Abstract

A procedure of finite-element modeling and beam-column modeling of ground anchors was proposed in this study to investigate the load transfer mechanism in ground anchors. The procedure included the modeling of soil, grout, and strand tendon and the interface modeling of soil–grout and grout–strand in ground anchors. A series of finite element analyses and beam-column analyses were performed using the proposed models on ground anchors. The numerical predictions were compared with observed measurements in a field load test. The results indicated that the numerical simulation of load transfer mechanism on ground anchors can provide reasonable predictions.

Keywords: Ground anchors; Finite element method; Beam column method; Load transfer

1. Introduction

Ground anchors are steel tendons or strands used to transmit an applied tensile load into soil or rock through cement grouting. A ground anchor is much more complicated than a pile mechanism since the load is transferred from the tendon to the grout, and then, to the soil. The load distribution and load transfer mechanism of a ground anchor must be clearly identified to properly design anchored retaining walls or anchored slopes. The load transfer behavior of various types of ground anchors has been studied and reported by Weerasinghe and Littlejohn [36], Benmokrane et al. [6], Barley [3,4], Jarrel and Haberfield [25], Woods and Barkhordari [37], Briaud et al. [11], and Kim [27]. Although the previous studies have given insights into the mechanism of the soil–anchor interaction, the load transfer mechanism of ground anchors needs to be investigated to better understand the behavior of ground anchors.

Numerical techniques may be very efficient for investigating the load transfer of ground anchors. Desai et al. [17] performed a numerical simulation of a ground anchor to investigate the mechanism of stresses and deformations in an anchor–soil system. In the simulation of ground anchors, the modelings of soil–grout and grout–strand interfaces are important. Grout–strand and grout–soil interface must be modeled in detail to carry out a more feasible design and analysis of ground anchors.

The finite elements technique to handle interfaces such as slippage and separation has been quite well established, and numerous researches on this subject were performed by Goodman et al. [21], Ghaboussi et al. [20], Hermann [23], Pande and Sharma [32], Frank et al. [19], Carol and Alonso [12], Desai et al. [16], Beer [5], and Griffiths [22].

The beam-column method has been widely used to predict the behavior of piles or retaining walls subjected to horizontal or vertical loads. The load–deflection curves (p – y curves) or the load–settlement curves (q – w curves) have been used to represent the soil–structure interaction problems in the beam-column analysis. Many studies on beam-column analysis have been performed by Dunnavant and O’Neil [18], Briaud [9], Briaud and Kim [10], Kim et al. [28], and Jeong and Seo [26].

The details of finite-element modeling and beam-column modeling of low-pressure grouted straight shaft ground anchors are presented in this study.
anchors were proposed in this paper to investigate the load transfer mechanism. The modelings of soil, grout, and strand tendon and the modelings of soil–grout and grout–strand interfaces are presented in this paper. A series of finite element analyses and beam-column analyses of the ground anchors in weathered soil were performed in this study. The numerical simulation of the load transfer mechanism on ground anchors was evaluated by comparing its predictions with the measurements obtained from the field load test.

2. Background

2.1. Design of anchors

The ultimate capacity of low-pressure grouted straight shaft 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.

The ultimate friction resistance \( Q_{uf} \) at the soil–grout interface can be calculated as follows:

\[
Q_{uf} = \pi DL_a f_{\text{max}},
\]

\( f_{\text{max}} = ax S_u \) (cohesive soil),

\( f_{\text{max}} = K\sigma'_{ov} \) (cohesionless soil),

where \( Q_{uf} \) is the ultimate friction; \( D \) the diameter of anchor or effective diameter of borehole; \( f_{\text{max}} \) the maximum friction between soil and grout; \( L_a \) the anchor-bonded length of tension anchors or bonded transmission length of compression anchors; \( a \) the empirical reduction factor; \( S_u \) the undrained shear strength of clay; \( \sigma'_{ov} \) the effective overburden pressure; and \( K \) is the coefficient of friction, which is equal to \( K_1 \tan \phi \), as presented by Littlejohn [29]. \( K_1 \) is the earth pressure coefficient and \( \phi \) is the friction angle of the soil. The maximum friction of \( f_{\text{max}} \) can also be correlated to various soil properties and anchor types, as reported by PTI [33].

