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Development of umbrella anchor approach in terms of the requirements of field application

Burak Evirgen*, Ahmet Tuncan[a] and Mustafa Tuncan[b]

Department of Civil Engineering, Eskisehir Technical University, 26555, Eskisehir, Turkey

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Abstract. In this study, an innovative anchoring approach has been developed dealing with all relevant aspects in consideration of previous works. An ultimate pulling force calculation of anchor is presented from a geotechnical point of view. The proposed umbrella anchor focuses not only on the friction resistance capacity, but also on the axial capacity of the composite end structure and the friction capacity occurring around the wedge. Even though the theoretical background is proposed, in-situ application requires high-level mechanical design. Hence, the required parts have been carefully improved and are composed of anchor body, anchor cap, connection brackets, cutter vanes, open-close ring, support elements and grouting system. Besides, stretcher element made of aramid fabric, interior grouting system, guide tube and cable-locking apparatus are the unique parts of this design. The production and placement steps of real sized anchors are explained in detail. Experimental results of 52 pullout tests on the weak dry soils and 12 in-situ tests inside natural soil indicate that the proposed approach is conservative and its peak pullout value is directly limited by a maximum strength of anchored soil layer if other failure possibilities are eliminated. Umbrella anchor is an alternative to conventional anchor applications used in all types of soils. It not only provides time and workmanship benefits, but also a high level of economic gain and safe design.

Keywords: umbrella anchor; anchorage; pullout strength; slope stability; field application

1. Introduction

Anchoring is known as the tying of various covering members and structures to stronger soil layers within deep excavations, foundations of wind turbines or the pinning of movable sea platforms by connecting members in case of insufficient passive force created by retaining structures constructed against lateral earth pressure. On the other hand, the most important goal of anchor use in application is to reduce the driving depth of the bearing members while also adhering to safety requirements. However, efforts to upgrade the conventional anchors, which are still inadequate in terms of time, labor, cost and application, are at the forefront in current studies. It is worth calling attention to the innovative anchors, which depend on the geometry, mechanical details and working principle, which can alter pull out performance of conventional anchors.

The prominent innovative anchors have been mostly involve plate, helical and torpedo type anchors developed for only vertical or close to vertical use inside the weaker saturated soils during past few decades. Analytical and experimental studies regarding plate anchors have commonly focused on anchor performance, pullout capacity and deformations based on geometry, embedment depth, soil conditions and strengthening elements as a keying flap (Song *et al.* 2008, Yang *et al.* 2010, Tian *et al.* 2014, Aubeny and Chi 2014, Liu *et al.* 2017). If plate anchors are used inside normal soils, excavation along the borehole is required equal to the anchor diameter. After this, the hole can be filled with various materials; for instance, granular soil (Rao *et al.* 2007). The pullout capacity of horizontal or inclined strip anchor plates are directly related with the embedment ratio, angle of anchor, angle of slope and internal parameters of tying member applied soils (Bhattacharya 2017, Bhattacharya and Sahoo 2017). On the other hand, piles with belled end can be used against tension forces within similar manner (Moghaddas Tafreshi *et al.* 2014). Torpedo anchors are also fixing members that resist uplift forces with frictional resistance created by their own weights. Working in this area is usually focused on determining anchor behavior during the drag and installation phases (Wang *et al.* 2016, O'Beirne *et al.* 2017). In addition, helical type anchors are encountered as a quite new application. Tang and Phoon (2016) evaluated the uplift behavior of helical anchors in terms of factors influenced on model uncertainty, which is based on finite element models. Prisco and Pisano (2014) improved that telescopically extruded steel sockets used to tie of anchor body to the soil. The pull out strength increment was reported in the deeper anchors due to depth of the sockets as well as the extrusion proposal with minimum 400-bar pressure for highest effectiveness into stiff soil layers.

