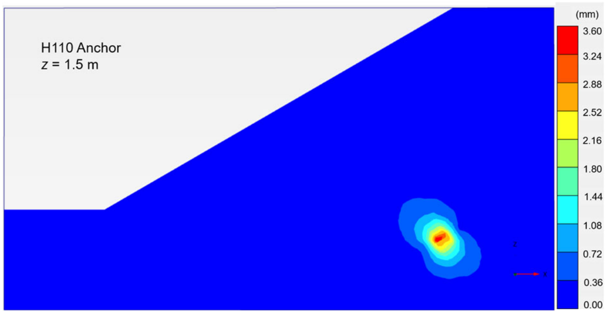


Fig. 18 Cross-section showing total displacements of the ground when calculation stopped due to soil collapse

Table 4. Parameters of the ground for FEM analysis

Item	Value
Unit weight of the unsaturated soil, γ_{unsat} (kN/m^3)	18.0
Initial void ratio, e_{init}	1.5
Modulus of elasticity, E' (kPa)	8400
Poisson's ratio, ν	0.40
Effective cohesion, c' (kPa)	18.0
Int. friction angle, ϕ' (deg)	0.0
Dilatancy angle, ψ (deg)	0.0
The earth pressure coefficient at rest, K_0	0.50

Table 5. Parameters of anchor plates (head)

Item	Value
Unit weight, γ (kN/m^3)	71.54
Thickness, d (mm)	50.0
Young's modulus, E (GPa)	176.0
Poisson's ratio, ν	0.27

Table 6. Parameters of the ground for FEM analysis

Anchor model	Total displacement (mm)	
	z = 1.5 m	z = 2.0 m
H110	3.6	3.6
HG100	12.3	41.9
HG180	17.8	57.2

5.2. Results of FEM analyses

Fig. 19 is a comparison of measured F_{max} vs. calculated F_{max} at each z. Similar to the results by LEM, F_{max} calculated by FEM were much smaller quantitively than the measured F_{max}. However, the qualitative trends were well consistent. In FEM, the effect of depth was more accurately reflected in F_{max}. Quantitative differences, like those in LEM, should be further reduced by improving the accuracy of the c_u values.

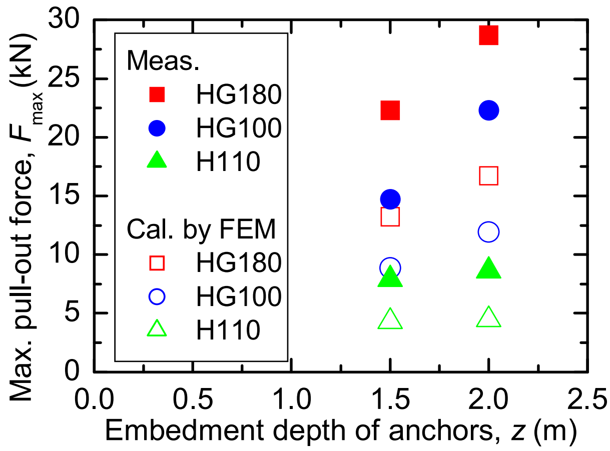


Fig. 19 Comparison of Measured & Calculated F_{max} by FEM

6. Concluding remarks

In this study, measured and calculated F_{max} of flip anchors on a slope ground consisted of cohesive soil were compared to examine estimation methods for F_{max} of flip anchors on slopes. The main findings are below.

1) The ground is only locally affected by the pulling of the flip anchor. Thus, when the anchors are installed even on a slope, pull-out resistance can be obtained.
2) If c_u can be measured on site, the pull-out force of flip anchors on a slope can be calculated using both LEM and FEM. The accuracy of c_u significantly affects the quantitative accuracy. By calculating c_u conservatively, the design values can be estimated lower for safety.
3) When installed in clay, the proposed method of LEM hardly reflects the impact of embedment depth on F_{max}. The experimental values were larger than calculation values. Further investigation is necessary regarding this in the future.
4) The F_{max} calculated in FEM qualitatively matched the measured values, as reflecting the effect of embedment depth.

In this study, the possibility to estimate the pull-out force of flip anchors on a slope consisted of clay was investigated. Based only on the results of DCPTs, pull-out force can be estimated by both LEM and FEM. Flip anchors will be useful for prompt slope stabilization work.

In the future, how much difference in pull-out force occurs between horizontal and sloped grounds for both clay and sandy soil conditions will be examined. In addition to that, practical verification of design for slope reinforcement using flip anchors was conducted with FEM.

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