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Numerical simulation of CFRP anchors using Finite Element Method

Leslie Opoku, Prince Mashavave
(Department Civil engineering, Faculty of Civil Engineering and Mechanics, Jiangsu University, China)

Abstract: *CFRP is a polymer matrix and embedded in this matrix are amalgamated aligned continuous organic fibers that have copious usages or applications. These advances have brought in carbon fiber reinforced plastics (CFRP) which have the solutions to the challenges been faced with steel anchor tendons.*

The analysis will be carried out to obtain numerical predictions of a new anchor system made of CFRP material. Numerical simulations will be performed using proposed models from the MIDAS GTS NX program. The numerical modeling results were compared to the experimental results. The main work is summarized as below:

The anchor will be subjected to pull-out load through numerical simulation to determine the strength and reliability of the news anchor. The obtained results will be compared with available ground anchors on the market.

The finite element analysis will be used to qualitatively and quantitatively model the movement of loads on ground anchors, including tension and compression anchors. This study provides a rational estimate of the load-displacement relationship of ground anchors.

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I. Introduction

There are known cases of steel ground anchor failures due to corrosion [1, 2]. Ground anchors are divided according to the mode of load transfer namely pressure type anchor[3], friction type anchor[4], and hybrid anchor[5]. Friction type anchors such tension anchors have tensile forces applied to the grout at the bonded length while compression anchors have compressive forces applied to the grout[2]. A compression anchor has benefits that outweigh the tension anchor. For the tension anchor, tensile failure can occur on the grout material[6] and tensile failure results in progressive failure of the ground anchor[7], but this is not the case for the compression anchor. The tendons at the tension anchor cannot be removed after excavation works[8], whereas tendons at the compression anchor are recoverable[9]. Although, researches on the compression anchor are scant compared to tension anchor, and even when designing compression anchor, design methods for tension anchor are used recently.

The soil and new type anchor (CFRP anchor) interaction will be one of the objectives of this study. The research will be conducted to obtain numerical predictions of a new anchor system using CFRP material.

The strengthening of the Cheurfas concrete dam in Algeria was among the earliest applications of ground anchors[10]. The strengthening and rehabilitation of existing structures by be achieved by using prestressed ground anchors [11].

Anchors employed in soil and rock, commonly called earth anchors, are primarily designed and used to resist outwardly directed loads imposed on structures such as foundations, earth retaining structures, and slopes. These outwardly directed forces are passed to the soil and rock at greater depth by the anchors.

Anchors are also used for tieback resistance of earth retaining structures[12], waterfront structures, at bends in pressure pipelines, and when it is necessary to control thermal stress. The earlier forms of anchors used in soil for resisting vertically directed uplifting loads were screw anchors[13]. These anchors were simply twisted into the ground up to a pre-estimated depth and then tied to the foundation. They were used either singly or in groups.

Classification of anchors by ground terminology

Anchor classifications in terms of ground terminology are predominantly three, and the anchor category is based on the topography and geology on which the anchor is used. There are soil anchors, rock anchors[14], and marine anchors[15]. Among the different soil anchors, the soil or ground anchors have the most extensive use. Since the early years of the twentieth century, the use of ground anchors for providing lateral and vertical support to retention structures in deep excavations has been dated. These soil anchors have been accepted and used for civil engineering projects in a multitude of ways such as tie-back diaphragm, cut slope retaining systems, bridge abatements, tunnel portals, stabilization of natural slopes and just to mention a few[16]. Anchors are currently used for bracing of retention systems in deep excavations[17], stabilization of slabs subjected to upward forces due to hydrostatic forces and soil heave[18], increase bearing capacity of unstable soils through pre-consolidation, to supply reactions to pile load test, to reduce and balance the effects of moments in power transmission, special roofs, ski jumps, and mobile homes, providing equilibrium in deep slabs of nuclear reactors[19], executing remedial measures for renovated structures, tie-down for underground storage containers and tanks.