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

\[
Q_{up} = \pi n D_e L_b f_{ub},
\]

where \( n \) is the number of strand; \( f_{ub} \) the ultimate bond stress between grout and strand; \( L_b \) the bonded length of strand; and \( D_e \) is the effective diameter of strand.

The ultimate tensile load of strand \( Q_{us} \) can be calculated as follows:

\[
Q_{us} = A_s f_{us},
\]

where \( A_s \) is the cross-sectional area of strand and \( f_{us} \) is the ultimate tensile stress of strand.

The ultimate compressive or shear resistance of grout \( Q_{ugb} \) can be calculated as follows:

\[
Q_{ugb} = A_g f_{uc},
\]

where \( f_{uc} \) is the ultimate compressive strength of grout or pure shear strength of grout and \( A_g \) is the grout area or shear area. This criterion depends on the type of anchor body, either end bearing plate or tube type.

2.2. Load transfer mechanism

The load transfer mechanism in a ground anchor is complex because it involves three different materials: soil, grout, and strand tendon. In understanding this mechanical behavior, it is helpful to first consider the load distribution in the three materials when the anchor is loaded to the ultimate load, which causes the complete failure of the soil in shear at the soil–grout interface. The load distributions in soil, strand, and grout at the anchor’s ultimate load are schematically described in Fig. 1, as reported by Briaud et al. [11]. As can be seen in Fig. 1a, the cumulative load resisted in shear by the soil varies. 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 can be calculated as follows:

\[
Q_{st} = \sum f_u \cdot p l,
\]

where \( f_u \) is the ultimate friction of soil, \( p \) is the perimeter of anchor, and \( l \) is the sum of bonded length and unbonded length. The load \( Q_{sb} \) resisted by soil at the boundary

![Fig. 1. Load distribution in ground anchor at ultimate load: (a) load resisted by soil, (b) load in strand, and (c) load in grout.](image-url)
between bonded length and unbonded length can be estimated as follows:

\[ Q_{sb} = \sum_{i} f_u \cdot \rho l_{bi}, \]  

(8)

where \( l_{bi} \) is the bonded length. Then, the maximum compression load \( Q_{gc} \) in the grout at the boundary between the bonded length and the unbonded length can be calculated as follows:

\[ Q_{gc} = Q_{st} - Q_{sb}, \]  

(9)

Also, the tension load \( Q_{gt} \) in the grout at that boundary can be obtained from the equation

\[ Q_{gt} = Q_{sb} - Q_{tb}, \]  

(10)

where \( Q_{tb} \) is the tension load in the strand at the boundary between the bonded length and the unbonded length. The \( Q_{gt} \) and the \( Q_{tb} \) are expressed as follows:

\[ Q_{gt} = A_gE_g \varepsilon_g, \]  

(11)

\[ Q_{tb} = A_tE_t \varepsilon_t, \]  

(12)

where \( A, E, \) and \( \varepsilon \) are the cross-sectional area, the elastic modulus, and the strain, respectively, for the grout (subscript \( g \)) and the strand (subscript \( t \)). Here, \( \varepsilon_t \) is equal to \( \varepsilon_g \). Therefore, the \( Q_{st} \) and the \( Q_{tb} \) can be rewritten as follows:

\[ Q_{gt} = \frac{A_gE_g}{A_gE_g + A_tE_t} Q_{sb}, \]  

(13)

\[ Q_{tb} = \frac{A_tE_t}{A_gE_g + A_tE_t} Q_{tb}. \]  

(14)

### 3. Field load tests

Anchor pullout load tests were performed on seven full-scale and low-pressure grouted anchors in weathered soil at the Geotechnical Experimentation Site at Sungkyunkwan University in Suwon, Korea. The anchors were 165 mm in diameter and embedded 9–12 m in weathered soil. Three were tension type and four were compression type anchors. Details of construction, instrumentation, testing procedures, and results are reported by Kim [27].

