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IDENTIFICATION OF SOIL MODELS BY SIMULATION OF GROUND ANCHOR TESTS, USING FEM

BY

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Abstract. Several types of soil models have been developed during time in order to simulate the soil behavior in finite element (FEM) analysis, so choosing the right soil model has a great importance on results. This study presents a method to establish the most suitable soil model used in FEM in order to calculate a temporary anchored retaining structure, method which is based on field tests. The test fields are simulated with FEM and are used several types of soil models, taken into consideration the time factor too, resulting the displacement of the fixed length of a ground anchor for each type of soil model. The measured displacement of the tested ground anchor is then compared with the obtained displacements and the closest value decides the type of soil model. Were simulated two tested ground anchors, one in cohesive soil and the other one in non-cohesive soil. This study can be helpful in generally by using the presented method in order to determine the right model type of soil and in particular by using the results for the two ground anchors analyzed.

Key words: fixed length; test field; soil model; displacement.

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1. Introduction

The general goal of this study is to present a method to establish the right soil model for finit element (FEM) analysis of structures which have ground anchors in their componence, by using two particular cases of analysis.

This can be realized determining by calculation the displacement of the fixed length of a prestressed ground anchor, for the various types of soil models and the calculated value closest to the measured one decides soil model to be used. The soil models which are defined in FEM calculation and were used in the analysis, are: Mohr Coulomb; hardening soil; hardening soil with small-strain stiffness.

The other soil models were not used because of their obvious unsuitability for the analysed case (the linear elastic – linear elastic behavior, the soft soil model – used for soft cohesive soils, Hoek-Brown – used for rock, etc.). The three soil simulation models are divided into several categories depending on their drainage state, as follows: drained; undrained *A*; undrained *B*; undrained *C*.

To easily highlight the right soil model, were choosed two ground anchors which have the fixed length positioned entirely within one type of soil, one cohesive and one non-cohesive. Thus were chosen:

a) Anchor no. *A*1 – the fixed length is positioned entirely in clay (l_{fixed} = = 5 m);

b) Anchor no. *A*2 – the bulb positioned entirely in the sand (l_{fixed} = = 2.5m).

Anchor *A*1 Anchor *A*2

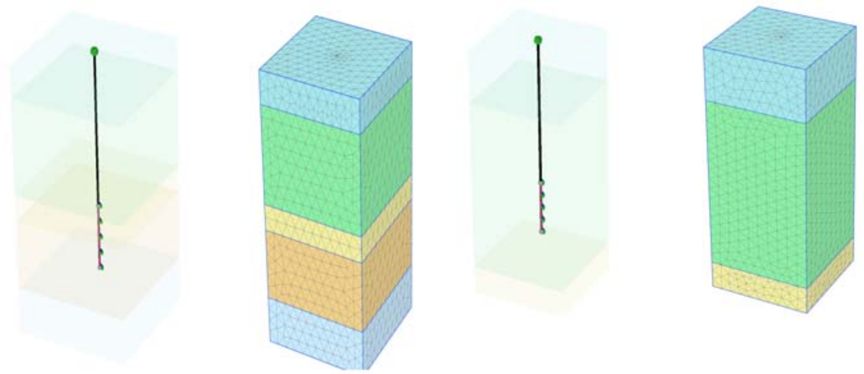


Fig. 1 – Illustration of the 3-D calculation models, together with their discretization, for the two ground anchors.

In setting up the 3-D model calculation were chosen the dimensions $L \times B \times H = 10 \times 10 \times 23$ m for anchor *A*1 and $5 \times 5 \times 12$ m for anchor *A*2, models which with their 3-D dimensions do not affect the anchors zone of influence. The 3-D model views are presented in Fig. 1.

The geotechnical parameters which were used in the calculation, are presented in Table 1.

