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SYNOPSIS The cylindrical ground anchors has gained wide acceptance as an economical and highly versatile anchoring method over the past decade, particularly due to fast and simple performance by using the soil/rock boring and grouting procedure. However, these cylindrical anchors reache very low bearing capacities when they are performed in such a soil as a clay, silt or sand. The paper is concerning with the set of data and results which are collected after the in situ investigations of some 30 short vertical anchors installed in clay and in silty sand, as well. The bearing capacity of cylindrical and spherical anchors were also compared. Spherical cavity at the bottom of the borehole was produced by controled point blasting effect, which was studied in the first place. Finally, the proper analytical method for estimation of the ultimate uplift capacity was established, based on a very useful hypothesis of Vesić (1965) and some his later works, Vesić (1971). This model has showed a good agreement with field test pullout results.

1. INTRODUCTION

In general, ground anchors may be classified by the way in which they transmit their loads to the soil/rock. Otherwise, in that case the character of the anchor tail is taken as a competent classification criterion. This simple classification of ground anchors was proposed by Muhovec (1983), which distinguishes anchors with, point, line, plane and volume transmission of load (Fig.1.)

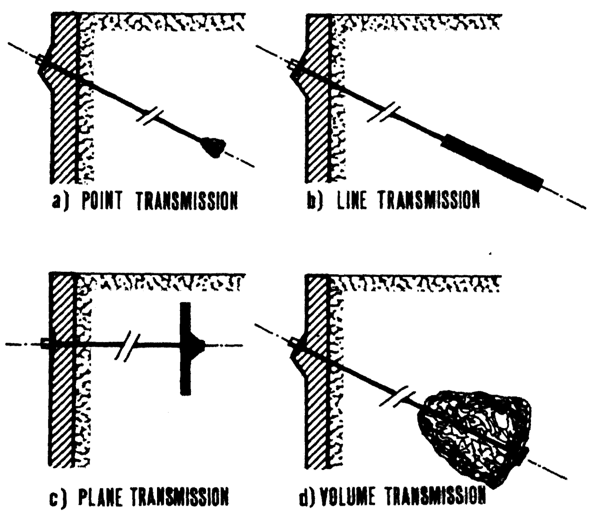


Fig. 1. General Anchor Classification According to the Character of the Load Transmission

Over the last few decades anchors with line load transmission tail are experiencing fast and wide developement and application. Usually these anchors are being performed in soil/rock by the drilling method, whereupon the tie rod is being inserted and afterwards grouting of the anchoring lenght follows. In that case the anchor tail becomes prolonged cylinder, so these kind of anchors are offen called cylindrical anchors. The bearing capacity of cylindrical anchors performed in a rock is usually high, but in case these anchors are performed in a soil, the bearing capacity is substantially lower what is the consequence of soil properties. This problem can be quite good prevailed by using the previous consolidation pressure grouting technique (with usage of high injection pressure). Unfortunately, this technique won't give useful results if cylindrical anchors ought to be performed in the soil of low permeability, or in some other soils of very low shear strength.

In these cases it would be suitable to replace the cylindrical anchor tail with some volume tail. Just this "replacement" using the blasting effect is in the middle of interes of scientific project which has been carried out for the last few years on the Geotechnical Faculty in Varaždin. Summary of some results of this investigations will be also presented in this paper.

2. BASIC WORKING PROGRAMME

The conception of that part of programme which is so far accomplished had included short vertical ground anchors performed in clayey and sandy soil soils. Two basic types of anchors were carried out on the site: spherical anchors and cylindrical anchors. The aim was to compare bearing capacities of those anchor types.

Besides, it was also important to investigate what effects the blasting extension of sphere cavity will cause in the soil around the zone of the future anchorage.

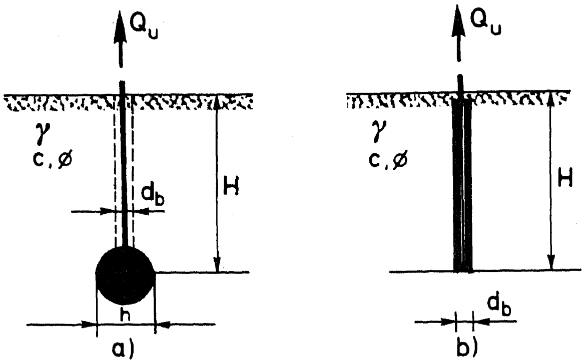


Fig. 2. Basic Scheme of Spherical and Cylindrical Anchors
a) Spherical Anchor (Volume Anchor Tail)
b) Cylindrical Anchor (Line Anchor Tail)

Finally, the purpose of work was to establish proper theoretical model which will be in good coincidence with obtained results. In general the stated intentions of the exposed investigation programme, have been successfully performed.