Details of elevation and components of test anchor are schematically illustrated in Fig. 2. The subsurface soil in the site consists of medium dense silty sand (fill) from the ground surface to a depth of 4 m, medium dense sandy clay (alluvial deposit) from the bottom of the fill to a depth of 5.8 m, weathered soil up from the bottom of the alluvial deposit to a depth of 12 m, and weathered rock below the depth of 12 m. The percent passing the No. 200 sieve of the weathered soil was less than 20% with the coefficients of uniformity and gradation of \( C_u = 10 \) and \( C_c = 1.2 \), respectively. Details of the site conditions are summarized by Kim [27].

### 4. Finite-element modeling

In this study, the program ABAQUS [2] was used for the finite element analyses of ground anchors. Details of the finite-element modeling are proposed and presented in this paper.

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**Fig. 2.** Elevation and components of test anchor (schematic).
4.1. Finite element mesh

The ground anchor was modeled as axisymmetric case. Because of the symmetry about the anchor centerline, only a half plane of the cylinder was considered in the finite element analyses. A refined mesh was adopted to minimize the effect of mesh efficiency on the finite element analyses, as illustrated in Fig. 3. The mesh consisted of 6147 nodes and 1981 elements for the tension anchor and consisted of 6672 nodes and 2152 elements for the compression anchor. Locations of mesh boundaries were selected based on the study by Desai et al. [17]. As can be seen in Fig. 3, these finite element meshes extend to a depth of 20 m below the ground surface and laterally to a distance of 10 m from the anchor centerline.

4.2. Soil element model

In the finite element analyses, the soil was simulated with 2D four-noded axisymmetric brick elements with reduced integration option. The soils were assumed to be elasto-plastic materials obeying the Drucker–Prager failure criterion together with the non-associated flow rule proposed by Davis [14]. The Drucker–Prager model parameters are the angle of friction \( \phi \) and the cohesion \( c \) on the space of the first invariant of the stress tensor \( J_1 \) and the second invariant of the deviatoric stress tensor \( J_2^{\text{D}} \). The model parameters of \( \phi \) and \( c \) are computed by using the Mohr–Coulomb strength parameters of the friction angle \( \phi_{\text{vc}} \) and cohesion \( c_{\text{vc}} \) in conjunction with the parameters of \( \phi \) and \( c \), as referred to by Desai and Siriwardane [15] and ABAQUS [2]. The dilatancy angle \( \psi \) was obtained from Eq. (15) based on the Rowe’s stress–dilatancy theory [34] and on the results proposed by Bolton [7].

\[
\sin \psi = \frac{\sin \phi - \sin \phi_{\text{vc}}}{1 - \sin \phi \sin \phi_{\text{vc}}},
\]

where \( \phi_{\text{vc}} \) is the constant critical state friction angle. The soil stiffness \( E_s \) was calculated based on an empirical relationship reported by Janbu [24] as follows:

\[
E_s = m \sigma_3 (\sigma_1 / \sigma_3)^{1-a},
\]

where \( m \) is the modulus number, \( \sigma_3 \) the atmospheric pressure (98–101 kN/m\(^2\)), \( \sigma_3 \) the confining pressure, and \( a \) is the pure number (between 0 and 1). Soil material parameters used in the finite element analyses are summarized in Table 1.

4.3. Anchor element model

In the analyses, the strand in the anchor was simulated with 2D four-noded axisymmetric brick elements. This brick model was treated as a linear elastic material. The strand material properties are as follows: the diameter of the strand = 12.7 mm, the elastic modulus of the strand = \( 2.07 \times 10^8 \) kN/m\(^2\), and the cross sectional area of the strand for anchors with five strands = 494 mm\(^2\). The grout in the anchor was simulated with 2D eight-noded axisymmetric brick elements with reduced integration option. The grout

