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Load Transfer of Tension and Compression Anchors in Weathered Soil

인장형 앵커와 압축형 앵커의 하중전이에 관한 연구

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요 지

풍화토 지반에 설치된 그라운드 앵커의 하중전이 현상을 규명하기 위하여 성균관대학교 지반시험장에서 인발시험을 수행하였다. 지반과 구조물을 일체화시키는데 사용하는 앵커는 앵커체와 지반의 마찰력에 의해서 구조물을 지지하는 역할을 하며 앵커의 하중과 변형의 관계를 규명하기 위해서는 앵커의 마찰력 분포의 변화(하중전이)가 중요한 요소가 된다. 하중 재하 시 앵커체에 발생하는 하중전이 분포는 앵커의 인발 지지력과 밀접한 관계가 있고 앵커체의 종류(인장형 또는 압축형), 정착장의 길이, 지반 조건 등에 따라 분포 양상이 변하기 때문에 하중전이를 이해하기 위해서는 강선과 그라우트의 하중분포 그리고 앵커 그라우트체와 지반과의 마찰력 분포를 알아야 한다. 앵커의 자유장의 강선에 작용하는 응력, 그라우트체에 작용하는 응력, 그리고 정착장 강선의 응력을 계측하여 강선과 그라우트의 정착응력 및 그라우트와 지반에서의 마찰력 분포를 구함으로써 강선-그라우트-지반의 복합적인 거동에 따른 각 하중 단계마다의 하중전이 분포를 구하였다. 또한 현장시험 결과의 신뢰성 확보를 위하여 수치해석 모델링을 통하여 해석을 수행하여 비교하였다.

Abstract

Anchor pull-out tests were performed on seven instrumented full-scale gravity-pressure grouted anchors installed in weathered soil at the Geotechnical Experimentation Site at Sungkyunkwan University. The anchors were 165 mm in diameter and embedded 9 to 12 m in weathered soil. Four anchors are the compression type anchors and three are the tension anchors. Performance test, creep test, and long term relaxation test were performed and presented. The load distribution in a ground anchor is very complex because it involves three different materials(soil, grout, and steel) which sometimes act as composite sections. In order to verify a load transfer mechanism of ground anchors, it is essential to consider the load distribution in the three different materials. From the measurements, a load transfer mechanism of ground anchors was investigated and a numerical model to predict the load-displacement relationship of anchors in clay was developed and evaluated.

Keywords : Anchor, Beam-spring analysis, Compression anchor, Load distribution, Load test, Load transfer, Tension anchor

1. Introduction

Ground anchors, commonly referred as tieback or tie down, are essentially steel elements secured in ground by grouting. Various types of anchor are used for the uplift resistance of transmission tower, utility poles, aircraft moorings, submerged pipeline, and tunnel. Ground anchors are also used for permanent earth retaining structures, waterfront structure, and temporary excavation. For the corrosion protection purposes of

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permanent anchors, a compression type anchor was developed and has been used since 1970. An extractible-strand compression anchor becomes popular in a congested area to get a permission of a private land to install anchors. Compression anchors afford better corrosion protection because the whole unbonded length is covered by plastic sheath filled with grease and they have less susceptibility to creep (Pfister et al., 1982, Briaud et al., 1998). Temporary ground anchors have been studied by several researchers (Ostermayer et al., 1978, Littlejohn, 1968, 1970), and the topics of permanent ground anchors have been reviewed and summarized in a series of publications by FHWA (Nicholson et al., 1982; Otta et al., 1982; Pfister et al., 1982; Weatherby 1982; Weatherby et al., 1997; Cheney 1988).

Anchor pull-out tests were performed on seven instrumented full-scale gravity-pressure grouted anchors installed in weathered soil at the Geotechnical Experimentation Site at Sungkyunkwan University. Four anchors are the compression type anchors and three are the tension anchors. Performance test, creep test, and long term relaxation test were performed. From the measurements, load transfer mechanisms of tension and compression ground anchors were investigated and were evaluated by a numerical model.