3. FIELD AND LABORATORY WORKS

Two locations near the city of Varaždin were chosen to carry out the investigation works: place Čret (30 km) and place Cerje Tužno (20 km from Varaždin). By soil mechanical investigation drillings and laboratory testing of soil samples it has been obtained that there are clayey formations on the Čret location (mean values: $c=10kN/m^2$, $\phi=25°$, $\gamma=19\ kN/m^3$) while the sandy soil with some silt and clay particles were found on the Cerje Tužno location (mean values: $c=0,2kN/m^2$, $\phi= 32,3°$, $\gamma=19,5kN/m^3$). On these two locations almost fifty vertical anchor bore-holes were performed, among which the 70% was in function of spherical anchors, while other 30% was in function of cylidrical anchors. (Ground water level wasn't reached on both locations). A certain number of these bore-holes (almost 20) were used only for the purpose of investigation of blasting effect, so the anchor installation was anticipated for 30 bore-holes which remaind. Because one of the bore-holes with sphare cavity in sand had collapsed (C4), the anchor tie rod wasn't installed in it. Similarly, two adjacent bore-holes (C5 and C7) had partly collapsed during grout mass casting, so they were excluded from further investigation.

Hence, the number of performed and pull-out tested vertical anchors was finally reduced to 27 pieces, from which 15 with spherical anchor tail and 12 with cylindrical tail (Table I.)

Concerning two testing locations, type of soils and geometrical properties of installed anchors, all the anchors were grouped in three test fields (TF1, TF2, TF3) and five groupes (G1 to G5). Each group contents a certain number of spherical anchors (GS) and a certain number of comparative cylindrical anchors (GC).

Main features of anchors of each individual group are presented in Table II.

TABLE I. List of Anchors Included in the Analysis

DESIGNATION OF TEST LOCATIONS			LIST OF ANCHORS									
			SPHER. ANCH. (GS)					CYLIN. ANCHORS (GC)				
TEST SITE	TEST FIELD	ANCHOR GROUP	pc	ANCHOR DESIG.				pc	ANCHOR DESIG.			
Čret	TF 1	G1	4	A1	A2	A3	A4	3	A1a	A8	A9	–
		G2	4	A13	A15	A16	A17	4	A10	A10a	A12	A18
Cerje Tužno	TF 2	G3	2	B4	B5	–	–	3	B12	B16	B17	–
		G4	2	B7	B9	–	–					
	TF3	G5	3	C1	C2	C3	–	2	C9	C10	–	–

While performing the anchors with spherical tail, the spherical cavity was carried out by using explosive "Amonal, Strenghtened" and "Amonal V" types (v=4200-4500 m/s) which were inserted on the bottom of the bore-holes (Fig.3.). According to previous investigations (by using mass of explosive charge between 50 to 500 g) it was established that optimal blasting results in clay could be achieved by using 100 grammes of the explosive mass (M_e=100g).

In this way, the compression of soil around the cavity will appear due to expansion of explosion gas, and afterwards an increased density and decreased porosity of a limited clay zone around cavity will develope as well (Hudec, Krajcer et al. (1989)). The quantity of explosive should not be overdosed if damages of the soil structure or a conical crater are to be avoided.

Cavity creation results by explosion effect in a sandy soil look similarly, but slightly less successful.

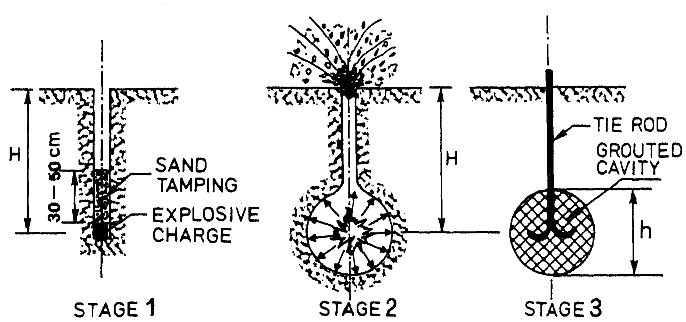


Fig. 3. Performance of Spherical Anchors
Stage 1 – Inserting of Explosive Charge with Sand Tamping
Stage 2 – Blasting
Stage 3 – Tie Rod Installation and Cavity Grouting

4. TESTING OF ANCHORS

Before the spherical anchors were installed, the measurement of shape and size of certain existing cavities had been carried out. It was done by using the simply made mechanical device which provides quite satisfy results, which were checked afterwards by digging out some anchors. (Fig.6.).