Table 1
The Model and Geotechnical Characteristics of Soils Used

Parameter	Name	Fill	Sand I	Stiff Clay I	Stiff Clay II	Sand II
General						
Unit weight above phreatic level, [kN/m^3]	γ	16	18	18	19	18
Unit weight below phreatic level, [kN/m^3]	γ_{sat}	20	20	20	20	20
Parameters						
Secant stiffness for CD triaxial test, [kN/m^2]	E_{50}^{ref}	10,000	32,500	10,000	13,000	32,500
Tangent oedometer stiffness, [kN/m^2]	E_{oed}^{ref}	10,000	16000	20,500	17,500	32,500
Unloading/ reloading stiffness, [kN/m^2]	E_{ur}^{ref}	30,000	97,500	50,000	65,000	97,500
Power for stress level dependency of stiffness	m	0.5	0.5	1	1	1
Cohesion, [kN/m^2]	c_{ref}	25	1	40	60	1
Friction angle, [º]	Φ	15	32.5	15	15	35
Dilatacy angle, [º]	ψ	0	4	0	0	3
Poisson's ratio	v_{ur}	0.2	0.2	0.2	0.2	0.2
Interfaces						
Interface strength	–	Manual	Manual	Manual		
Interface reduction factor	R_{inter}	0.65	0.7	0.5	0.6	Rigid
Initial						
K_0 determination	–	Auto	Auto	Auto	Auto	Auto

Because the layers Clay II and Sand II does not influence the behavior of anchor A2, have been removed from calculation, in order to simplify it and to reduce running time calculation.

2.1. Simulation with FEM of Anchor *A*1 Test

Initially, the loading/ unloading steps were extracted from the field recordings during anchor test, recordings presented in Table 2. Those steps were introduced in FEM calculation, keeping their dependency from one to another, maintaining from one stage to another the plastic deformations produced.

Testing of anchor A1 was performed using the following steps of loading/ unloading, presented in the below steps description:

a) S t e p 1 – load of anchor with a reference force P_a = 93 kN.

b) S t e p 2 – applying the first load step P_1 = 232 kN and maintaining it for 5 min.

c) S t e p 3 – unload anchor down to reference load P_a = 93 kN.

d) S t e p 4 – applying the second load step P_2 = 371 kN and maintaining it for 15 min.;

e) S t e p 5 – unload anchor down to reference load P_a = 93 kN.

f) S t e p 6 – applying the third load step P_3 = 511 kN and maintaining it for 15 min.

g) S t e p 7 – unload anchor down to reference load P_a = 93 kN.

h) S t e p 8 – fourth step application load P_4 = 627 kN and maintaining it for 3 min.

i) S t e p 9 – unload anchor down to reference load P_a = 93 kN.

Table 2

Displacement Recordings During Test of Anchor A1

Load, [kN]	Time, [min.]					
	1	2	3	5	10	15
93						
232	10.43	10.48	10.82	10.97		
93	6.00					
371	20.84	20.98	21.02	21.08	21.22	21.22
93	9.92					
511	34.44	34.52	34.82	34.90	35.07	35.14
93	14.10					
627	53.63	57.22	61.75			
511	63.76	63.76	63.78	63.78	63.82	63.93
93	40.50					

Note: Displacements are in mm.

Of our interest is the soil behavior induced by the loading of anchor fixed length, and the above measurements include also the elongation of strands on their free length, so is necessary to remove strands elongation from the measured values. The parameters characterizing the strands are

a) E = 195,000 N/mm^2;

b) A= 150 mm^2 × 6 strands = 900 mm^2;

c) l_{free}= 12,000 mm.

For the elastic elongation calculation was used the relation

$$\Delta l_s = \frac{l_{\text{free}} P}{EA}, \qquad (1)$$

where: E is the elastic modulus of strands, [N/mm^2]; A – total area of six strands, [mm^2]; l_{free} – free length of anchor, [mm]; P – loading force, [N]; Δl_s – total elongation of strands.

Because the displacements are measured after reference load application, the elongation resulted from reference load must be eliminated from the total elongation

$$\Delta l_{s1} = \Delta l_s - \Delta l_{sr}, \tag{2}$$

where: Δl_{sr} is the elongation of strands when applying the reference load.

The displacement of the fixed length is:

$$d_{\text{fixed}} = d_m - \Delta l_{s1}, \tag{3}$$

where: d_{fixed} is the displacement of the anchor fixed length, [mm]; d_m – displacement measured at the anchor head, [mm].

The results of the calculation for strands elongation removal, are presented in Table 3.