While there were wide applications of the anchors with steel tendons worldwide, there were some technical challenges that affected the usages of ground anchors. Those challenges in anchors with steel tendons included; creep [20](potential time-dependent movement), performance with time, corrosion prevention for tendons [21] and quality control systems[22], etc. It is worth mentioning that although these limitations exist, there have been technological advancements to develop better corrosion control programs, improvement in the corrosion protection systems[23], grouting, and as well as increasing the tension capacity of steel prestressed tendons. However, with these reliable quality control systems and corrosion programs for steel anchors, the steel tendons in-ground anchors easily corrode under harsh soil conditions thus the need for more improved and better corrosion-resistant tendons for ground anchors[24].

The use of CFRP anchors in recent years over conventional prestressing steel tendon anchors can be attributed to various advantages of CFRP over conventional prestressing steel tendons [25]. The advantages are not limited to; CFRP tendons are lightweight (15%-20% less heavy than prestressing steel tendons), have high corrosion resistance, high longitudinal tensile strength, and the inclusion of monitoring devices such as optical fibers for real-time monitoring of the performance of the ground.

II. Numerical Analysis

The finite element method will be used to analyze the soil and ground anchor interaction under varied overburden pressures. The finite element solution unlike the analytical solution which deals with lots of computations, the FEM provides solutions for each element and later combines series of solutions for the whole problem and analysis.

Conversely, boundary problems in engineering can be solves using the computational technique of the finite element method. The dependent variables of interest are the field variables.

The software MIDAS GTS NX makes provisions for various constitutive models such as Cam clay, Mohr - Coulomb's, Drucker – Prager, and other models to help simulate the soil conditions using soil parameters obtained from the field tests.

Numerical modeling for the ground anchor

The reliability of the numerical analysis, numerical modeling method will be applied to the applied previous numerical and field test results using Midas GTS NX and using CFRP anchor in compression.

Case: Compression Anchor

Kim et al conducted previous studies using the finite element model and beam modeling of a compression anchor using Midas GTS NX. The model consisted of 42, 571 nodes and 43, 245 elements as well. The grout used had a cross-sectional area of 20,888mm2 as well as having a compressive strength of 20MPa, the tensile strength of the grout was 2.0 MPa and the elastic modulus of the grout was $2.1\ x\ 10^7\ kN/m^2$. Soil-grout and grout strands were modeled using the Coulomb friction model in Midas GTS NX.

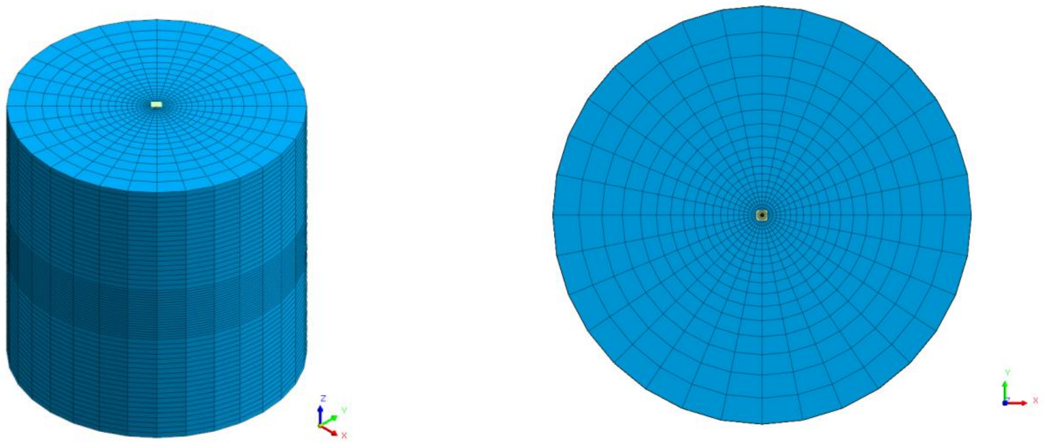

Figure 1 A 3D Model for the experiment

Case: Tension Anchor

The soil-grout and grout-strand interface surface model was considered using the Coulomb friction model in the MIDAS GTS model. In the end, the pull-out load was sequentially added to the design load (657.3 kN). The ground depth was 20 m below the surface of the ground and the ground diameter was 20 m laterally. For the soil element, the criterion of failure of Drucker-Prager was applied.