2. Current Design Practice

The ultimate capacity of tension type anchors is determined by the friction resistance between the anchor grout and the soil, or the pullout resistance between the grout and the strand, or the ultimate tensile strength of strand, whichever is smaller. The ultimate capacity of compression anchors is determined by the friction resistance between the anchor grout and the soil, or the compressive strength of grout, or the ultimate tensile strength of strand, whichever is smaller;

Ultimate friction resistance between anchor grout and soil can be calculated as follows;

$$Q_{uf} = \pi D L_a f_{max} \quad (1)$$

$$f_{max} = \alpha S_u \text{ (cohesive soil)} \quad (2)$$

$$f_{max} = K\sigma_{ov}' \text{ (cohesionless soil)} \quad (3)$$

where Q_{uf} is an ultimate friction, D is a diameter of anchor or effective diameter of borehole, f_{max} is the maximum friction between the soil and the grout, L_a is an anchor bonded length of tension anchor or bonded transmission length of compression anchors, α is an alpha value, S_u is an undrained shear strength of clay, σ_{ov}' is an effective overburden pressure, K is a coefficient of friction which is. qual to $K_1 \tan\phi$ (Littlejohn, 1980). K_1 is the earth pressure coefficient and K_1 value ranges from 1.4 to 2.3 for medium dense to dense sandy gravel with low injection pressure, where ϕ is the friction angle of soil.

The pullout resistance between strand and grout can be calculated as follows;

$$Q_{up} = n\pi D_e L_b f_{ub} \quad (4)$$

where n = number of strand, f_{ub} = ultimate bond stress between grout and strand. L_b = bonded length of strand, D_e = effective diameter of strand.

The ultimate tensile load of strand Q_{us} can be calculated as follows;

$$Q_{us} = A_s f_{us} \quad (5)$$

where A_s is a strand area, f_{us} is an ultimate tensile stress of the strand.

The ultimate compressive strength of grout Q_{ug} can be calculated as follows;

$$Q_{ug} = A_g f_{uc} \quad (6)$$

where f_{uc} is an ultimate compressive strength of the grout and A_g is a grout area.

3. Anchor Pullout Load Test

3.1 Geotechnical Experimentation Site

Anchors were constructed at Geotechnical Experimentation Site at Sungkyunkwan University located in Suwon, Korea. The subsurface soil consists of medium dense silty sand (fill) up to a depth of 4 m, medium dense sandy clay (alluvial deposit) to a depth of 5.8 m, weathered soil up to a depth of 12 m and weathered rock below a depth of 12 m. The water table is observed to be at 13.8 m below ground surface. The subsurface profile of the anchor test site and the standard penetration number are shown in Fig. 1 and Fig. 2 respectively. The anchor layout and testing setup are shown in Fig. 3 and Fig. 4.

3.2 Construction and Instrumentation

The anchors were installed using a rotary-type drill auger and grouted with a pressure of 0.5 mPa. The water cement ratio of grout was about 50 percent and the 28 day compressive strength was an average of 22.5 MPa.