Table 1
Soil material parameters examined in the finite element analyses

<table>
<thead>
<tr>
<th>Material</th>
<th>( \gamma ) (kN/m(^3))</th>
<th>( \nu )</th>
<th>( E_s ) (kPa)</th>
<th>( \phi ) (°)</th>
<th>( K_a )</th>
<th>( K_o )</th>
<th>( \psi ) (°)</th>
<th>( c ) (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fill</td>
<td>18.6</td>
<td>0.3</td>
<td>15,000</td>
<td>25</td>
<td>0.6</td>
<td>1.0</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Sandy clay</td>
<td>17.6</td>
<td>0.3</td>
<td>20,000</td>
<td>30</td>
<td>0.5</td>
<td>1.0</td>
<td>4</td>
<td>10</td>
</tr>
<tr>
<td>Weathered soil</td>
<td>19.6</td>
<td>0.3</td>
<td>45,000</td>
<td>38</td>
<td>0.4</td>
<td>1.0</td>
<td>6</td>
<td>20</td>
</tr>
</tbody>
</table>

\( K \) is the ratio of the yield stress in triaxial tension to the yield stress in triaxial compression.

Fig. 3. Finite element mesh: (a) tension anchor and (b) compression anchor.
was modeled as a linear elasto-perfect plastic material. The grout material properties are as follows: the cross sectional area of the grout = 20,888 mm², the average compressive strength of the grout = 20 MPa, the tensile strength of the grout = 2.0 MPa, the tensile strain failure = 1.0 × 10⁻⁴ by Neville [31], and the average elastic modulus of the grout = 2.1 × 10⁷ kN/m² obtained from the following formula:

\[ E_c = 4.73 \sqrt{f_{ck}}, \]  

(17)

where \( E_c \) is expressed in GPa and \( f_{ck} \) in MPa, as reported by Neville [31].

4.4. Soil–grout and grout–strand interface surface model

The soil–grout interface was modeled using the Coulomb friction model provided in ABAQUS. The model proposed relates the shear stress across the interface to the contact pressure between the soil and the grout. As can be seen in Fig. 4a, this model defines the critical shear stress as follows:

\[ \sigma_{cr} = \gamma z \]

\[ \sigma_{t0} = K_0 \sigma_{cr} \]

\[ E_c = 4.73 \sqrt{f_{ck}} \]

where \( E_c \) is expressed in GPa and \( f_{ck} \) in MPa, as reported by Neville [31].
where $\mu$ is the constant friction coefficient and $p$ is the contact pressure. The friction coefficient $\mu$ of 1.7 for the weathered soil proposed by Kim [27] was used in the analyses.

The interface between the grout and the strand was modeled using the Coulomb friction model with the maximum shear stress limit $\tau_{\text{max}}$. This model provides the $\tau_{\text{max}}$, so that, regardless of the magnitude of the contact pressure stress, sliding will occur if the shear stress reaches this limit (Fig. 4b). For the analyses, the maximum shear stress $\tau_{\text{max}}$ was considered as the maximum bond stress between the grout and the strand, and the value of $\tau_{\text{max}} = 1.9 \times 10^3 \text{kN/m}^2$ was calculated based on an empirical relationship given by AASHTO [1] as follows:

$$\tau_{\text{max}} = 4.8 \sqrt{f_{\text{ck}}/d},$$

where $\tau_{\text{max}}$ is the maximum bond stress, $f_{\text{ck}}$ the ultimate grout strength, and $d$ is the diameter of strand. For the analyses, the cement grout was assumed to be completely adhered to the strand unless the debonding occurred, thus, high friction coefficient was assumed and applied to the interface between the grout and the strand.

For modeling the behavior in the normal direction of the interface at the end of grout body and strand, a contact model available in ABAQUS to define an exponential contact pressure–overclosure relationship was used in the analyses. The contact pressure transmitted at the end of anchor reduces to zero as the clearance $c^0$ is reached, as shown in Fig. 4c. The overburden pressure of $\sigma_3$ was used as the contact pressure $p^0$, and the clearance $c^0$ ranging between $10^{-2}$ and $10^{-4}$ m was examined in the finite element analyses.