An umbrella shaped anchor elements often appear in the patents more than academic studies since addressed to the practical application in the direction of various intended

*Corresponding author, Ph.D.
E-mail: burakevirgen@eskisehir.edu.tr
[a]Professor
E-mail: atuncan@eskisehir.edu.tr
[b]Professor
E-mail: mtuncan@eskisehir.edu.tr

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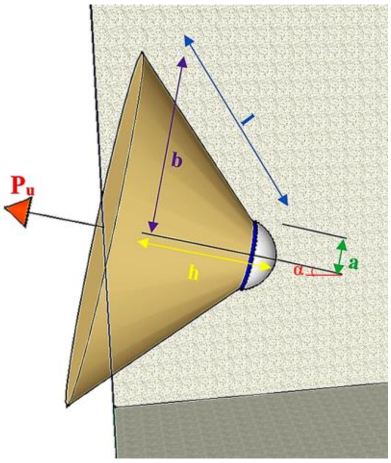


Fig. 1 Acceptance of pulling strength due to proposed umbrella anchor

purposes such as slope stability, under-foundation pile and fixing of reinforced concrete elements. These umbrella anchors consist of expanding end creation as a main aim at the end of the unpacking process of wing or vanes via pull, push or rotation motions. Some inventors have proposed miscellaneous details for instance the movement of the worm gear on the main body, the extruded system, the mechanical locking mechanisms, and the use of springs or rods (Bowman and Smith 1966, Shibata 1976, Green 1981, Lu 1987, Olthoff *et al.* 1993, Yasuhiro 2002, Qiao *et al.* 2013, Nanchang Inst. Technology 2014, Univ. of Science & Tech Beijing and Sinohydro Bureau 14 Co. Ltd. 2016, Evirgen *et al.* 2017).

Especially in the last 10 years, it has been stated that umbrella shaped anti-float anchors have been tried to be developed in order to meet adequate uplift resistance. Unfortunately, only few experimental and simulation works can be found dealing with the behavior of umbrella anchors in the literature. Zhu *et al.* (2014) indicated that diameter, embedment depth, elasticity modulus of soil and shear strength factors have a serious effect on the uplift capacity of umbrella shaped ground anchor. It has been proposed that sub-base tension piles are used to fix the more stable soil layers. The pipe-in-pipe assembly type of anchor body with support element model specified as great potentiality and prominent superiority was designed by Xu *et al.* (2009). Liu *et al.* (2008) evaluated that the applicability of grouted and without grouted umbrella shaped anchors have proposed simple mechanism. It was stated that, pullout capacity depends on the weight of soil was wrapped by anchor head and shear strength along the interface surface. Some details about the implementation of similar system was given by Zhang (2006). Yang *et al.* (2018) highlighted the greatly increased moment bearing capacity was occurred when external skirt members were assembled on the umbrella suction anchors under different loading conditions. Furthermore, Li *et al.* (2017) presented the dynamic characteristics, damage possibilities and modal vibration modes of the members such as master cylinder, the tube skirt, and anchor branches of this model used for offshore wind turbines. Evirgen (2017) remarked the requirement of new anchoring approach in terms of ease of application compared with conventional fixing methods such as creating fixed ends in the root zone, back-to-back connection of the two slope surfaces together or fixing from the surface to the anchor base after open excavation reaching up to the required depth. On the other hand, improvement the strength of grouting material is used as a capacity increment method for standard root zones (Evirgen *et al.* 2019).

In spite of the aforementioned umbrella shaped designs, many of them have remained only as hypotheses. The main reason why umbrella anchors are not actively used in projects is that there are no effective proposals for the field application and they are not put into a theoretical background. Therefore, this paper presents the design and application of umbrella anchor, as well as a theoretical background, by taking into consideration all of these requirements. A reduction in the cost of well-known conventional anchorage constructions, in addition to safety and efficiency enhancement, are the primary objectives of this unique technique.