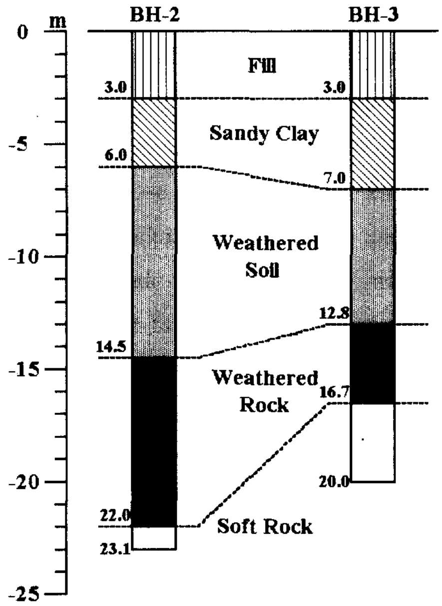


Fig. 1 Subsurface profile at anchor site

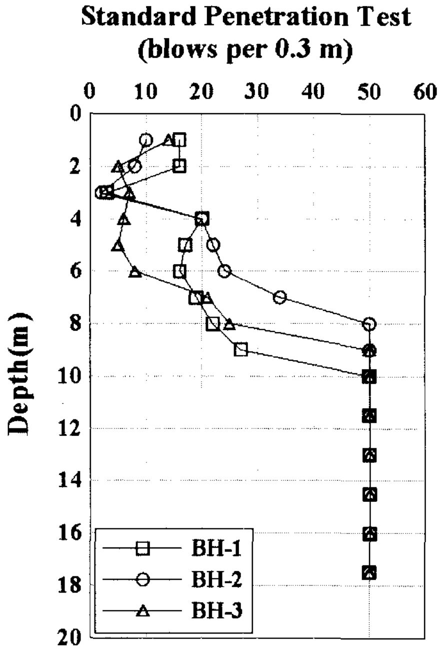


Fig. 2 SPT blows at test site

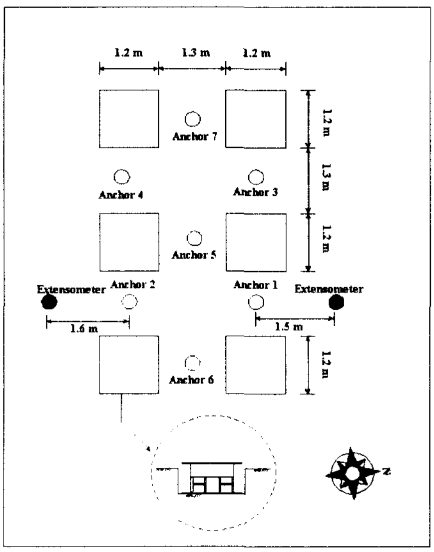


Fig. 3 Anchor layout

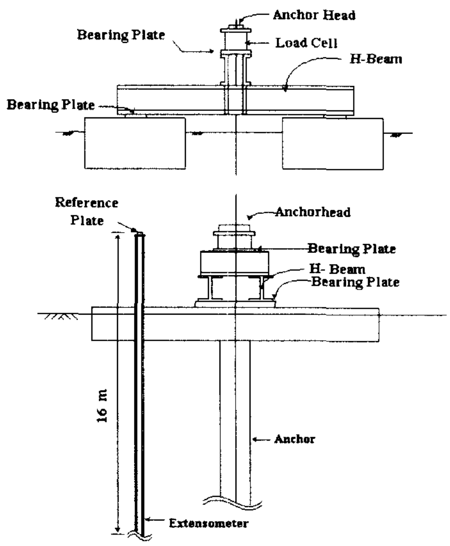


Fig. 4 Load test set-up

Table 1. Types of test anchors

Anchor No.	Type of anchor	Length (m)	Unbonded length(m)	Bonded length(m)	No. of strand
1	Tension	12	8	4	5
2	Compression	12	-	-	5
3	Extractable	12	-	-	4
4	Estractable	12	-	-	4
5	U-Turn Type	11.5	-	-	4
6	Tension	12	9	3	7
7	Tension	9	6	3	7

The anchors were 165 mm in diameter and 9 to 12 m long and the characteristics of test anchors are shown in Table 1. The cross section area of grout is 20688 mm^2, the diameter of strand is 15.2 mm, and the elastic modulus of strand is $2.25\times10^7\ kN/m^2$, the cross section area of strand is 715 mm^2 for anchors with 5 strands, the average elastic modulus of grout is $2.07\times10^8 kN/m^2$.

In order to measure the load distribution on strand and grout, test anchors were instrumented with vibrating wire strainmeters on the strand and vibrating wire embedment gages in the grout section. The gage locations for anchors No.1 and No.2 are shown in Fig. 5. The single point extensometers were installed near the anchor to measure the movement of anchor head.

3.3 Pullout Load Test

The three types of load tests conducted during the research program included proof, performance, and creep test which were carried out in accordance with testing procedures by AASHTO(AASHTO, 1990) and FHWA (Weatherby, 1998). Proof test should be performed on every tieback, except those that are performance-tested, and assures that the tieback will carry its design load. Performance test should be performed on five percent of anchors to demonstrate the short term cyclic-load carrying behavior of anchors. Performance test of an anchor involves a sequence of loading and unloading until 133 percent of the design load is reached. The ultimate load of an anchor is defined to be the load at which the residual movement is one-tenth of an anchor diameter or the total movement is one-tenth of anchor diameter plus the elastic elongation of anchor unbonded length. Creep test is performed to investigate the long term characteristics of an anchor. The creep movement can be calculated by subtracting the total movement at 1 minute from the total movement at the given time during a particular load hold. The creep rate is the creep movement over one log cycle of time.

