Jour of the KGS Vol 16, No 3, June 2000, pp 145~155

Load Transfer of Ground Anchors in Clay

점토지반에 설치된 앵커의 하중전이에 관한 연구

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요 지

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 정착장의 길이, 지반 조건 등에 따라 분포 양상이 변하기 때문에 하중 전이를 이해하기 위해서는 강선과 그라우트의 하중분포 그리고 앵커 그라우트체와 지반과의 마찰력 분포를 알아야 한다.

본 연구는 미국 Texas A&M University의 점성토지반에 계측기가 장착된 10개의 그라운드 앵커를 설치하여 인발시험을 수행하였다. 앵커의 자유장 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 하중전이를 얻어냈다. 또한 현장시험 결과의 역해석을 통하여 강선과 그라우트 사이의 하중과 변위의 관계와 그라우트와 지반의 하중-변위 관계를 분석하여 그라운드 앵커의 인발 특성을 예측 할 수 있는 수치해석 기법을 모델링하여 제시하였다.

Abstract

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. Anchor pull-out tests were performed on ten instrumented full-scale low-pressure grouted anchors installed in clay at the National Geotechnical Experimentation Site at Texas A&M University. The anchors were 0.3m in diameter and embedded 13.8 m in a very stiff clay. 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, Load distribution, Load transfer, Load test, Beam-spring analysis

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. The increase in use of ground anchors prompted to investigate the behavior of ground anchors. Temporary ground anchors have been studied by several researchers (Ostermayer

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1978, Littlejohn, 1968, 1970), and the topics of permanent ground anchors has 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; Cheney, 1988; Long et al., 1997; Mueller et al., 1988, Weatherby et al., 1997; Weatherby, 1998).

The basic mechanism of ground anchors is based on the load-displacement relationship and on the load distribution in the various component of anchors. 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.

In this research, ten full-scale small shaft low pressure grouted anchors are installed in clay at the National Geotechnical Experimentation Site at Texas A&M University. In order to measure the load distribution on the three different materials, anchors were instrumented and the pullout tests were performed.

2. Current Practice

Ultimate capacity of ground 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.

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

$$Q_{uf} = \pi D L_a f_{\max} \tag{1}$$

$$f_{\max} = \alpha S_u \tag{2}$$

where Q_{uf} = ultimate friction, D = diameter of anchor and $f_{\max}$ = unit friction between the soil and the grout, α = alpha value for friction, L_a = anchor bonded length, S_u = undrained shear strength of clay.

The friction resistance of the soil interface has been correlated to the undrained shear strength of the clay and quoted in references. Typical values for various clays are shown in Table 1.

The ultimate tensile load, Q_{us} in the strand can be calculated as follows;

$$Q_{us} = A_s f_{us} \tag{3}$$

where A_s = strand area, f_{us} = ultimate tensile stress of the strand.

Pullout resistance between the strand and the grout can be calculated as follows;

$$Q_{ub} = n \pi D_e L_b f_{ub} \tag{4}$$

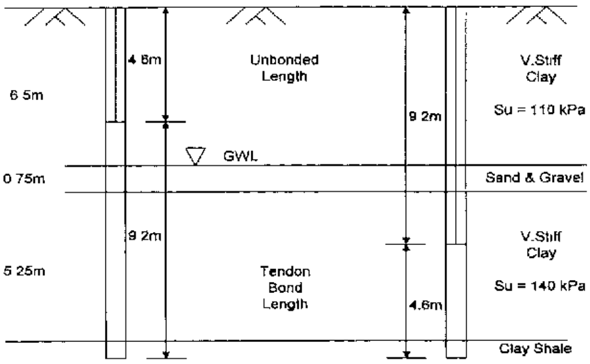
where n = number of strand, D_e = effective diameter of strand, L_b = bond length of the strand, f_{ub} = ultimate bond stress between grout and strand. The maximum allowable bond stress for bar tendons, stipulated by the British Code (Xanthakos, 1991) is shown in Table 2.