Details of Finite Element Model

This study considered the FEM problem was modeled as a non-linear model to investigate the performance of the new anchor.

Finite Element Method

In this study, the finite element method will be employed to analyze ground anchors. To minimize the effect of the mesh efficiency on the finite element analysis, a fine mesh will be adapted. Using the same parameters from previous studies, the system is modeled as a CFRP grout, and to simulate field conditions, the CFRP anchors are designed as an element embedded in the soil.

Material Modeling

The finite mesh constitutes the nodes and the finite elements thus the types and number of finite mesh affect the quality of the results during the final analysis. Considering the boundary conditions and applied loads are the keys to analyze the characteristics of the solid model. The underlying or basic equation could be simplified as follows:

$[K]\{r\} = \{R\}$, (1)

where, $[K]$ is the global stiffness, $\{r\}$ global displacement and $\{R\}$ is the global vector.

The non-symmetric solver in the Midas GTS NX is used to solve the system of equations. The Drucker – Prager criterion with the non-associated plastic flows was employed for soil and the resulting stiffness matrix $[K]$ is non-symmetric.

Interface parameter

Vertical rigidity modulus is usually 1 to 10 times smaller oedometer modulus between materials and also the shear rigidity modulus is generally 1 to 10 times smaller shear modulus between materials modulus K_t relies on the analytical process. The vertical rigidity modulus and shear rigidity modulus of interface elements were determined by trial and error.

Discretization

Discretization is used to model the problem into three-dimensional solid elements. In the model, the soil element model is constructed simultaneously with the CFRP anchor.

Soil element model

The soil in the finite element analyses will be modeled with a 3D hexahedral brick element having a reduced integration option. This constitutive material model is suitable for the design of soil anchors since the soil structure bond failure will be considered. Rowe's stress dilatancy theory will be used to provide the dilatancy angle needed.

Table no.1: Soil material parameters as provided by Kim et al (Kim 2007) examined in the finite element analyses using the novel CFRP anchor.

Material	γ	ν	E_s	ϕ	K_o	K^a	ψ	c
kN/m^3	kPa	(°)				(°)	kN/m^3	
Fill	19	0.3	12,500	23	0.6	1.0	3	6
Sandy clay	18	0.3	22,500	32	0.5	1.0	4	12
Weathered soil	20	0.3	44,000	40	0.4	1.0	8	24

Anchor element model

The CFRP strand in the anchor will be simulated with 3D hexahedral brick elements and considered as a linear elastic material. The grout used for grouting will be simulated as 3D axisymmetric elements thus the grout will be considered to a linear elasto – perfect plastic. The average compressive strength of the grout is about 20MPa while its tensile strength value is 2.0 MPa and the tensile strain is $1\ x\ 10^4$ and the average modulus of grout can be obtained from this formula below:

$E_c = 4.73\sqrt{f_{ck}}$, (2)

Where E_c is expressed in GPa and f_{ck} in MPa. The weight of the grout body shall be not regarded in the numerical simulation phase.

Materials Properties of CFRP

The tensile strength is 1450 MPa. The sleeve is a 20# seamless steel pipe with an ultimate strength of 410 MPa and yield strength of 245 MPa. The clip is made of 20CrMnTi alloy steel with an ultimate strength of 1080 MPa and a yield strength of 850 MPa. The outer anchor ring is made of 40Cr alloy steel. The nut used in the improved composite anchor is 40Cr alloy steel. The material property of the ribbed CFRP used as the anchor tendon is summarized below:

Table 2: Material Elastic properties

Material	density (kg/m^3)	ν	E_s (GPa)	d (mm)	K_o	K^a	ψ (°)	c (kPa)
CFRP	1650	0.24	142	10	-	-	-	-