Pull-out testing procedure was carried out for each individual anchor using the special hydraulic jack exerted on a simple steel provisory beam (Fig.4.).

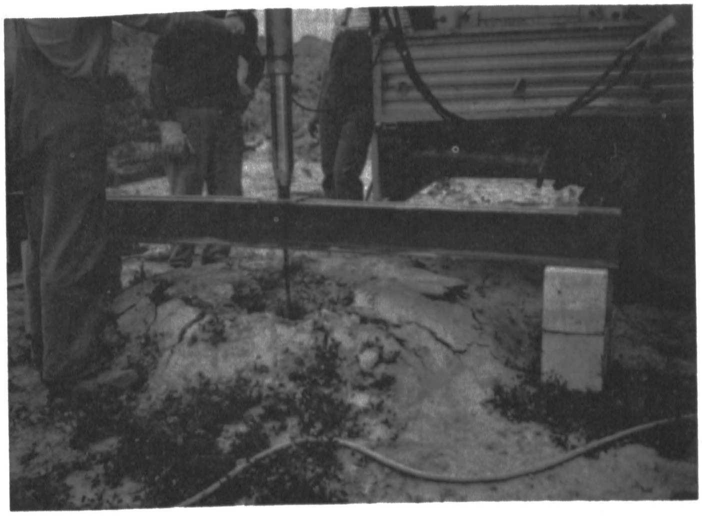


Fig. 4. Anchor Pull-Out Testing Procedure

The tension testing load had been applicated gradualy, but within a rather short time, so the application time lasted only for a few minutes (Fig.5.).

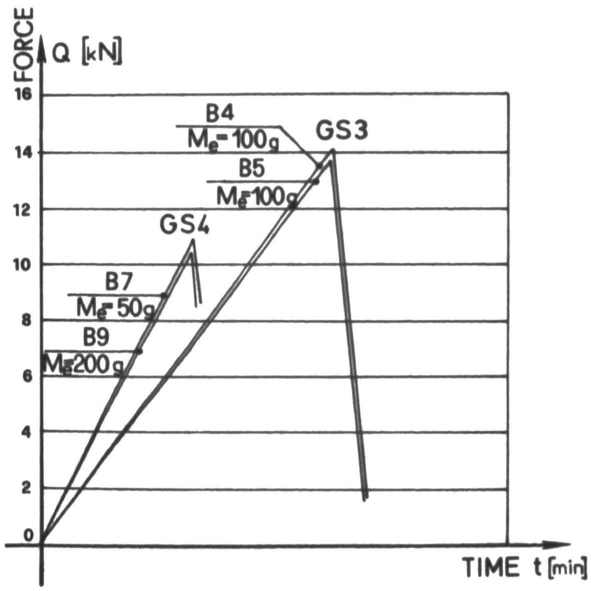


Fig. 5. Anchor Loading Diagram for Spherical Anchor Groups GS3 and GS4

During anchor pull-out testing procedure the displacement of each anchor tie rod top was observed, while displacement of soil surface points was carried out only for few anchors.

After reaching the anchor ultimate bearing capacity (Q_u), pull-out test was stopped. Some spherical anchors were completely dug out (Fig.6.), with purpose to chek the shape and size of the anchor tail. These measurements were compared with the previous ones which took place inside the cavity (after blasting effect).