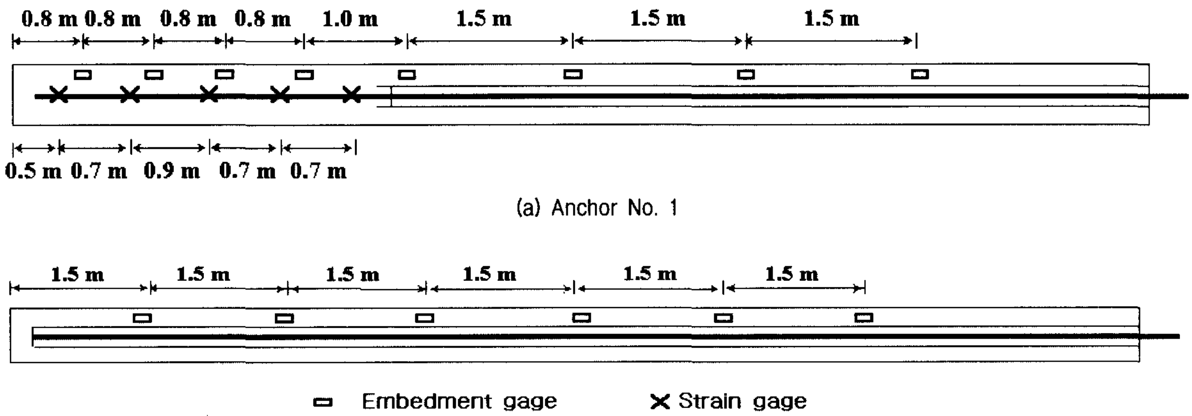


Fig. 5 Location of gages on the anchor No.1 and anchor No.2

4. Load Distribution on Anchor

The load distribution in a ground anchor is somewhat complex because it involves three different materials (soil, grout, and steel). In understanding this problem, it is helpful to first consider the load distribution in the three materials when the anchor is loaded up to the ultimate load, the load which causes complete failure of the soil in shear at the grout-soil interface. For this condition, the cumulative load resisted in shear by the soil varies as shown in Fig. 6(a). The load is equal to zero at the bottom of the anchor and to the ultimate load at the ground surface.

The ultimate load Q_{st} resisted by soil ;

$$Q_{st} = \sum_{1}^{n} f_u p l \tag{7}$$

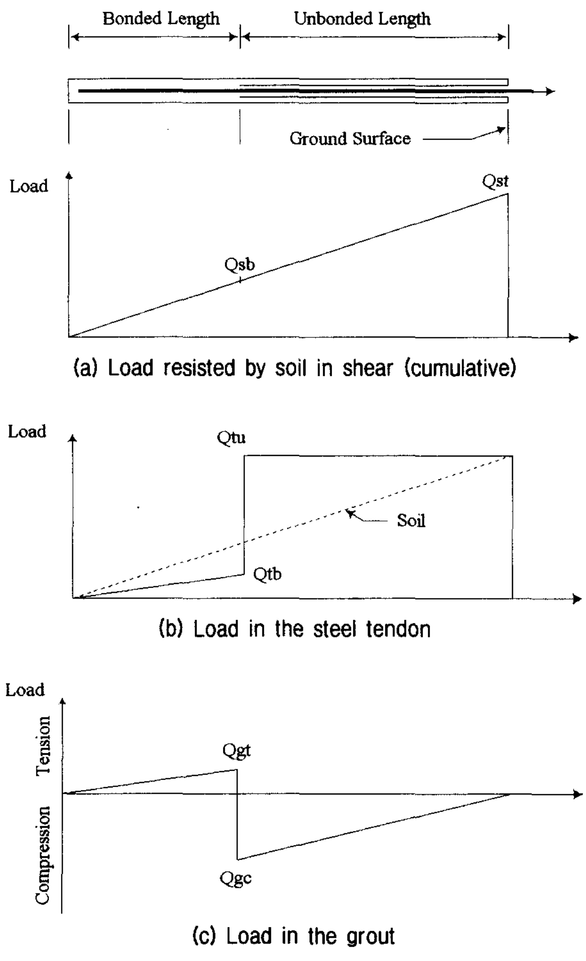


Fig. 6 Load distributiion on anchor at ultimate load

where f_u is the ultimate soil friction, p is the perimeter and l is the sum of the bonded length and the unbonded length. The maximum compression load Q_{gc} in the grout can be calculated as the difference between the ultimate load and the load Q_{sb} resisted by the soil in shear at failure at the bonded length/unbonded length boundary. The load Q_{sb} is ;

$$Q_{sb} = \sum_{1}^{n} f_u p l_{BL} \tag{8}$$

where l_{BL} is the bonded length. The maximum compression load in the grout Q_{gc} is then ;

$$Q_{gc} = Q_{st} - Q_{sb} \tag{9}$$

The tension load in the grout at the bonded length/ unbonded length boundary Q_{gt} is as follows ;

$$Q_{gt} = Q_{sb} - Q_{tb} \tag{10}$$

where Q_{tb} is the tension in the tendon immediately below that boundary. Also it is known that ;

$$Q_{gt} = A_g E_g \varepsilon_g \tag{11}$$

$$Q_{tb} = A_t E_t \varepsilon_t \tag{12}$$

where A, E, and ε are the cross sectional area, the modulus and the strain, respectively for the grout (subscript g) and the tendon (subscript t). Since plane sections remain plane, ε_t is equal to ε_g. Therefore, Q_{st} and Q_{tb} can be calculated as follows;.

$$Q_{gt} = \frac{A_g E_g}{A_g E_g + A_t E_t} Q_{sb} \tag{13}$$

$$Q_{tb} = \frac{A_t E_t}{A_g E_g + A_t E_t} Q_{sb} \tag{14}$$

5. Load Test Results

5.1 Ultimate Load and Maximum Friction

The ultimate load of an anchor is defined to be the load at which the residual movement is one-tenth of an anchor diameter or the total movement is one-tenth of anchor diameter plus the elastic elongation of anchor