Table 3

Removal of Strands Elongation from the Values Measured for Anchor A1

Loading force P, [kN]	Strands total elongation Δl_s mm	Strands elongation Δl_{s1} mm	Measured displacement d_m mm	Displacement of fixed length d_{fixed} mm
93	6.36	0.00	0	
232	15.86	9.50	10.97	1.47
93	6.36	0.00	6	
371	25.37	19.01	21.22	2.21
93	6.36	0.00	9.92	
511	34.94	28.58	35.94	7.36
93	6.36	0.00	15.1	
627	42.87	36.51	61.75	25.24
0	0.00	0.00	40.5	

In the first phase of calculation, to eliminate in short time the soil models which are far from truth, was used only the step 1 of loading (considering that the reference load is not taken into consideration for fixed length displacement) with $P_1 = 232$ kN, for various types of soil models, and the resulted displacements for each model are presented in Table 4.

It can be observed that from soil models used, the followings (which are highlighted in Table 4) are closer to the measured value in anchor test: Hardening Soil Drained, Hardening Soil Undrained *A* and Linear elastic Drained.

To make sure that no inappropriate soil models are eliminated, were kept for the next phase of analysis also the soil models Mohr Coulomb Undrained *C* and HS small drained.

In the second calculation phase, were used all loading steps, dependent one from each other, resulting the values from Table 5.

Table 4
Displacements Calculated in the First Phase of Analysis, for Anchor A1

Loading step	Soil model	Calculated displacement u_z, [mm]	Measured displacement mm
P_1 = 232 kN	**Hardening soil – drained**	**1.44**	1.47
	Hardening soil – undrained *A*	**1.19**	
	Hardening soil – undrained *B*	7.95	
	Mohr Coulomb – drained	50.87	
	Mohr Coulomb – undrained *A*	6.22	
	Mohr Coulomb – undrained *B*	6.22	
	Mohr Coulomb – undrained *C*	5.84	
	Linear elastic drained	**1.25**	
	Linear elastic undrained *A*	0.89	
	Linear elastic undrained *C*	0.87	
	HS small drained	0.38	
	HS small undrained *A*	0.3	
	HS small undrained *B*	0.29	

Table 5
Displacements Calculated in the Second Phase of Analysis, for Anchor A1

	Calculated displacement of fixed length, [mm]						
Load, [kN] / Soil models	232	0	371	0	511	0	627
Hardening soil – drained	2.05	0.32	4.02	1.78	10.43	7.68	31.46
Hardening soil – undrained *A*	**1.44**	**0.26**	**3.35**	**1.42**	**8.35**	**5.6**	**20.72**
Linear elastic drained	1.24	0	2	0	2.76	0	3.39
Mohr Coulomb – undrained *C*	0.93	0.044	1.58	0.13	2.44	0.4	4.93
HS small drained	0.4	0.06	0.75	0.2	1.34	0.31	2.78
Measured displacement, [mm]	1.47		2.21		7.36		25.24

It can be observed that with the soil model Hardening soil – undrained A were obtained the closest values to the measured ones. This type of soil model applies only to layer Clay II layer, located between depths –10 m and –17.4 m from surface, because the fixed length of anchor A1 is positioned only in this layer.

The calculated displacements using the soil model Hardening soil – undrained A, together with the zone influence of the fixed length, are ilustrated in Fig. 2.

2.2. Simulation with FEM of Anchor *A*2 Test

The procedure for determining the soil model closest to reality is relatively similar to the one used for anchor *A*1 from the previous section. The results from Tables 6,...,9 for testing anchor *A*2, was obtained in the following steps:

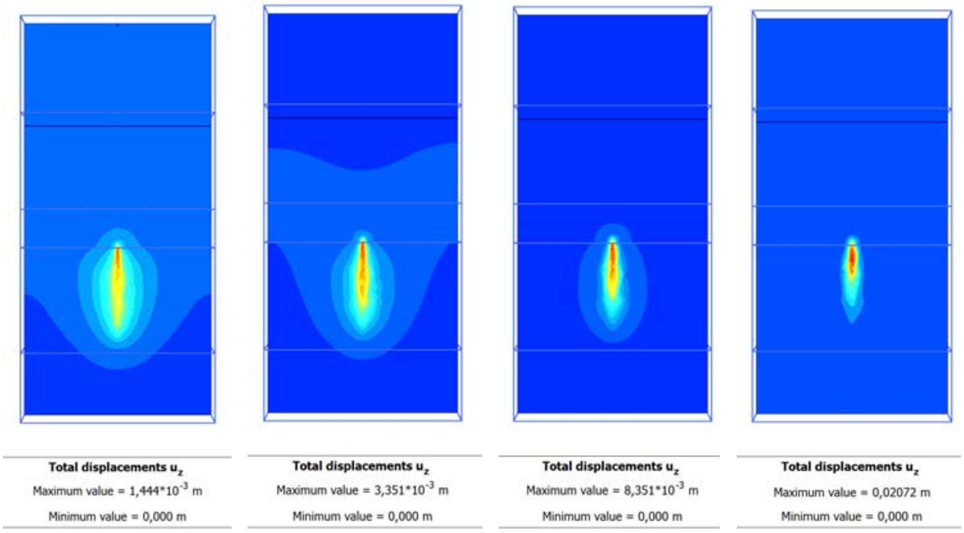
a) S t e p 1 – load of anchor with reference load $P_a = 46$ kN.