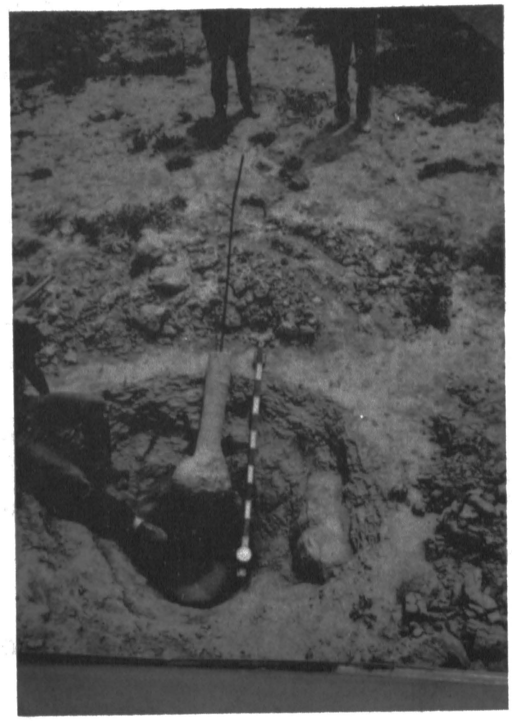


Fig. 6. Shape and Size of the Real Spherical Anchor Tail After Testing Procedure

5. TESTING RESULTS

According to expectation, the anchor pull-out testing results of the short soil anchors were better in clay than in sand (roughly, the bearing capacity ratio is between 2 and 3). At the same time, the bearing capacity of the spherical anchhors ($Q_{u\,sp.}$) is few times higher than bearing capacity of the cylindrical anchors ($Q_{u\,cy.}$). Once again, the rounded range of bearing ratio varies between 2 and 3. The relevant data are shown in the Table II.

6. THEORETICAL HYPOTHESIS OF BEARING CAPACITY

Vesic (1965) studied the problem of an explosive point charge expanding a spherical cavity close to the soil surface.

Vesic (1971) applied the results of his study to determine the ultimate bearing capacity of short vertical anchors with the circular plate anchor tail, with diameter h and located at a depth H below the ground surface (Fig.7a.). In case of cohesionless soil (c=0) Vesic established equation (1):

$$Q_u = A\gamma HF_q \qquad (1)$$

where F_q stands for dimensionless breakout factor for shallow circular anchor plate. The F_q factor is given in the chart (Fig.8a.) where F_q= F_q(H/h). In a similar manner, using the analogy of the expansion of long horizontal cylindrical cavities, Vesic determined the variation of the breakout factor F_q for the strip anchor plate shallow embedded below the soil surface.

TABLE II. Main Features of Five Tested Anchor Groups

DESIGNATION OF TEST LOCATIONS			SPHERICAL ANCHORS (GS)						CYLINDRICAL ANCHORS (GC)				Ratio:
TEST SITE	TEST FIELD	ANCHOR GROUP	No pc	M_e [g]	d_b [mm]	H [m]	h (mean) [cm]	$Q_{u\,is}$ (mean) [kN]	No pc	d_b [mm]	H [m]	$Q_{u\,is}$ (mean) [kN]	$Q_{u\,sp.}$ / $Q_{u\,cy.}$
Čret	TF 1	G1	4	100	101	1,0	440	32,5	3	101 (one 116)	1,0	15,0	2,17
Mean Soil Parameters c=10kN/m² ∅=25° γ=19kN/m³		G2	4	100 (one 150)	101	1,2	500	40,5	4	101 (one 116)	1,2	11,1	3,65
Cerje Tužno Mean Soil P. c=0,2kN/m² ∅=32,3° γ=19,5kN/m³	TF 2	G3	2	100	131	1,0	305	14,0	3	76 (one 131)	1,2	5,4	2,60
		G4	2	50 200	131	0,7 1,0	520	10,6					1,96
	TF 3	G5	3	100	76	1,0	463	15.8	2	76 116	1,0 1,3	6,6	2,39

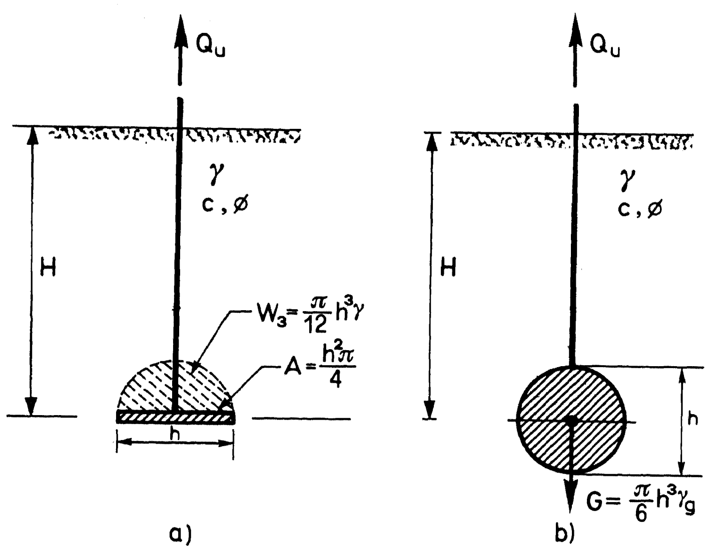


Fig. 7. Shallow Vertical Anchor with Circular Anchor Plate (a) and with Spherical Tail (b)