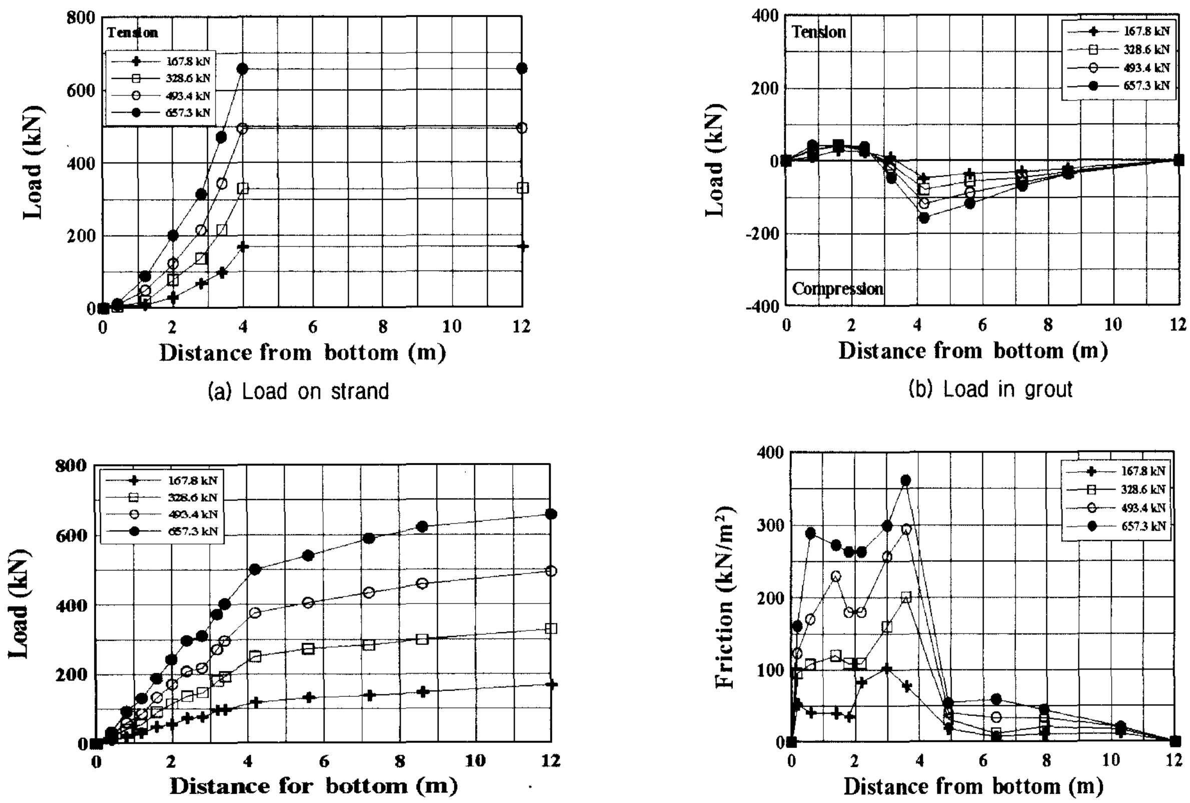
Table 2. Ultimate load from load test data

Anchor No.	Q_{ult} (kN)	L_a (m)	σ_{ov}' (kPa)	f_{max} (kPa)	K (f_{max}/σ_{ov}')	L_{bt} (m)
1	780	4	220	376	1.7	-
2	630	-	217	-	-	3.3
3	628	-	217	-	-	3.3
4	625	-	217	-	-	3.3
5	436	-	217	-	-	-
6	590	3	220	380	1.72	-
7	370	3	142	238	1.68	-

unbonded length. The residual movement, which is not recoverable, is the movement of anchor when the load is reduced to the alignment load. The elastic movement can be calculated by subtracting a residual movement from a total movement of anchor from the load movement curve of performance test.

The ultimate loads of the tension anchors No.1, No.6 and No.7 were obtained from the load tests, and are tabulated in Table 2. The maximum friction resistance and the coefficient K at ultimate load in equation (3) were calculated and are tabulated in Table 2. As shown in Table 2, the average K value of 1.7 was obtained for the maximum friction resistance of the weathered soil. The friction coefficient K in equation (3) was estimated to be 1.68 to 1.72, which is equivalent to the earth pressure coefficien K_1 of 2.4 with the friction angle of 35 degree.

where σ_{ov}' was calculated at the middle of bonded length.