### 4.5. Anchor loading simulation

The modeling of the anchor load consists of two phases as illustrated in Fig. 5. The first phase was to apply the gravity stresses on the entire solid involving the soil and the anchor, which was 10 m in width and 20 m in depth. In the soil element, the lateral stresses were calculated with a lateral earth pressure coefficient $K_o$. The second phase is
to apply the pullout load at the top of the anchor. The load was sequentially applied up to the final design load.

5. Beam-column modeling

A simple beam-column numerical model was proposed in this study to investigate the load transfer mechanism of ground anchors. The constitutive equation for the anchor pullout is expressed as follows:

\[
\frac{d^2w}{dx^2} + \frac{pK}{AE_a}w = 0, \quad (20)
\]

where \( p \) is the perimeter of anchor, \( A \) the area of anchor, \( E_a \) the elastic modulus of anchor, and \( K \) is the axial stiffness of soil response on pile movement curve. The beam-column analysis developed by Coyle and Reese [13] and Vijayvergiya [35] was used to solve the equation. A program BMCOL 76 introduced by Matlock et al. [30] was used to simulate ground anchors.


The beam-column modeling of the tension anchor was divided into two parts. First, the load transfer in the grout–strand interface was analyzed by using bond stress–deflection curve assumed to be elasto-perfectly plastic, as seen in Fig. 6a. Second, the load transfer in the soil–grout interface was analyzed by using friction–deflection curve exhibiting elasto-perfectly plastic behavior, as shown in Fig. 6b, and by applying the bond stress obtained in the first step along the grout.

The compression anchor was modeled by applying the anchor load at the end of the anchor. The peak friction value at the soil–grout interface was set as follows:

\[
f_{\text{max}} = K\sigma^\phi_{\text{ov}}, \quad (21)
\]

where \( K = 1.7 \) as proposed by Kim [27]. The vertical displacement necessary to mobilize \( f_{\text{max}} \) was assumed to be 2.5 mm, as reported by Briaud [8]. The bond stress of 1900 kPa for the slip between the grout and the strand was used, and the vertical displacement of a 2.5 mm for mobilization of the bond stress was used in the analyses. The axial stiffness of the strand was \( 9.08 \times 10^4 \) kN, and the axial stiffness of the grout was \( 4.32 \times 10^5 \) kN.

6. Results and discussion of numerical simulations

6.1. Load–displacement curves

The displacements at the anchor head predicted by the finite element analysis and beam-column analysis were compared with the measured values, as shown in Fig. 7. The total pullout load of 780 and 733 kN was applied in five increments, respectively, to the tension and compression anchors.

For the tension anchor, the finite element analysis and beam-column analysis gave a displacement of approximately 93.6 and 96.6 mm for the test load of 780 kN, respectively, 5–8% smaller than the measured value of 102.1 mm. For the compression anchor, the finite element analysis and beam-column analysis showed displacements of approximately 95.7 and 101.3 mm for the test load of 732.8 kN, respectively. These values were within 0.4–5.2% errors compared with measurements.

The yield in finite element analysis or the plastic movement in beam-column analysis has occurred only in interface and the soil element adjacent to the bond length. The displacement of ground anchors depends on the soil modulus, the level of shear stress transferred through the bonded length. The reason why the predicted displacement shows less error than the predicted load distribution is that the most displacement comes from the free elongation of unbonded length, namely the elongation of steel wires. The load–displacement curves predicted by the proposed numerical simulation showed a reasonable correlation with the measured load–displacement curves.

Fig. 9. Predicted load transfer on compression anchor: (a) load in grout, (b) load resisted by soil, and (c) load transfer distribution.
6.2. Load distribution and load transfer mechanism on tension anchor

The load distribution in the strand, and the grout and the load transfer distribution of the tension anchor at the load of 657.3 kN were predicted by the proposed numerical simulations, as shown in Fig. 8a–c. The finite element prediction of the load distribution of the grout overestimated the load 44% larger than the measurement at the bonded/unbonded length boundary of the tension anchor, as shown in Fig. 8b. The beam-column prediction overestimated the load 164% larger than the measurement at the middle of the bonded length of the tension anchor. The predicted load transfer distribution underestimated the load 21–35% smaller than the measured load at the peak friction value as shown in Fig. 8d. For the load higher than the proposed design load of 657.3 kN, the measurements were quite scattered and could not be compared.