2. Theoretical background

Ultimate pull out force calculations can be found in the literature connected with lateral earth pressure carried out according to various tolerances (Mackenzie 1955, Teng 1962, Das 1984). Although there are many different anchor types and their capacity calculations can be found, plate anchors have the closest working mechanism with umbrella anchors theoretically. Embedment depth, layer depth, overburden pressure, breakaway conditions and geometrical shapes of anchors were given as critical factors for plate anchors in clay type of soils (Rowe and Davis 1982a). If calculation is required for sandy type soil, friction angle, dilatancy and initial stress state come into prominence in addition to the embedment depth (Rowe and Davis 1982b). In the case of cyclic loading occurs for plate anchors in dense sand, anchor capacity is affected by the magnitude of the peak cyclic load and soil is primarily subjected to shear rather than densification (Chow *et al.* 2015).

Among the theoretical studies, the well accepted failure behavior has been given in truncated cone shape that occurs in case of general shear failure at passive zone (Deshmukh *et al.* 2010, Liu *et al.* 2012, Consoli *et al.* 2013). This soil behavior was first mentioned in Mors (1959); an approach focusing only on soil weight, and ignoring friction behavior generally. Therefore, the ultimate pulling capacity is proposed according to a combination of conical shear wedge located in front of the composite anchor end and friction surface together, rather than only the slippage capacity of the grouted root part. In the proposed umbrella anchoring system, ultimate pulling force equations have been developed for sandy and clayey dominated soils as shown in Fig. 1. In this expression, geometric dimensions of the passive cone are the key parameters, which is directly affected by the strength of the fixed soil of anchor.

The recommended calculation method that is a combination of surface friction (τ_s) on the wedge surface (Das 1984) and weight of the total passive soil component inside the conical shape is given in Eq. (1).

$$P_u = \tau_s + (V_s . \gamma_{soil}) K_p \cos\alpha \quad (1)$$

If required parameters are placed in a raw equation, the ultimate anchor pulling force (P_u) on sandy soils can be given as follows (Eq. (2)). In addition, Eq. (3) is proposed for clayey soils

$$P_u = \pi(a+b)l * \bar{\sigma}_0' * K_p * tan\emptyset' + \left\{\frac{1}{3}\pi h(a^2+ab+b^2) * \gamma_{soil}\right\} K_p \cos\alpha \quad (2)$$

$$P_u = \pi(a+b)l * c_a + \left\{\frac{1}{3}\pi h(a^2+ab+b^2) * \gamma_{soil}\right\} K_p \cos\alpha \quad (3)$$

This is where: V_s is an volume of soil that is located inside the cone; γ_{soil} is an unit weight of soil; $\emptyset'$ is an effective internal friction angle of soil; $\bar{\sigma}_0'$ is an average effective vertical stress; K_p is a passive earth pressure coefficient directly related with the overburden pressure (Hanna *et al.* 2011); 'c_a' is a coefficient of adhesion; 'α' is the angle of an anchor with horizontal and 'l' is a surface length of shear cone at the appropriate angle. In this geometrical assumption, 'a' denotes the lower radius of the resulting cone and equal to the radius of the selected anchor. In addition, 'b' is an upper radius of the resulting cone, which are directly related with the angle of wedge. Although a minimum factor of safety value of '2.00' is recommended in the anchorage calculations under normal conditions at the root zone (Das 1984), the factor of safety value is not used in these calculations. It is also predicted that a much lower factor of safety values will be sufficient for in-situ applications when compared with a conventional application.

3. Experimental investigations

In order to evaluate the theoretical assumption a total of 52 pullout tests were conducted using different diameters of anchor plates at different depths in various dry soils. Experiments have been carried out to observe shear wedge formations in the worst-case scenario of environmental conditions even though the anchor vanes are fully opened. Within this purpose, dry and quite weak soils without grouting were selected as embedment layer. On the other hand, circular steel plates simulates the fully opened umbrella anchors have 50.00, 100.00, 150.00 and 200.00 mm diameters with tie bar. A real scaled application in natural conditions were carried out in the field as given in the next section, too.