Table 3: Interface properties namely vertical rigidity modulus and shear rigidity modulus

Material		K_n (kN/m^3)	K_t (kN/m^3)	(kN/m^3)	Remarks
	Strand-grout (unbonded)	0	0		
	Strand-grout (bonded)	20,900	209,000		
Grout-soil	Soil (0-4 m)	12,500	125,000	23	$K_n = 1 \times E_{soil}$ $K_t = 10 \times E_{soil}$
	Soil (4-6 m)	22,500	225,000	32	$K_n = 1 \times E_{soil}$ $K_t = 10 \times E_{soil}$
	Soil (6-12 m)	44,000	440,000	40	$K_n = 1 \times E_{soil}$ $K_t = 10 \times E_{soil}$

III. Results

Tension Anchors

For the strain condition, the load distribution in the grout, load resisted by soil, friction stress distribution, and load distribution in the soil are plotted using the soil conditions.

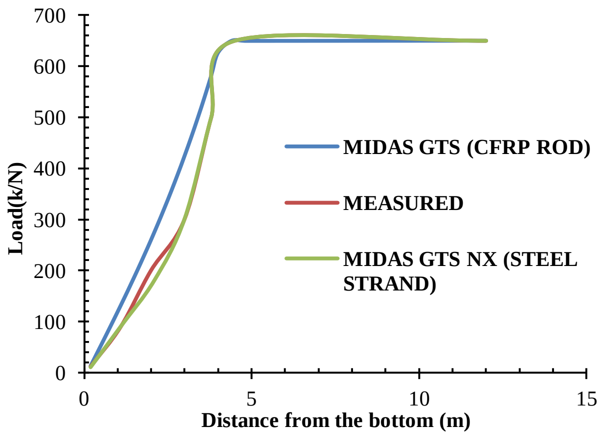

Figure 2 Distribution of the load in the rod of tension anchor (case 1)

From figure 2 it was observed that the load distribution in CFRP bar (MIDAS GTS NX -CFRP Rod) had similar load distribution properties similar to both the empirical(measured) as well as steel strand (MIDAS GTS NX – steel strand. This similar property of the CFRP bar thus makes a very suitable option to be used in ground anchors in tension.

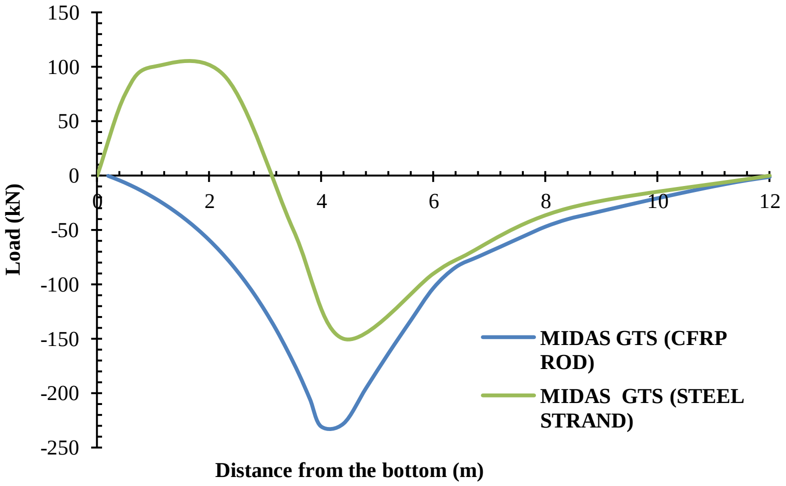

Figure 3 Distribution of the load in the grout of tension anchor (case 1)

The distribution of the load in the grout for the CFRP bar on the other hand is low as compared to the that of the steel strand. The bonded length of the tension anchor tends to transfer load to the soil via the grout.