Further more, based on the same concept Vesić (1971) established an ultimate bearing capacity equation (2) for clayey soil (ϕ = 0 condition, so: $c = c_u$):

$$Q_u = A\,(\gamma H + c_u F_c) \qquad (2)$$

Theoretical variation of the breakout factor F_c with the embedment ratio H/h, which corresponds to shallow embedded circular anchor plate, is also given (Fig.8b.).

Based on the preciding Vesić's works, Muhovec and Krajcer (1992) modified equations (1) and (2) to adjust them for the anchors with spherical anchor tail (Fig.7b.) Further more, they combined these equations in order to establish new one (3) which can be used for spherical anchors in the c, ϕ soils,

$$Q_u = Q_{u\phi} + Q_{uc} - G - W_s \qquad (3)$$

where:
- Q_u - total anchor ultimate bearing capacity in a c, ϕ soil
- $Q_{u\phi}$ - ultimate bearing capacity in c = 0 soil
- Q_{uc} - ultimate bearing capacity in ϕ = 0 soil
- G - weight of spherical body (unit weight γ_g)
- W_s - weight of soil above spherical body (unit weight γ)

Analitically:

$$Q_{u\phi} = \frac{h^2\pi}{4}\left[\gamma H F_q + \frac{h}{3}(2\gamma_g - \gamma)\right] \qquad (4)$$

$$Q_{uc} = \frac{h^2\pi}{4}\left[\gamma H + cF_c + \frac{h}{3}(2\gamma_g - \gamma)\right] \qquad (5)$$

$$G = \frac{\pi}{6}h^3\gamma_g \qquad (6)$$

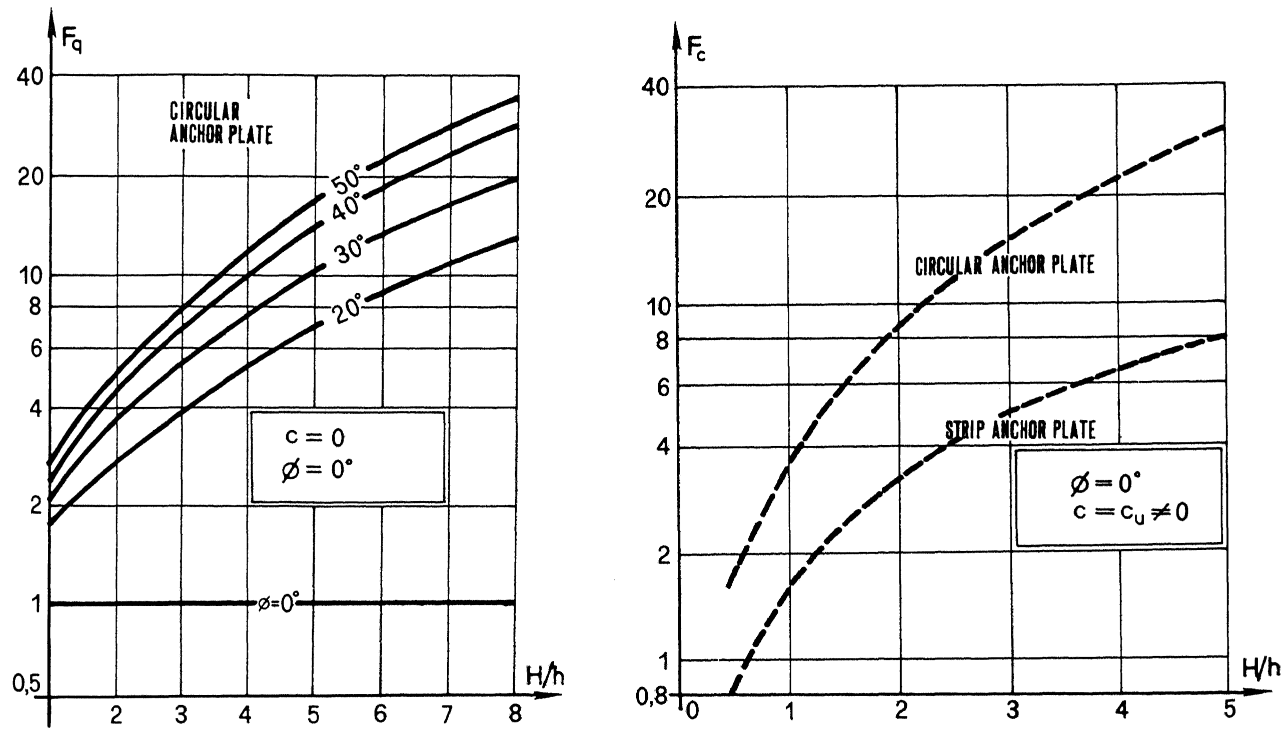
$$W_s = \frac{\pi}{4}h^2\gamma\left(H - \frac{h}{3}\right) \qquad (7)$$