3.1 Soil properties

Sandy (SP), silty (ML) and clayey (CL) soils were used in the anchorage pullout tests. The grain size distribution curves are given in Fig. 2, with their properties being given in Table 1. During filling of the experimental cell, sand samples were discharged at two different heights named as a dry pluviation technique to provide different density values. Therefore, the void ratio values were calculated as 66.10% and 49.40% for loosest and denser states. On the other hand, the cohesion and internal friction angle values of the soils are required in order to calculate the pulling force in the prediction of the theoretical approach. For this reason, direct shear tests were carried out under 3.00 kg and 6.00 kg axial loads for each of the soils. The internal friction angle values of loose sand, denser sand, silt and clay samples were calculated as 6.80º, 8.00º, 3.40º and 4.60º, respectively. The cohesion values were found to be zero since the soils were dry. It can be seen that these extremely low parameters are representing the worst environmental condition.

Table 1 Properties of used soils

	Specific gravity	Amount of grains (%)			Atterberg limits (%)			
		Gravel	Sand	Silt & Clay	Shrinkage limit	Plastic limit	Liquid limit	Plasticity index
Sand (SP)	2.58	1.30	98.30	0.40	-	-	-	-
Silt (ML)	2.37	0.00	1.50	98.50	21.10	40.00	41.00	1.00
Clay (CL)	2.68	0.80	48.10	51.10	13.20	18.30	22.20	3.90

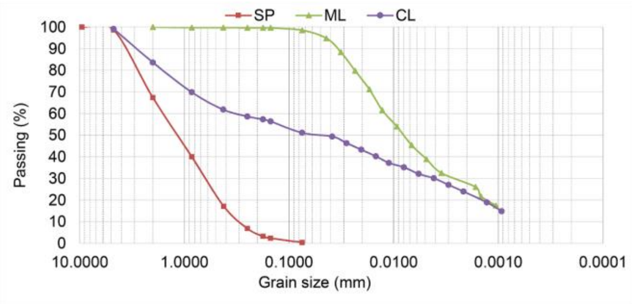


Fig. 2 Grain size distribution curves of used soils

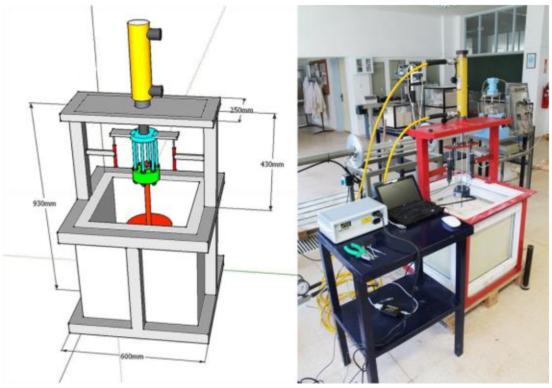
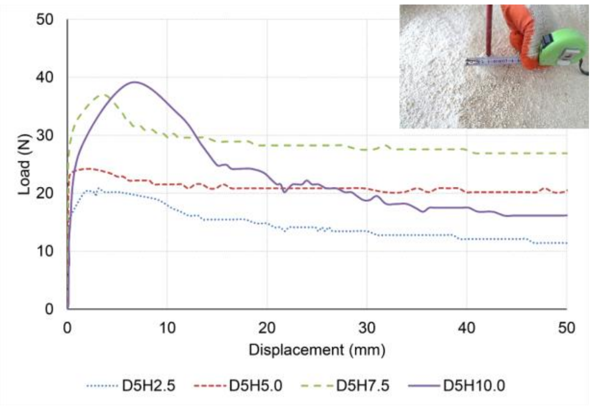


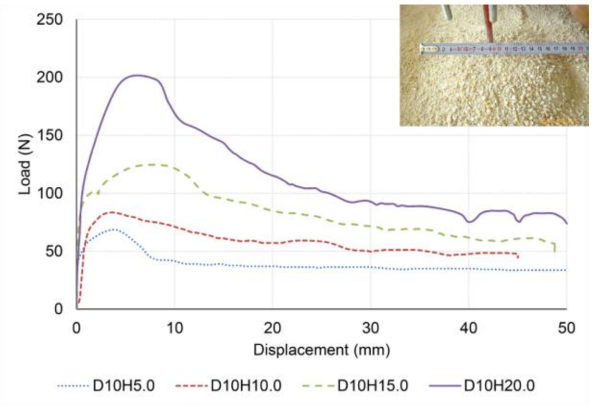
Fig. 3 Anchor pullout mechanism; sketch and experimental setup