The discrepancies may come from the scatter of the measured data, and from the unreal numerical parameters.

The parameters for interface may have a great influence on the load transfer distribution. The sensitivity analysis was performed and presented in the following section.

6.3. Load distribution and load transfer mechanism on compression anchor

The results of finite element analysis and beam-column analysis on the compression anchor with a design load of 658.3 kN are presented in Fig. 9. The numerical predictions of load in grout, load resisted by soil, and load transfer distribution were compared with the measurements. The predictions of load distribution correlated well with the measurements, within 12% errors at the maximum friction value. The analysis results for the compression anchor show similar load distribution to the measurements. The results of the simulation matched with the results of the load test for the compression anchor better than for the tension anchor. The reason why the prediction on compression anchors were better than tension anchors may be

![Fig. 10. Effect of the friction coefficient $\mu_{\text{strand-grout}}$ between the strand and the grout on tension anchors: (a) load in strand, (b) load in grout, and (c) load transfer distribution.](image)

![Fig. 11. Effect of the friction coefficient $\mu_{\text{grout-soil}}$ between the grout and the soil on tension anchors: (a) load in strand, (b) load in grout, and (c) load transfer distribution.](image)
the much simpler loading mechanism in compression anchors than tension anchors.

6.4. Sensitivity analysis of numerical parameters

Sensitivity analyses were performed to get an insight of the numerical parameters used in interface elements. The loading transfer mechanism in tension anchors is basically the friction between the strand and the grout and also between the grout and the soil. The key parameters to simulate the ground anchors numerically are the friction coefficient $\mu_{\text{strand-grout}}$ between the strand and the grout, the friction coefficient $\mu_{\text{grout-soil}}$ between the grout and the soil, and the debonding or maximum shear stress $\tau_{\text{max}}$ at the strand–grout interface.

The results of sensitivity analyses were shown in Fig. 10–12 for tension anchors and shown in Fig. 13 for compression anchors, respectively. The sensitivity analysis implies that the parameters calculated may be smaller or larger than the real values. The research needs to be focused further on those friction values of ground anchors.

6.5. Suggestions on numerical analysis of ground anchors

The finite element analysis and the simple beam analysis can be used to simulate a load distribution on ground anchors qualitatively on tension anchors, and quantitatively on compression anchors. If the experimental way to measure the load distribution on ground anchors is not possible, the numerical methods can be used to see the load transfer distribution. Both finite element analysis and beam-column analysis give a good prediction on load–displacement relationship of ground anchors, and underestimate the load between the soil and the grout on tension anchors.

The advantages of a beam-column method are the simplicity and a few input parameters. The finite element method is complex to use and the parameters of interface element have great influence on the results. The finite element analysis and beam-column analysis predict the load distribution on compression anchors better than tension anchors.

7. Conclusions

Procedures of finite-element modeling and beam-column modeling on ground anchors were proposed in this study. Procedures included the modelings of soil, grout, and strand and the interface modeling of soil–grout and grout–strand in ground anchors. A series of finite element analyses and beam-column analyses were performed using the proposed models of ground anchors. The numerical predictions were evaluated by comparing with the measurements. On the
basis of the results of this study, the following conclusions can be drawn:

1. The results on load transfer mechanism of ground anchors by numerical simulations were greatly influenced by the modelings of soil–grout and grout–strand interfaces. The numerical models for soil–grout and grout–strand interface were proposed.

2. For the tension anchor, the load distribution predicted by numerical analyses underestimated the peak friction value 21–35% smaller than the measured load.

3. For the compression anchor, the predictions of load distribution correlated well with the measurements, within 12% errors at the maximum friction value. The load transfer distribution predicted by numerical simulations for the compression anchor matched better than for the tension anchor.

4. The finite element analysis and beam-column analysis can be used to simulate a load distribution on ground anchors qualitatively on tension anchors, and quantitatively on compression anchors. Both analyses give a good prediction on load–displacement relationship of ground anchors.

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