Breakout factors F_q and F_c can be obtained using the Vesić's circular plate charts on Fig.8.

Using the preciding equations (3), (4), (5), (6) and (7) the anchor in situ testing data (Table II) have been processed. First of all, the comparison between values of in situ anchor ultimate bearing capacities ($Q_{u\,in\,situ}$) and computed ultimate bearing capacities ($Q_{u\,cal}$) were done. All relevant data are shown in the Table III.

The ratio $Q_{u\,in\,situ}/Q_{u\,cal}$ in the last calomn which are around value 1,0, showes a high agreement between in situ results and computed values of the spherical anchor bearing capacities.

Thus, this is a new verification of likable Vesić's teoretical concept, but in the same time a good confirmation of the extended equation (3).



ʼig. 8. Vesić's (1971) Breakout Factor Charts a) $F_q = F_q(H/h)$ b) $F_c = F_c(H/h)$

ʼable III. Comparison of the In Situ and Computed Ultimate Bearing Capacities of the Spherical Anchors

LOCATION		SOIL PARAMETERS (mean)	ANCHOR FEATURES & BEARING CAPACITY COMPUTATION										Q_u [kN]		Ratio: $Q_{u\,in\,situ}$ / $Q_{u\,cal}$
			ANCHOR GROUP	H [m]	h [m]	H/h	F_q	F_c	$Q_{u\emptyset}$ [kN]	Q_{uc} [kN]	G [kN]	W_s [kN]	$Q_{u\,cal}$	$Q_{u\,in\,situ}$	
Čret TF 1		c=10kN/m², ∅=25°, γ=19kN/m³	G1	1,0	0,44	2,3	3,8	10	11,62	18,74	1,07	2,47	26,82	32,5	1,21
			G2	1,2	0,50	2,4	3,9	11	18,40	27,02	1,57	3,85	40,00	40,5	1,01
Cerje Tuzno	TF 2	c=0,2kN/m², ∅=32,3°, γ=19,5kN/m³	G3	1,0	0,30	3,3	6,5	17	9,16	1,82	0,34	1,24	9,40	14,0	1,50
			G4	0,85	0,52	1,6	3,0	6	11,60	4,82	1,77	2,80	11,85	10,6	0,91
	TF 3		G5	1,0	0,46	2,2	4,2	9,5	14,34	4,28	1,22	2,74	14,66	15,8	1,08

ʼinally, it should be emphasised that bearing ːapacity extended formula (3) is practicaly a ːunction of four variables:

$$Q_u = Q_u(c, \emptyset, h, H) \qquad (8)$$

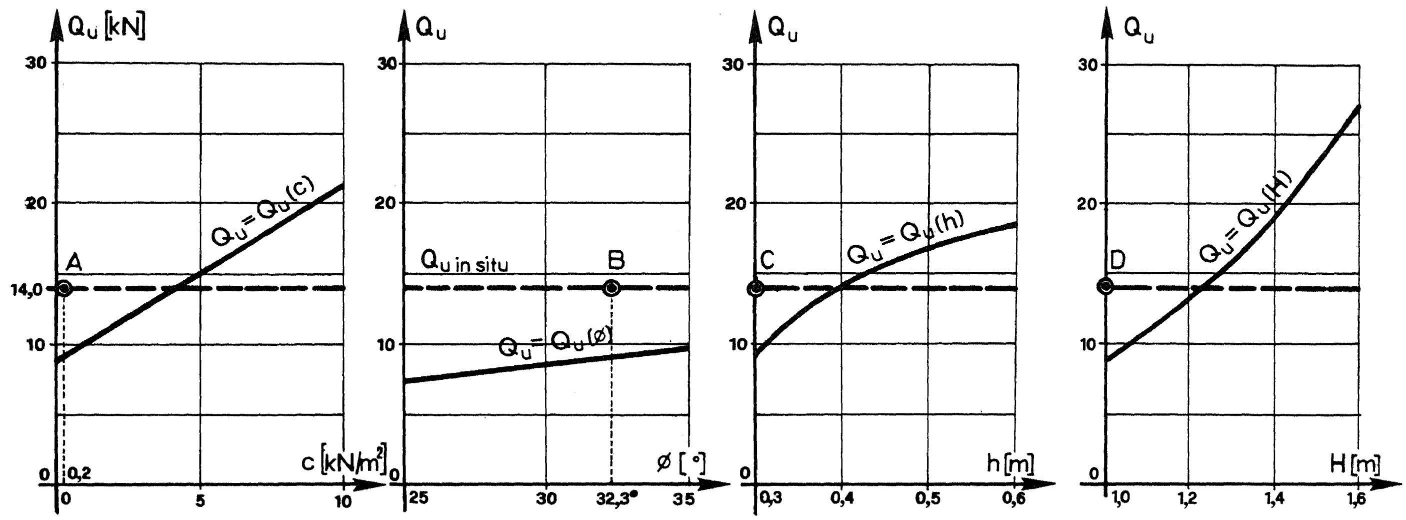
ʼoil unit weight γ most frequently ranges between ıarrow limits (mostly γ=17 to 19 kN/m³),but grout ınit weight γ_g is more or less around value γ_g=24kN/m³. So, γ and γ_g can be considered as a ːonstants.

ıs an illustration of Q_u analytical dependency of ːhe four variables c,∅,h,H, the group of anchors ʼS3 have been procesed by equation (3).

ʼour curves: $Q_u = Q_u(c)$, $Q_u = Q_u(\emptyset)$, $Q_u = Q_u(h)$ and $Q_u = Q_u(H)$ were obtained (Fig.9.). The points A, ː, C and D situated in the charts, indicate real ıeasured state of $Q_{u\,in\,situ}$ for this anchor group.

7. CONCLUSION

In the paper autors present the basic results concerning ultimate bearing capacity for a number of short vertical anchors performed in clayey and sandy soil. Regarding the fact that cylindrical anchors demonstrate a quite low bearing capacity in these soils, shape "replacement" of the anchor tail was carried out. Instead of cylindrical anchor tail the spherical anchor tail was performed. It was successfully realised by carefully dosed and controled blasting effect activated in the bottom of the anchor bore-hole (slightly inferior results were obtained in the sandy soil). By pull-out testing procedure the values of in situ ultimate bearing capacity were obtained. This results show that spherical anchors have roundly between 2 and 3 times better bearing capacities than cylindrical anchors. Similarly, the spherical anchors performed in clay show a 2-3 times higher values of bearing capacities than other spherical anchors which was performed in sandy soil.



EARTH ANCHOR GROUP GS3

Mean soil parameters: c=0,2kN/m²; ∅=32,3°; γ=19,5kN/m³. Mean anchor features: h=0,3m; H=1,0m; $Q_{u\,in\,situ}$=14,0kN. Four diagram lines: $Q_u = Q_u(c)$, $Q_u = Q_u(\varnothing)$, $Q_u = Q_u(h)$, $Q_u = Q_u(H)$ indicate the computational variation of the anchor bearing capacity versus c, ∅, h and H. Diagram points A,B,C,D indicate measured state.

Fig. 9. Analytical Relationships Among Ultimate Bearing Capacity of Spherical Anchors (Q_u) and Four Main Variables: c, ∅, h, H.

Finally, in the paper is shown a high agreement among in situ bearing capacity values $Q_{u\,in\,situ}$ on one side and computed values $Q_{u\,cal}$ on the other side.

$Q_{u\,cal}$ has been calculated by using the modified and extended formula (3), originated from Vesić's concept (1965) and his later work (1971).

The scientific investigation programme concerning short anchors is still under execution. Now the stress in the programme is putted on the problems of rheological behaviour which characterize anchors in soil, particularly in clay.

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