b) S t e p 2 – application of the first load step $P_1 = 348$ kN and maintaining it for 5 min.

c) S t e p 3 – unload anchor down to reference load $P_a = 46$ kN.

d) S t e p 4 – applying the second load step $P_2 = 650$ kN and maintaining it for 15 min.

e) S t e p 5 – unload anchor down to reference load $P_a = 46$ kN.



232 kN 371 kN 511 kN 627 kN

Fig. 2 – Illustration of calculated displacements and zone of influence, using soil model Hardening soil – undrained *A*, for anchor *A*1.

Table 6

Displacement Recordings During Test of Anchor A2, [mm]

Load kN	Time, [min]							
	1	2	3	5	10	15	20	30
46								
302	21.31	21.36	21.36	21.36	21.51	21.51		
348	25.80	25.80	25.80	25.80	25.80	25.80		
46	5.28							
395	30.65	30.76	30.81	30.85	30.95	31.21	31.27	31.55
418	33.87	33.88	33.89	34.02	34.04	34.05		
464	39.04	39.05	39.06	39.06	39.11	39.20		
511	44.06	44.06	44.06	44.07	44.19	44.35		
650	64.08	64.57	65.03	65.56	66.39	66.81	66.99	
46	18.54							
673	84.00							
46	41.53							

Note: displacements are in mm.

f) S t e p 6 – load the application of the second stage P_3 = 673 kN and maintaining it for 15min.

g) S t e p 7 – unload anchor down to reference load P_a = 46 kN.

Table 7

Removal of Strands Elongation from the Values Measured for Anchor A2

Loading force P, [kN]	Strands total elongation Δl_s, [mm]	Strands elongation Δl_{s1}, [mm]	Measured displacement d_m, [mm]	Displacement of fixed length d_{fixed}, [mm]
46	3.67	0.00	0	
348	27.76	24.09	25.08	0.99
46	3.67	0.00	5.28	
650	51.85	48.18	66.09	17.91
46	3.67	0.00	18.54	
673	53.69	50.02	84	33.98
46	3.67	0.00	41.53	

Table 8

Displacements Calculated in the First Phase of Analysis, for Anchor A2

Loading step	Soil model	Calculated displacement u_z, [mm]	Measured displacement mm
P_1 = 348 kN	Hardening soil – drained	24.51	0.99
	Hardening soil – undrained *A*	5.24	
	Hardening soil – undrained *B*	129.4	
	Mohr Coulomb – drained	74.77	
	Mohr Coulomb – undrained *A*	115.6	
	Mohr Coulomb – undrained *B*	52.64	
	Mohr Coulomb –undrained *C*	59.31	
	Linear elastic drained	2.3	
	Linear elastic undrained *A*	1.2	
	Linear elastic undrained *C*	1.08	
	HS small drained	15.06	
	HS small undrained *A*	**3.99**	
	HS small undrained *B*	37.13	

The soil model with the calculated value closest to the measured value is Hardening Soil with small-strain stiffness (HS small) – Undrained A. For this model will be calculated the displacements for all load steps.