3.2 Test setup and instrumentation

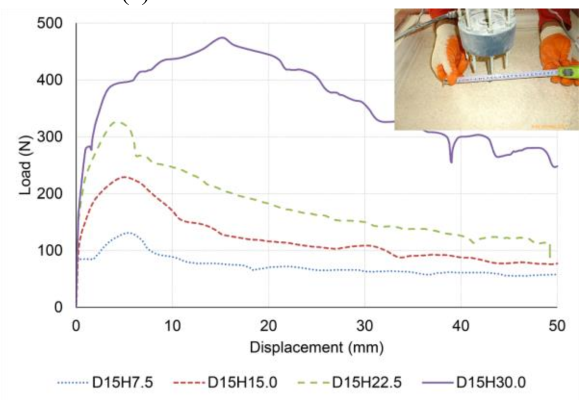
A cubic pvc cell with a unit length of 500.00 mm was supported with steel profiles surrounded on the outside with the frame formed as shown in Fig. 3. Elastic connectors were used at the connection points especially in sidewalls within the scope of minimize the boundary effect. The required members were assembled starting at the top of the steel frame; these being a 90.00 kN capacitive hydraulic jack, tension plate, tension bars, 20.00 kN capacitive load



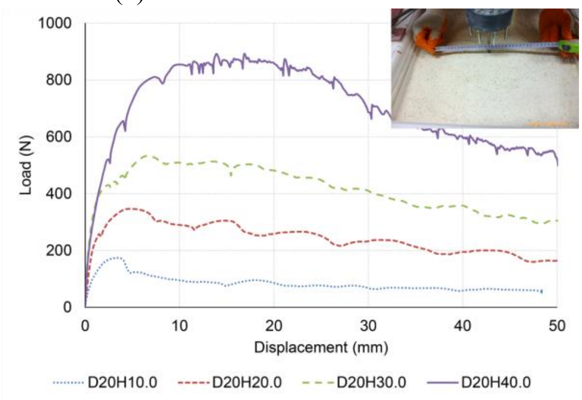
(a) 50.0 mm in anchor diameter



(b) 100.0 mm in anchor diameter