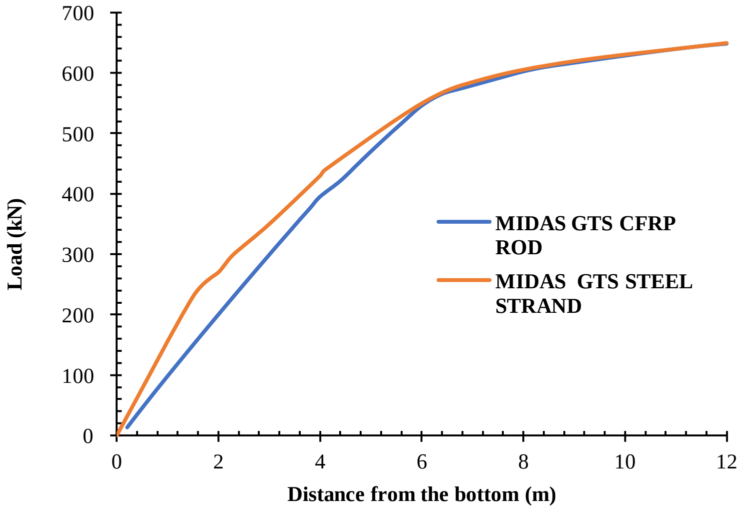

Figure 4 Resistance by soil to the load of tension anchor (case 1)

The resistance of the soil in both simulated anchors are quite similar represented by the fig. 4.

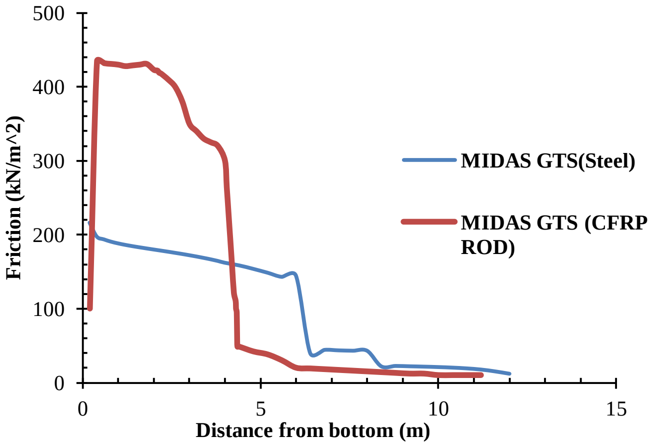

Figure 5 Friction stress distribution of tension anchor (case 1)

Although both anchors have similar trends in Figure 5, the CFRP bar tend to have a higher friction stress distribution than that on the steel stand due to the ribbed surface the CFRP bar. The maximum bond tension was also discovered to be at the loaded end.

Compression Anchor

The load distribution in the CFRP rod tendon due to the compressive force, force distribution in the grout, load distribution in the soil, and finally the friction stress distribution of the compression anchor are all characteristics of the simulation results for the compression anchor.

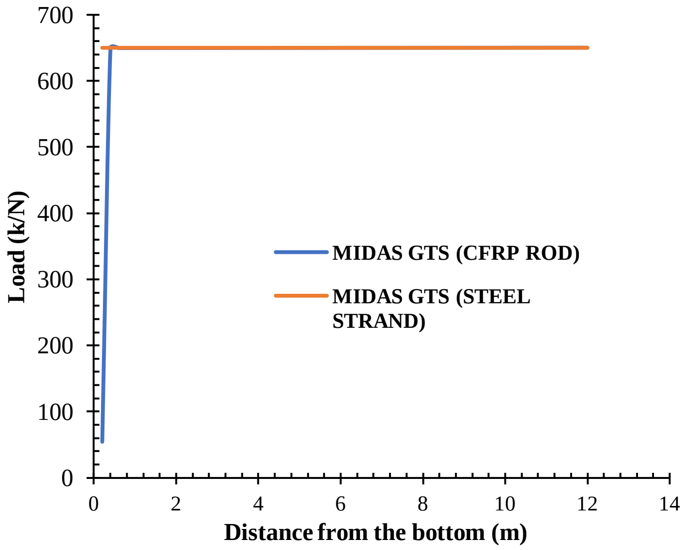

Figure 6 Load distributions in the CFRP rod of compression anchor (case 2)

Figure 6 shows that the load distribution in CFRP bar (MIDAS GTS NX –CFRP Rod) was identical to both the empirical(measured) and steel strand (MIDAS GTS NX –steel strand) load distribution properties.