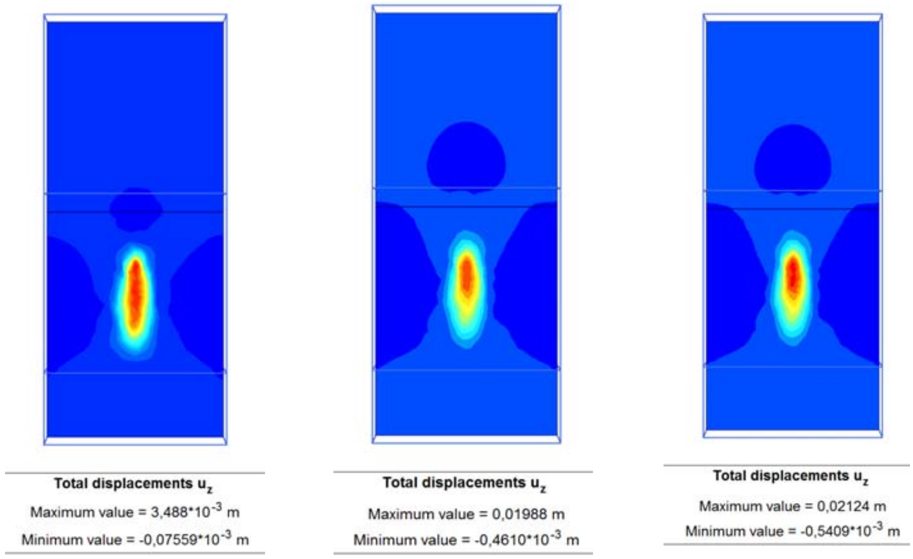
Table 9

Displacements Calculated in the Second Phase of Analysis, for Anchor A2

	Calculated displacement of fixed length, [mm]				
Soil models \ Load, [kN]	348	0	650	0	673
HS small undrained *A*	3.99	2.45	19.88	17.89	21.24
Measured displacement, [mm]	0.99		17.91		33.98

It can be observed that the calculated displacements of the anchor fixed length are close to the ones measured.

In Fig. 3 the illustration of displacements, together with the zone of influence of the anchor fixed length is presented.



348 kN 650 kN 673 kN

Fig. 3 – Illustration of calculated displacements and zone of influence, using soil model Hardening soil with small-strain stiffness, for anchor *A*2.

5. Conclusions

The purpose of this study is to establish the correct soil model for the computation of geotechnical works with finite element method, in particular the temporary anchored retaining structures.

The general idea is to use the response of ground anchors during testing, to simulate this response with finite element method, using several soil models and to establish the closest soil model which supplies results close to the ones measured. In this way it's eliminated the ambiguity of choosing the wrong soil model and to get unrealistic results.

For this method, can be considered the following steps:

a) execution of anchors tests in different types of soil on the site, before starting the design, in order to cover as much as it can the soil layers which can affect the retaining structure;

b) simulation of anchor tests using various types of soil models;

c) comparison of results, taking into consideration all the aspects (including free length elongation and time);

d) establishing the soil model which gives the closest results with the ones measured.

In order to highlight these steps and method efficiency, were used two ground anchors, tested, simulated and for which soil model were established.

This method involves to execute the anchor tests before design, tests which are anyway mandatory before starting execution, but with their positioning in time before design, can be obtained an optimized anchored retaining structure, leading either to cost reduction, either to risk reduction of structural failure, or both.

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IDENTIFICAREA MODELELOR DE PĂMÂNT PRIN SIMULAREA TESTELOR PE ANCORAJE, FOLOSIND METODA ELEMENTULUI FINIT

(Rezumat)

Mai multe modele de pământ s-au dezvoltat de-a lungul timpului, cu scopul de a simula comportamentul pământului în analiza cu metoda elementului finit (FEM) a structurilor geotehnice, prin urmare şi alegerea modelului de pământ potrivit are o importanţă semnificativă pentru rezultate. Acest studiu prezintă o metodă prin care se poate stabili modelul de pământ cel mai potrivit ce urmează a fi utilizat în FEM, cu scopul de a calcula o structură de sprijin ancorată cu caracter temporar, metodă ce are la bază încercări în amplasament ale ancorajelor . Comportamentul ancorajelor în timpul testării este simulat utilizând FEM folosind mai multe modele de pământ, luând în considerare şi factorul de timp, rezultând deplasarea lungimii de ancorare (bulb) pentru fiecare model în parte. Deplasarea măsurată a ancorei testate este ulterior comparată cu valorile calculate şi valoarea cea mai apropiată decide tipul de model de pământ cel mai potrivit pentru a fi folosit. Au fost simulate două ancoraje testate, una în pământ coeziv şi cealaltă în pământ necoeziv. Acest studiu poate fi folositor în general prin folosirea metodei prezentate în vederea stabilirii modelelor de pământ potrivite şi în mod particular prin folosirea rezultatelor obţinute pentru cele două ancoraje testate şi analizate.