Table 1. Representative alpha value for various soils

Soil type	Shear Strength	α	Reference
Stiff London Clay	90 kPa	0.3–0.35	Littlejohn, 1968
Stiff Overconsolidated Clay at Taranta Italy	270 kPa	0.28–0.36	Sapio, 1975
Stiff to Very Stiff Marl at Leicester, England	287 kPa	0.48–0.6	Littlejohn, 1970
Stiff Clayey Silt at Johnnesburg South Africa	95 kPa	0.45	Neely et al, 1974
Heavily Overconsolidated Clay in Sweden	50 kPa	0.5	Broms, 1968

Table 2. Maximum allowable bond stress for bar tendons (Xanthakos, 1991)

Type of Bar	Characteric Strength of Grout (fcu N/mm^2)			
	20	25	30	40 +
	Maximum Bond Stress (N/m^2)			
Plain	1.2	1.4	1.5	1.9
Deformed	1.7	1.9	2.2	2.6



(a) Anchor No 5, 6, 7, 8, 9, 10 (b) Anchor No 1, 2, 3, 4

Fig. 1 Soil layers and anchor layout

3. Anchor Pullout Load Test

3.1 National Geotechnical Experiment Site

Anchors were constructed at National Geotechnical Experiment Site on Texas A&M University. The subsurface soil consists predominantly of very stiff overconsolidated clay. The clay deposit at the location of the anchor load test consists of a 6.5 m thick layer of clay with the following properties; water content w = 24.4 %, plastic limit w_p = 20.9%, liquid limit w_L = 53.7% natural unit weight γ_t = 19.6 kN/m^3, undrainded shear strength s_u = 110 kN/m^2 , cone penetrometer tip resistance q_c = 2MPa, pressuremeter limit pressure p_l = 0.8 MPa, SPT blow count N = 12 blows/0.3 m. The water table is 6m deep and a 0.5m to 1m thick layer of sand and gravel exists at a depth of around 6.5 m. This sand and gravel layer is underlain by a layer of very stiff clay down to 12.5 m with the following average characteristics; water content w = 24.5 %, plastic limit w_p = 22%, liquid limit w_L = 65.5%, natural unit weight γ_t = 19.5 kN/m^3, undrainded shear strength S_u = 140 kN/m^2, cone penetrometer tip resistance q_c = 6 MPa, pressuremeter limit pressure p_l = 2.2 MPa, SPT blow count N = 32 blows/0.3 m.

3.2 Instrumentaion and Construction

The anchors were installed using a rotary-type drill auger with a grout pressure of 0.69 MPa. The anchors were 0.3 m diameter and embedded 13.8 m a stiff clay. Four anchors had a tendon bond length of 4.6 m (anchor No. 1, 2, 3 and 4) and six anchors had a tendon bond length of 9.2 m. (anchor No. 5, 6, 7, 8, 9 and 10). The layout of anchors are shown in Fig.1. The anchor diameter is 305mm, diameter of strand is 15.4 mm. The cross section area of grout is 72045 mm^2, the elastic modulus of grout is 2.07 × 107 kN/m^2, the cross section area of strand is 980 mm^2, the elastic modulus of strand is 2.07×10^8 kN/m^2.

The anchors were instrumented with vibrating wire strainmeters on the strand and vibrating wire embedment gages in the grout section. The gage locations for anchor No.1 are shown in Fig.2. For measuring displacement of anchor head, the extensometers were installed near the anchor.

3.3 Pullout Load Test

The three types of load tests conducted during the research program includes proof, performance, and creep tests which were carried out in accordance with testing procedures by the AASHTO(AASHTO, 1990).

Proof test should be performed on every tieback, except those that are performance-tested and assures that the tieback will carry its design load. Elongation of the tieback results from straining the tendon and strain of the anchor-soil system. On this test, the load which is equal to 1.33 times design load is reached and held for 10 minutes. During the load hold, the anchor head displacement is read at 1 minute, 2, 3, 4, 5, 6, and 10 minutes. If the the move