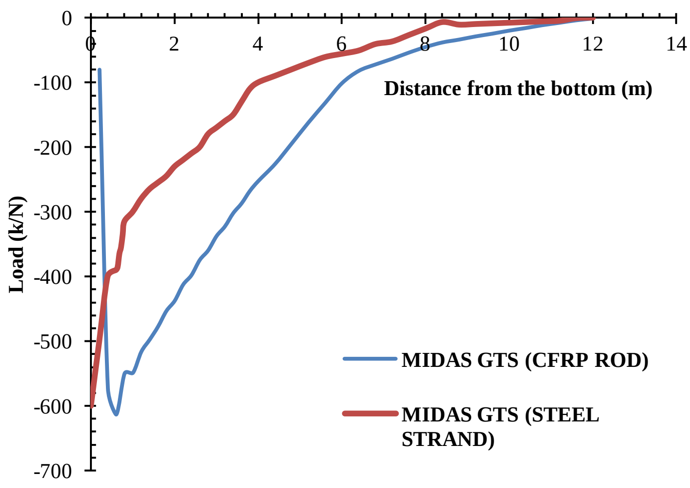

Figure 7 Load distributions in the grout of compression anchor (case 2)

In figure 7, the graphs indicate both the steel and CFRP have unbonded lengths which are not in direct contact with the grout thus the decrease in the load distribution for the grout.

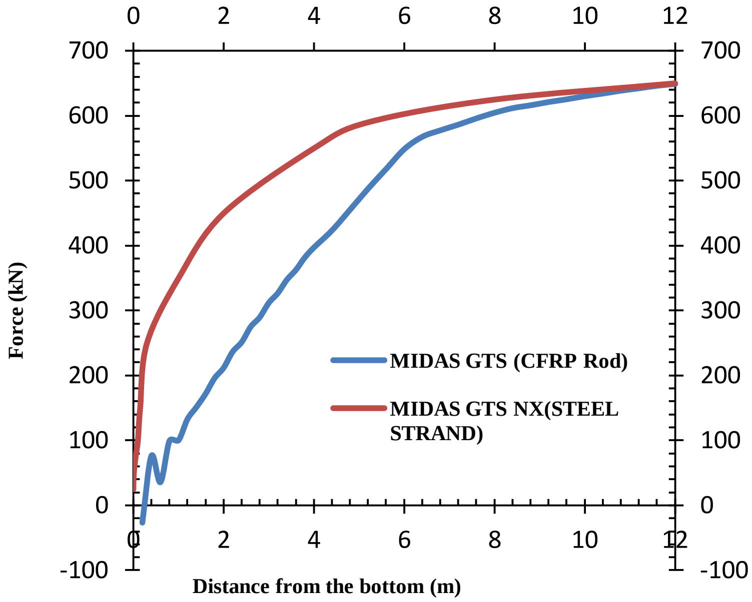

Figure 8 Load resistances in the soil due to compression anchor (case 2)

The graphs in fig. 8 depict the smallest linear increase in carrying capacity as bond length increases in compression anchors