(a) Load on strand

(b) Load in grout

(c) Load resisted by soil

(d) Load transfer distribution

Fig. 7 Load transfer on tension anchor No.1

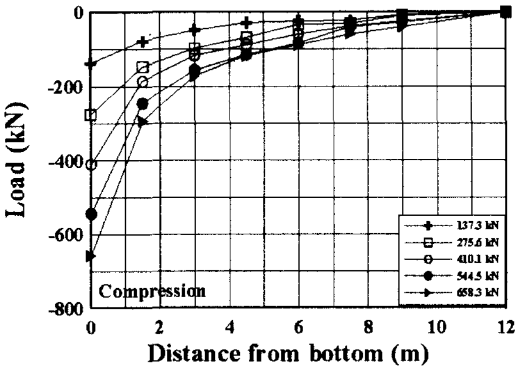
5.2 Load Transfer Mechanism

The load transfer mechanism was identified with measurements of load test. As explained in section 5, the load transfer of anchor depends on the load distribution on grout and strand. The load distribution on grout and strand was obtained from the measured strain data at each fraction of the ultimate load during load test and are shown in Fig. 7 and Fig. 8.

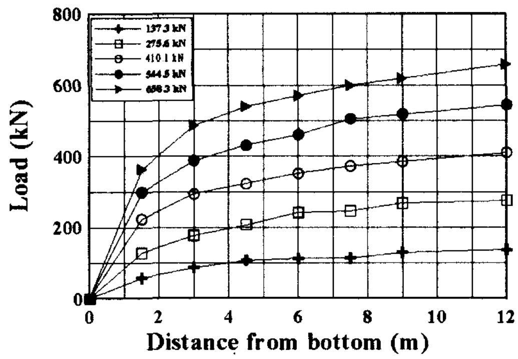
In the tension anchor No.1, the tensile load was observed in the bonded length and compressive load was measured in the unbonded length. The tensile load was limited to Q_{cr}, the load at which cracks in the grout occur. The load Q_{cr} was estimated by;

$$Q_{cr} = A_g E_g \varepsilon_{cr} \tag{15}$$

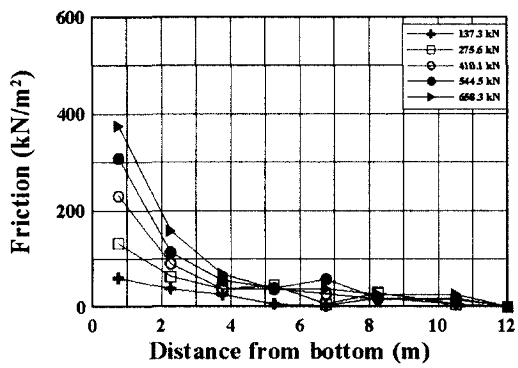
where A_g is grout section area, E_g is elastic modulus of grout, ε_{cr} is a strain at failure, 1×10^{-4} for the grout in tension. At the load level of 327 kN, 40 percent of the ultimate load, the tensile load exceeded this limit, and the crack may have developed. That is the reason why compression anchors have better capability of corrosion protection than tension anchors. As shown in Fig. 8, the compressive load was observed all along the length of compression anchor No.2.



(a) Load in grout



(b) Load resisted by soil



(c) Load transfer distribution

Fig. 8 Load transfer on compression anchor No.2

The load transfer on compression anchors was observed to be different from tension anchors. As shown in tension anchor No.1 (Fig. 7d), load started being transferred to the soil near the beginning of anchor bonded length. As the load increases, the friction resistance becomes larger while being distributed all along the bonded length. However, the friction resistance in compression anchors started developing at the end of anchors (Fig. 8c), and the maximum friction resistance occurred at the end of anchors throughout the test load. This load transfer mechanism explains why the compression anchors have less susceptibility to load loss due to the creep. The load loss due to the creep movement of anchors can be defined as follows;