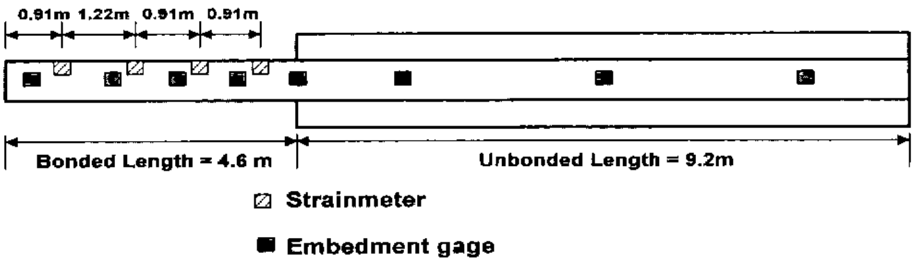
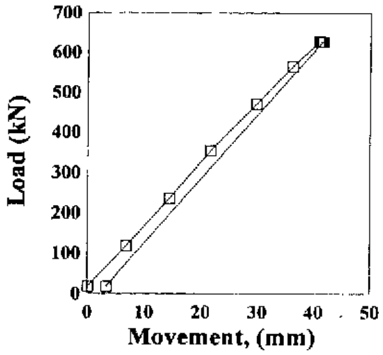
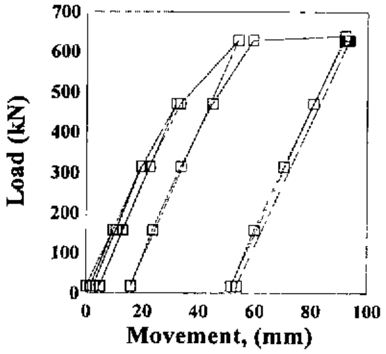


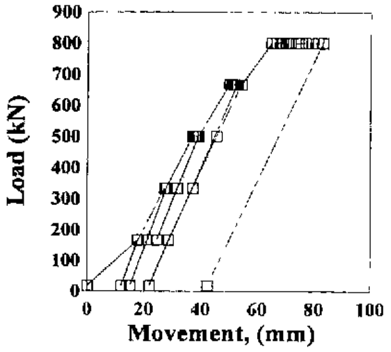
Fig. 2 Location of gages on the anchor no.1



(a) Proof Test



(b) Performance Test



(c) Creep Test

Fig. 3 Load displacement curve of load test

ment does not exceed 2.0 mm per log cycle of time, then this anchor is considered acceptable to carry the design load. If anchor movement does exceed 2.0 mm, then the anchor should be modified. The schematic diagram of the proof test is shown in Fig.3-(a).

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. If the residual movement at the 133 percent of design load is less than one-tenth of an anchor diameter, the anchor is acceptable. The slope of the load-movement curve from this test should also be checked to verify the free length of an anchor. The performance test is shown in Fig.3-(b).

Creep test is performed to investigate the long term characteristics of an anchor. This type of test is especially important for permanent anchors or anchors installed in cohesive soils having a plasticity index exceeding 20. 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 moment over one log cycle of time. If this value does not exceed 2 mm per log cycle, then the anchor is acceptable. The creep movement of load versus total movement is shown in Fig.3-(c)

The ultimate loads of anchors and the alpha value for equation (2) are obtained from the load test and tabulated

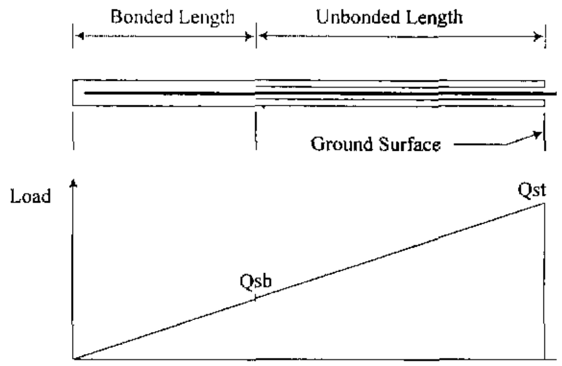
Table 3. Ultimate loads and alpha values

Anchor Number (1)	Ultimate load (kN)	Bonded Anchor Length(m)	Friction stress at failure(kN/m^2)	α Value
1	867	4.57	65.9	0.53
2	1080'	4.57	82.1	0.66
3	ID[a]	4.57	–	–
4	934	4.57	71.0	0.57
5	ID[a]	4.57	–	–
6	712[b]	4.57	54.1	0.43
7	801	9.15	60.9	0.49
8	747	9.15	56 8	0.45
9	ID	9.15	–	–
10	801	9.15	60.9	0.49

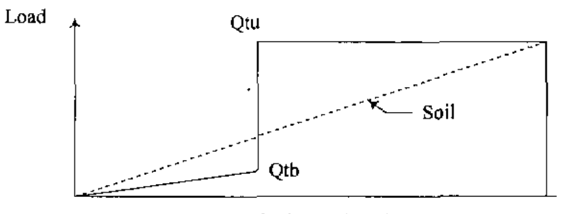
[a] Insufficient displacement

[b] Installation difficulties encountered; 60% of anchor not grout under pressure but simply free-fall