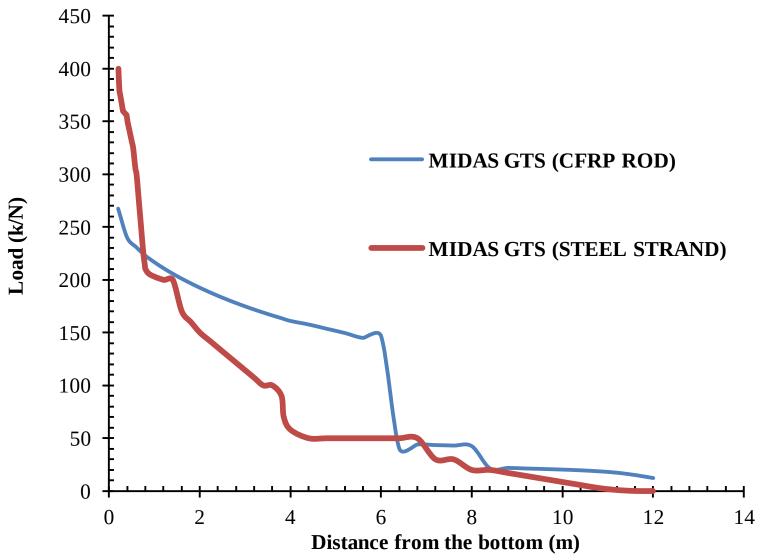

Figure 9 Friction stress distribution of compression anchor (case 2)

Friction distribution in figure 9 for both anchors in compression anchors decreases with increase in depth. This resulted from the soil been compressed the anchor body at the tip of the ground anchor buried in the soil.

IV. Discussion

There is a load distribution for the tension anchor and the compression anchor having CFRP rod, grout load transfer, forces opposed load by soil, and eventually friction stress distribution.

Tension Anchor

Load distribution in the grout, load resisted by soil, friction stress distribution, and the load distribution in the soil are plotted for the tension condition using the aforementioned conditions for the pull-out loads as well as the soil conditions. The lines of the graphs are characterized into two main components namely; the MIDA GTS NX (Steel strain) plot and the Midas GTS (CFRP Rod) plot. The MIDA GTS NX (Steel strain) plots denoted FEM data obtained from previous studies using steel strands in the anchor whereas the previously measured plots are related to the previous results obtained from previous lab studies.

Compression Anchor

The results obtained by the simulation process for the compression anchor are characterized as follows; load distribution in the CFRP rod tendon due to the compressive force, force distribution in the grout, the load distribution in the soil, and lastly the friction stress distribution of the compression anchor. The load distribution as shown in Fig. 8 was obtained by deducting the load distribution values in the grout shown in Fig. 7 from the load distribution values in the CFRP rod in Fig. 6. The stress results obtained as a result of the friction forces between the soil, CFRP rod, and the grout were plotted on the vertical axis while plotting the distance from the bottom on the horizontal axis. The graphs in Fig. 8 and other graphs related to the compression anchor fit well with previous numerical methods used in the analysis of steel strain compression anchor.

V. Conclusion

Finite-element simulation techniques on ground anchors were introduced in this research. The techniques involved soil, grout, and strand modeling and the system of soil – grout and grout – strand modeling in field anchors.

Many finite element analyses were carried out using the proposed ground anchor models. The numerical predictions were tested by contrasting them with the numerical study using steel ground anchors. The findings of the load transfer process of the ground anchors through computational simulations are heavily affected by the soil – grout and grout – strand interface modeling. Numerical models for soil – grout and grout – strand interfaces have been suggested.

The finite element model can be used to simulate the application of loads on ground anchors on both tension anchors and compression anchors. All analyzes have a strong estimate of the load-displacement relationship of the ground anchors.

The reliability of the finite element system was implemented by evaluating the previous numerical implementations of the tension anchor and the compression anchor having a steel strand to anchors with ribbed CFRP. The results of the load transfer mechanism of the ground anchors by numerical simulations were strongly influenced by the soil–grout and grout–strand interface modeling. Numerical models for soil–grout and grout **-** strand interfaces have to be proposed.

It can be concluded that CFRP fiber anchor bars are more suitable for practical engineering than traditional anchors after a comprehensive and detailed comparison of displacement (deformation) and stress.

Chang, S.-H., C.-S. Chen, and T.-T. Wang, *Sediment Sluice Tunnel of Zengwen Reservoir and construction of section with huge underground excavation adjacent to neighboring slope.* Engineering Geology, 2019. **260**: p. 105227.

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