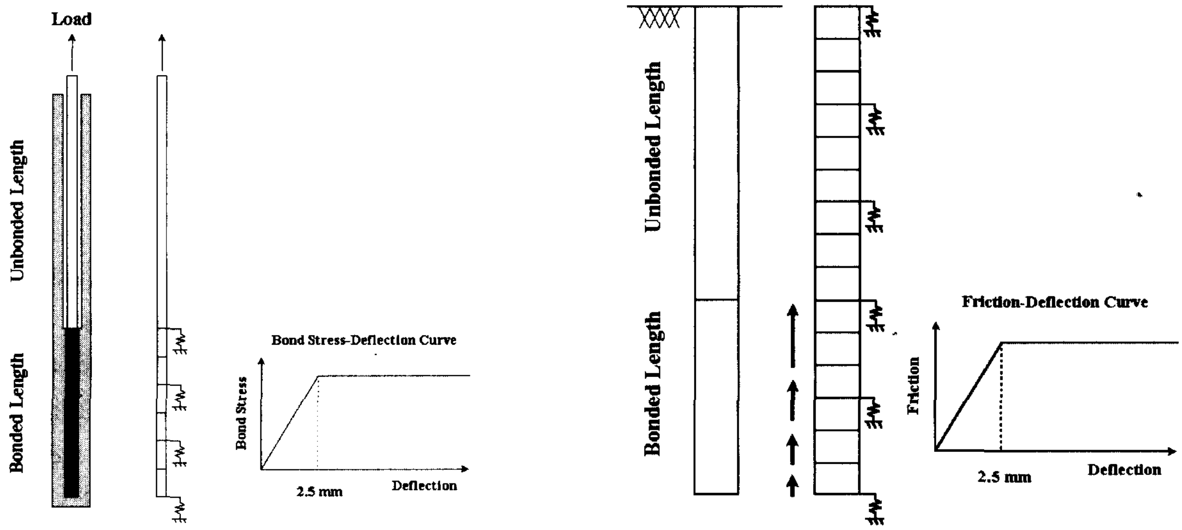
$$P = \frac{AE_t}{L_f} \Delta = K \bullet \Delta \tag{16}$$

The equivalent free length L_f of compression anchors is longer than that of tension anchors and then the slope K in equation (16) is smaller than the tension anchors.

6. Modeling and Numerical Analysis

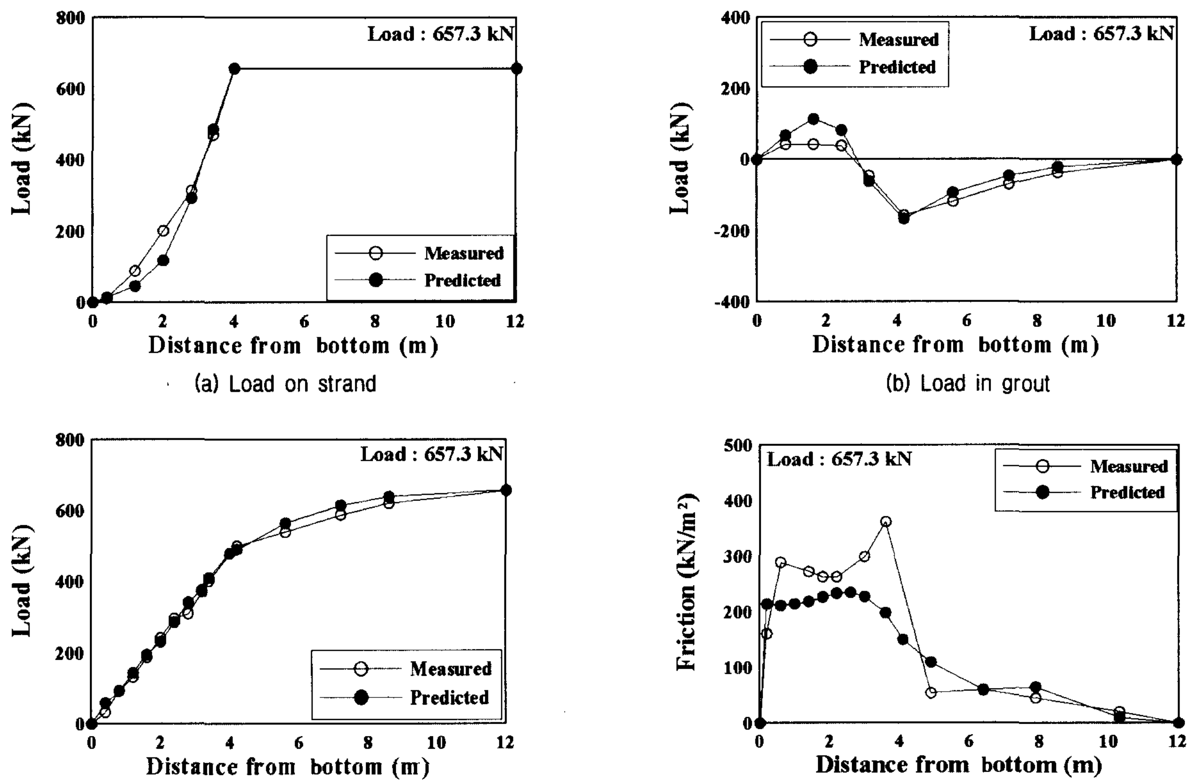
6.1 Beam-Spring Approach (t-z Curve Approach)