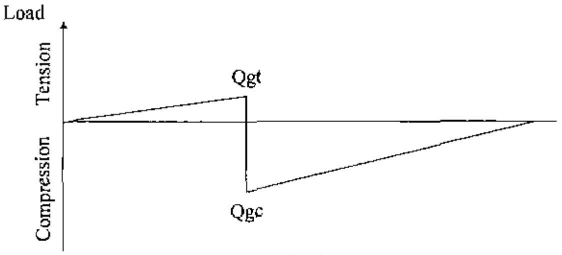
in Table 3 (for details, refer to Briaud et. al. 1998). From these tests, the load distribution of an anchor was measured and analysed.



(a) Load resisted by soil in shear (cumulative)



(b) Load in the steel tendon



(c) Load in the grout

Fig. 4 Load distribution at ultimate load

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 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 on the example in Fig. 4(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 ;

$$Q_{st} = \sum_{1}^{n} f_u p l \qquad (5)$$

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 ;

$$Q_{sb} = \sum_{1}^{n} f_u p l_{BL} \qquad (6)$$

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

$$Q_{gc} = Q_{st} - Q_{sb} \tag{7}$$

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

$$Q_{gt} = Q_{sb} - Q_{tb} \tag{8}$$

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

$$Q_{gt} = A_g E_g \varepsilon_g \tag{9}$$

$$Q_{tb} = A_t E_t \varepsilon_t \tag{10}$$

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_{gt} and Q_{tb} can be calculated as follows;

$$Q_{gt} = \frac{A_g E_g}{A_g E_g + A_t E_t} Q_{sb} \tag{11}$$

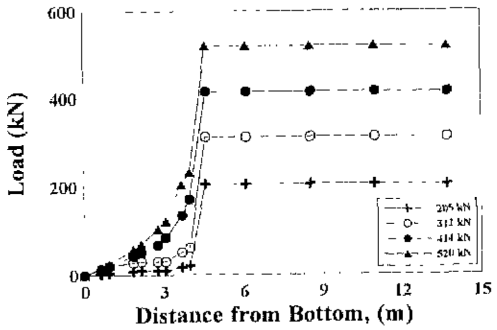
$$Q_{tb} = \frac{A_t E_t}{A_g E_g + A_t E_t} Q_{sb} \tag{12}$$

The load distributions in grout and strand obtained from the measurements are shown in Fig. 5(a) and 5(b). The cumulative load resisted by soil and the load transfer is shown in Fig. 5(c) and 5(d). The load data for the test load more than 520 kN could not be obtained because of the scatter of the data. The numerical technique was developed, verified with these test results, and used to extrapolate the data up to the ultimate load.

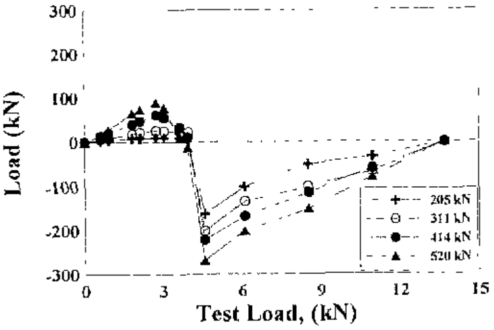
5. Modeling and Numerical Analysis

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

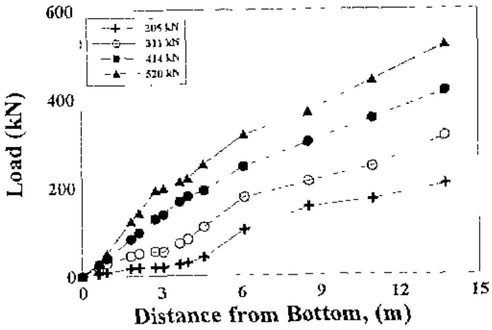
The constitutive equation for the anchor pull out is described in (13) as follows;