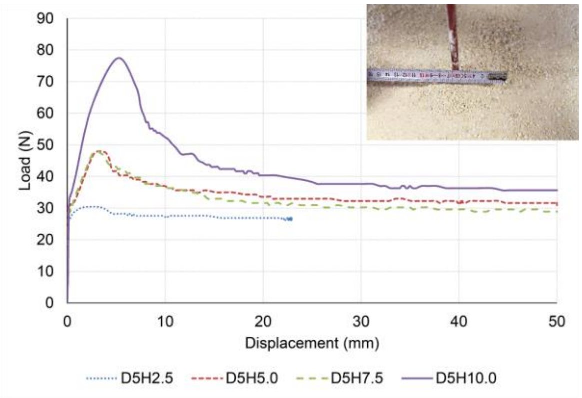


(c) 150.0 mm in anchor diameter

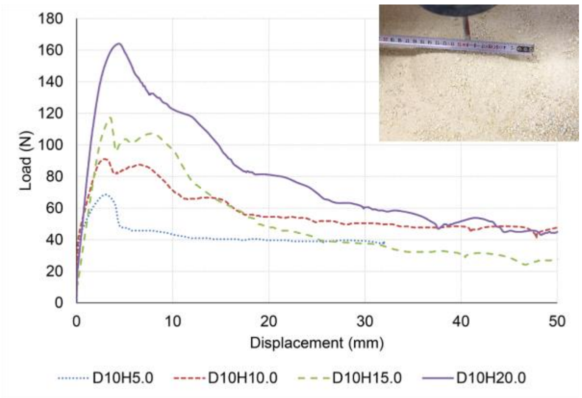


(d) 200.0 mm in anchor diameter

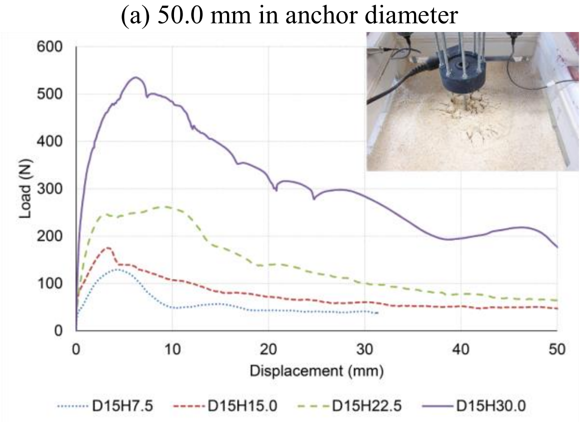
Fig. 4 Load-Displacement curves of anchors in loose sand



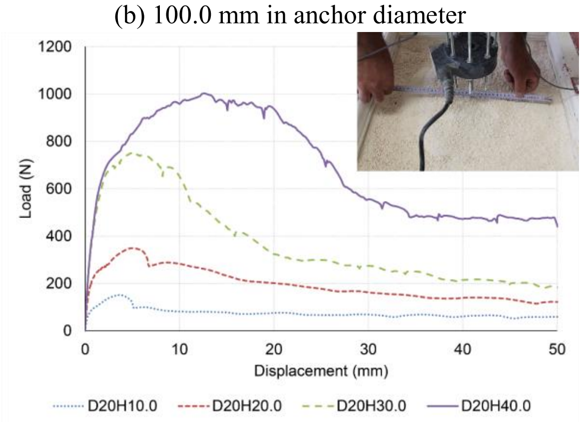
(a) 50.0 mm in anchor diameter



(b) 100.0 mm in anchor diameter

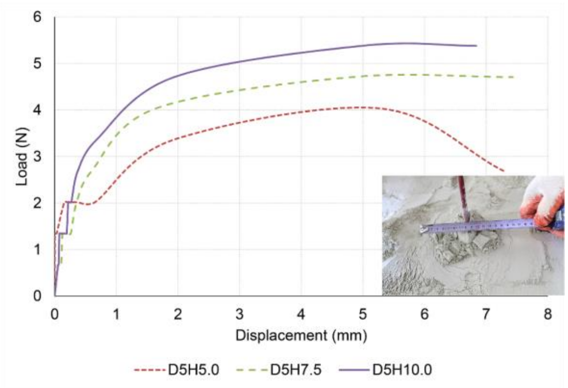


(c) 150.0 mm in anchor diameter

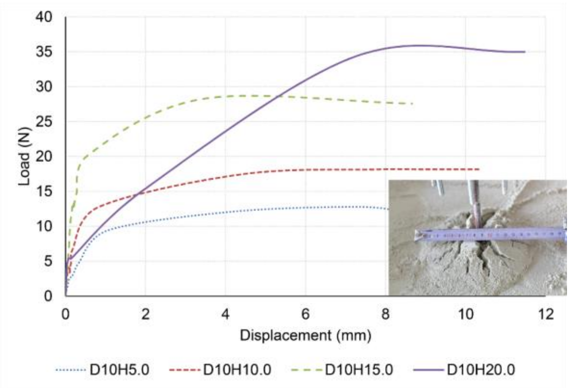


(d) 200.0 mm in anchor diameter

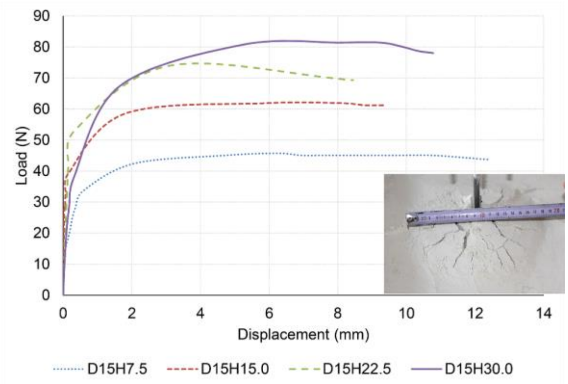
Fig. 5 Load - Displacement curves of anchors in dense sand