The constitutive equation for the anchor pull out is described in (17) as follows;



(a) Modeling of bonded length (b) Modeling of soil interface

Fig. 9 Modeling of an anchor



(a) Load on strand (b) Load in grout

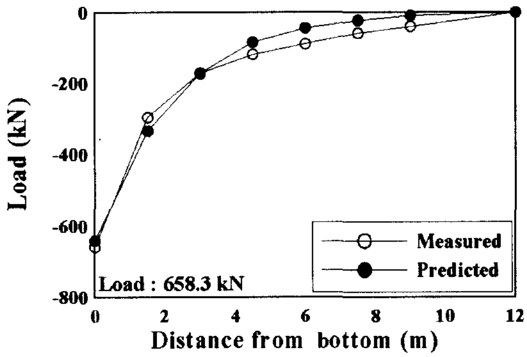
(c) Load resisted by soil (d) Load transfer distribution

Fig. 10 Analysis result of tension anchor

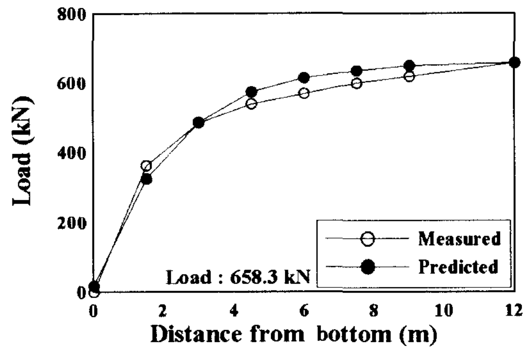
$$\frac{d^2w}{dx^2}-\frac{pK}{AE_a}w=0 \qquad (17)$$

where p is the perimeter of anchor, A is the area of anchor, E_a is the elastic modulus of anchor, K is the axial stiffness of soil response and pile movement curve. The beam-spring analysis (t-z curve method) developed by Coyle et. al. (1966) and Vijayvergiya (1977) was used to solve the equation.

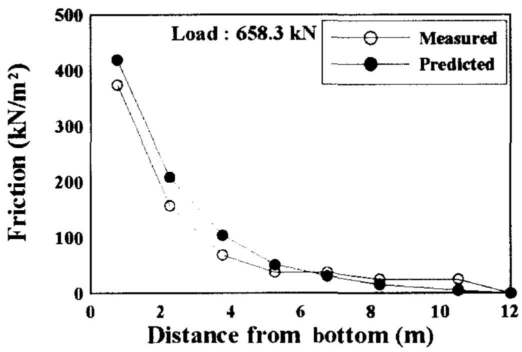
The beam-spring modeling of the tension type anchor is different from the compression anchor. The beam-spring analysis of the tension anchor was divided into two parts. First, the load transfer in the bonded length was analyzed as shown in Fig. 9(a). Second, the load transfer in anchor-soil interface was analyzed as shown in Fig .9(b). The analysis of the compression anchor was performed as shown in Fig. 9(b) by applying the anchor load at the end of anchor. The bond stress of 1600 kPa for the slip between the strand and grout was used and the peak friction value at the soil-grout interface was used to be the same as f_{max} obtained in Table 2.



(a) Load in grout



(b) Load resisted by soil



(c) Load transfer distribution

Fig. 11 Analysis result of tension anchor

6.2 Beam-Spring Analysis Results

The results from the first step of beam-spring analysis are compared with the measurements of load distribution on the strand and of load distribution on the grout on Fig.7 and Fig.8. The results from the second step of beam-spring analysis are compared with the measurements of the load distribution at the anchor-soil interface (Fig.9).

The result of the analysis shows the similar trend of the load transfer of an anchor up to a load level of 657 kN. For the highest load level of 775 kN, the measurements were quite scattered and could not be compared. The measured and predicted load distributions on the grout, strand, and anchor-soil interface were plotted on Fig.7 through Fig. 10. It may be concluded that the load transfer distribution from the measurements is reasonably correct.

7. Conclusions

The anchor pull-out load tests were performed on 7 instrumented full scale anchors installed in weathered soil in Korea. The following conclusions were drawn from the load test results.

(1) The load transfer distributions on tension anchor and compression anchor were identified based on the measured load distribution on each elements involved; grout and strand.

(2) In a weathered soil, the maximum friction resistance increases proportionately with the effective overburden pressure. The earth pressure coefficient $K = f_{max} / \sigma_{ov}'$ was obtained to be about 1.7.

(3) The beam-spring modeling technique (t-z curve approach) was proposed to evaluate the load transfer distribution from the anchor load test.

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