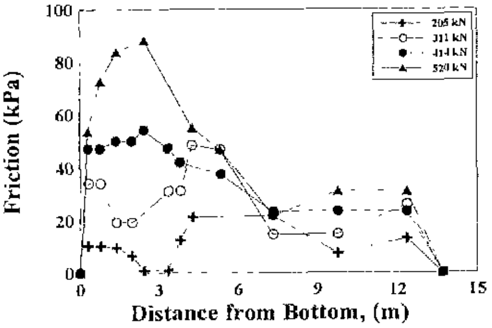
(a) Load Distribution in Grout



(b) Load Distribution in Strand



(c) Load Resisted by Soil



(d) Load Transfer on Anchor

Fig. 5 Load distribution from measurements on anchor no.1

$$\frac{d^2w}{dx^2} - \frac{pK}{AE_a}w = 0 \tag{13}$$

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 analysis of an anchor was divided into two parts. First, the load transfer in the bonded length was analyzed as shown in Fig.6(a). Second, the load transfer in anchor-soil interface was analyzed as shown in Fig.6(b). The bond stress deflection curve was obtained by back analysis to match the measured load distribution on strands. The friction deflection curve (as suggested by Briaud, 1998) was obtained by back analysis to match the load transfer on anchors at the soil-grout interface. The bond stress of 1500 kPa for the slip between the strand and grout was used, a little higher value than plain bar tendons as shown in Table 2. The peak friction value at the soil-grout interface was used to be the same as the undrained shear strength and the residual value was obtained by multiplying the undrained shear strength by average α value of 0.59.

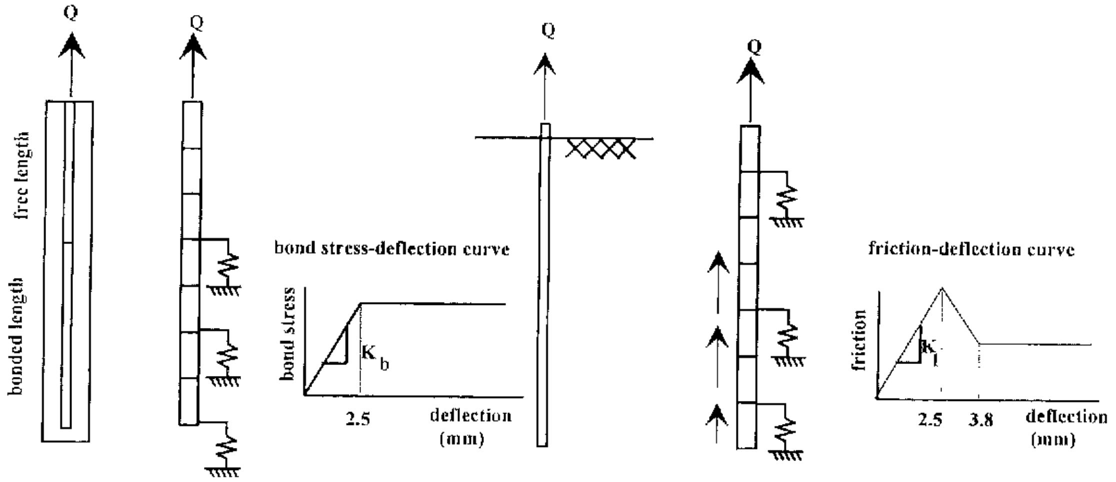
5.2 Beam-spring Analysis Results

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 from the proposed modeling shows the similar trend of the load transfer of an anchor up to a load level of 520 kN. For the highest load level of 775 kN, the measurements were quite scattered and the load transfer of the anchor could not be obtained. The load transfer at the load level of 775 kN was obtained by the proposed beam-spring analysis are shown in Fig.11. The measured and predicted load distributions on the grout, strand, and anchor-soil interface were plotted on Fig.7 through Fig.10. The load-movement curve predicted by the proposed modeling was compared with the load test results in Fig.12.