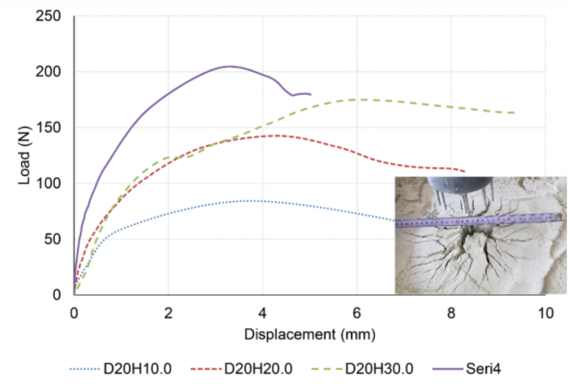
(a) 50.0 mm in anchor diameter - silt



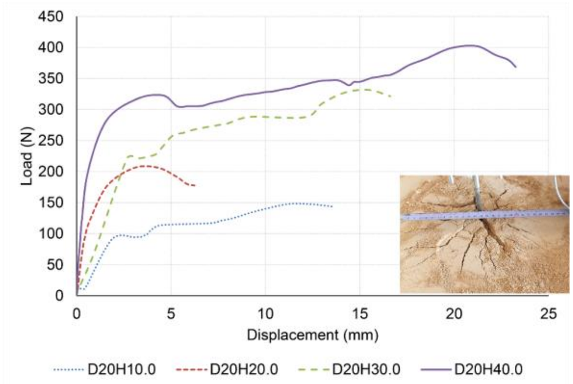
(b) 100.0 mm in anchor diameter - silt



(c) 150.0 mm in anchor diameter - silt



(d) 200.0 mm in anchor diameter - silt



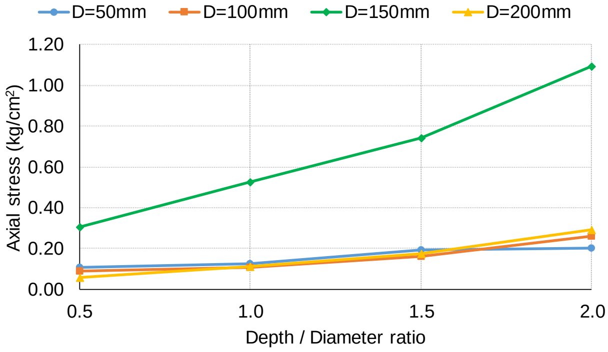
(e) 200.0 mm in anchor diameter - clay

Fig. 6 Load - Displacement curves of anchors in fine grained soils

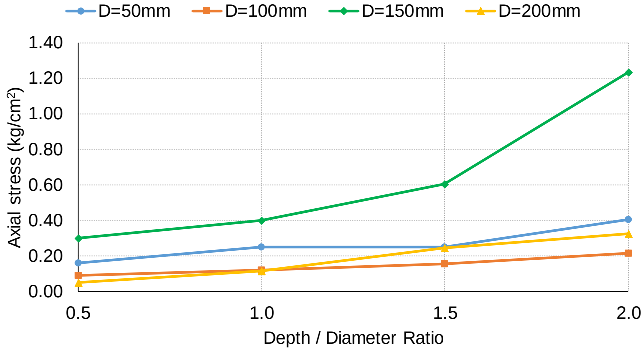
cell with 0.05% accuracy and steel anchor elements of various diameters, respectively. Two 50.00 mm capacitive displacement transducers have 0.0002 strain/mm sensitivity connected to a data acquisition system were placed bilaterally and these collected simultaneous load-displacement values. 0.40 kN/sec pace rate was selected due to minimum capacity of manually operated hydraulic power unit. Pull out tests were carried out at 0.50, 1.00, 1.50 and 2.00 diameter/depth ratios of anchors in tests. For ease of application, the anchors are pulled vertically. Otherwise, it will be essential to support them with external beam-like structures by forming a sloped or vertical soil surface.