6. Conclusion

Ten anchors were constructed at National geotechnical Experimentation Site at Texas A&M University. The



a) Modeling of bonded length

b) Modeling of anchor

Fig. 6 Modeling of an anchor

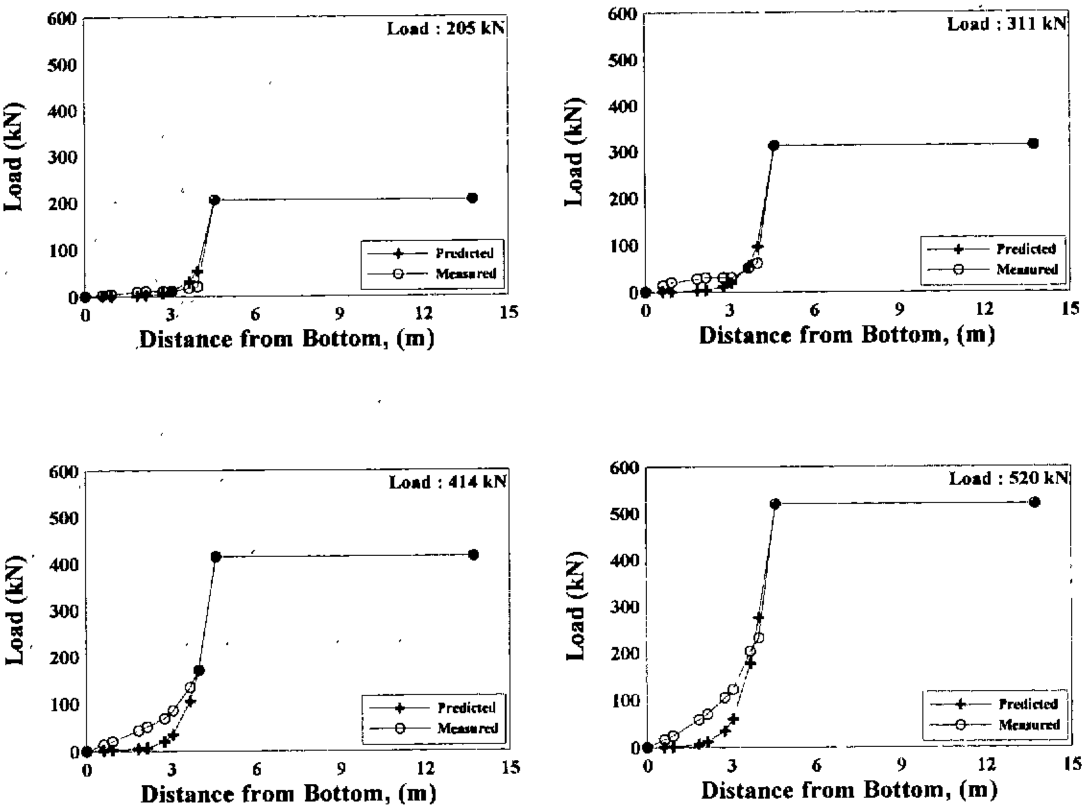


Fig. 7 Load distribution in grout on anchor no.1

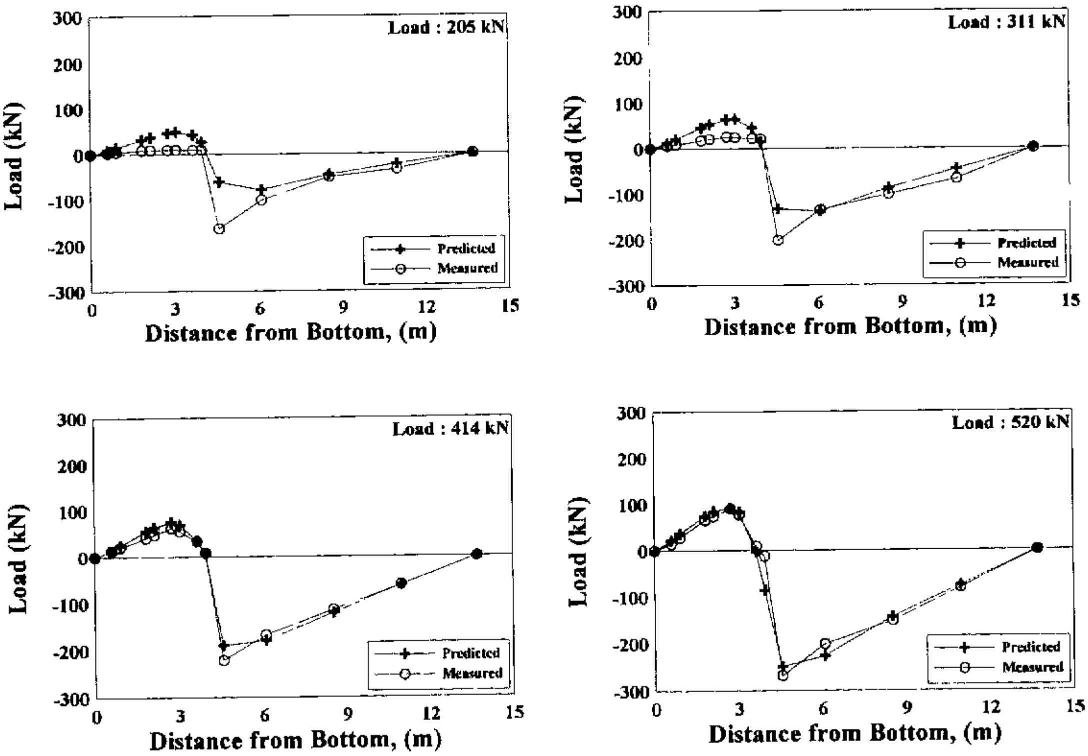


Fig. 8 Load distribution in strand on anchor no.1

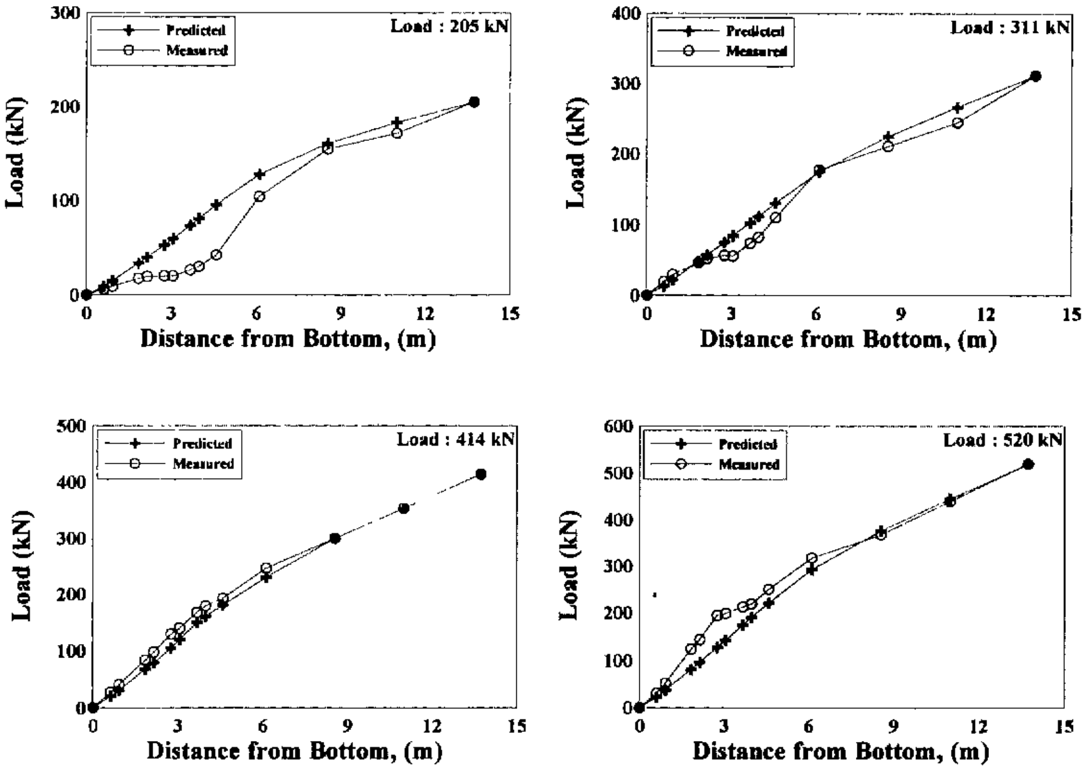


Fig. 9 Load resisted by soil on anchor no.1

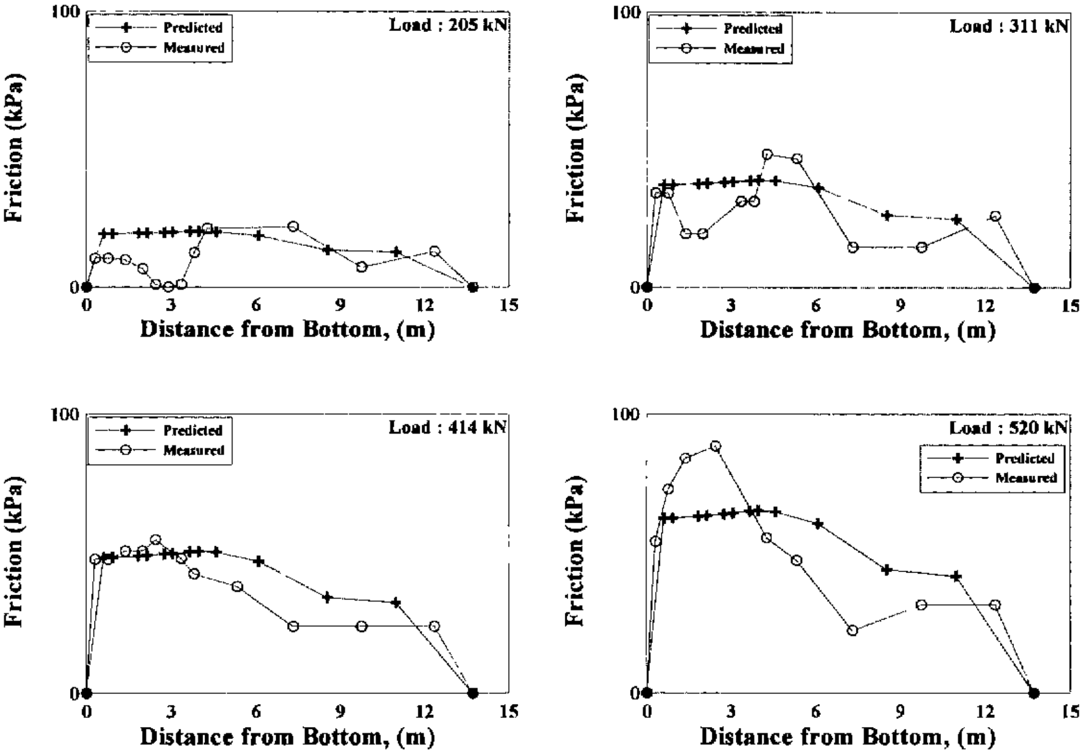


Fig. 10 Load transfer on anchor no.1

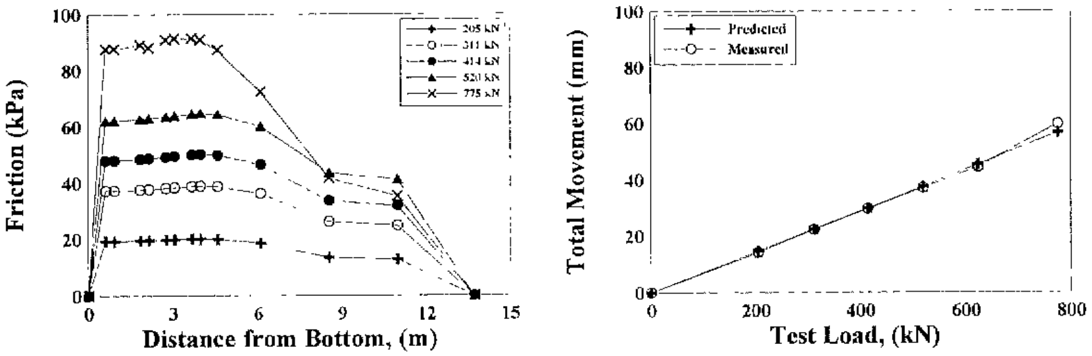


Fig. 11 Predicted load transfer on anchor no.1

anchor pullout load test on 10 instrumented anchors in clay was performed. The following conclusions were drawn from the measurements.

1) The average α value of 0.59 was obtained for the ultimate load on anchors which have the bonded length of 4.57 m. This results show that the current design practice for ground anchor in clay is appropriate. The ultimate load was defined to be the load which creates the residual movement of one-tenth of the anchor diameter.
2) The basic load transfer mechanism of anchors in clay was identified with the measurements on anchors. The load transfer at each fraction of the ultimate load was obtained from the measurements up to the load level of 520 kN.
3) The beam-spring modeling was proposed to identify the load transfer mechanism of anchors. The model was evaluated by comparing the results with the measurements and used to predict the load transfer at the load of 775 kN near ultimate load.
4) The load movement prediction by the proposed model shows good agreement with the measured one.

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(received on May., 19, 2000)