3.3 Analysis of experimental results

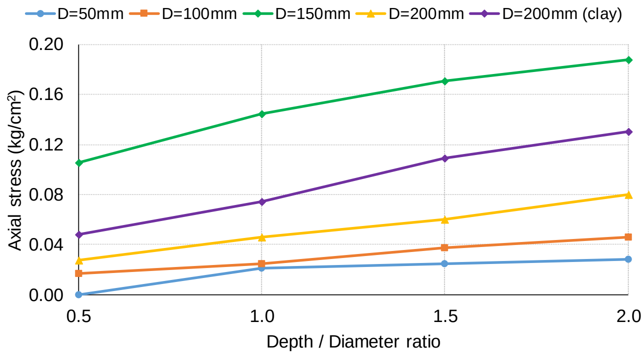
The load-displacement curves of experimental pullout tests are given in Figs. 4-6 for loose sand, dense sand and fine grained dry soils, respectively. The letters 'D' and 'H' were used as abbreviations for the diameter and depth parameters. For example, the name 'D5H2.5' refers to having a 50.00 mm diameter and a 25.00 mm depth of anchor sample. In all cases, although the pulling forces increase with an increment in diameter and depth, these increase rates differ according to the soil type and the relative density values of the soil. Generally, similar tendencies were observed on sandy soils regardless of the relative density, even though in some cases partial reduction were obtained with the increase of density. It can be clearly seen that denser state of sand specimens have 1.08 times greater pullout strength than loose ones, if average values are taken into consideration. On the contrary, the average displacements corresponding to the peak load values decrease around 23.22% with the increase in relative



(a) Loose sand



(b) Dense sand



(c) Silt & clay

Fig. 7 Axial stress values obtained from experimental pullout tests due to depth / dimeter ratio

density of sandy specimens. The fluctuations occurred in the curves of loose sand due to the irregular voids are also became smoother with the increase in density.

Moreover, pullout strength values were calculated as being relatively low on fine-grained soils due to the dryness of soils and did not allow for the formation of cohesion in particular. Although, the average pullout strength of silty specimen was lower than sandy ones 72.58% approximately, it showed that 50.60% more displacement behavior. The ultimate pullout stress values of the circular plate having 200.00 mm diameter in clay were increased about 81.40% in comparison with silty case, despite the fact that 46.90% decrease with respect to the sandy one.

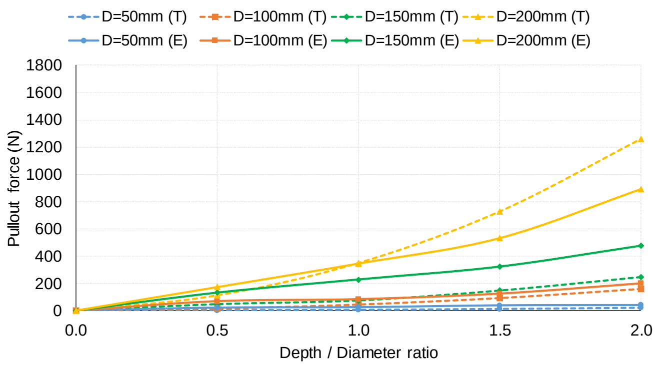
Shortly, if the diameter/depth ratio of the implemented anchor increases, the pullout loads are enhanced up to a specific point, essentially dependent on the strength of the soil. Since more passive mass has been located inside the shear wedge, the capacity was increased when the relative density of dry sands was increased. On the other hand, it seems that the method is not applicable; especially if circular plates that have small diameters are used in fine-grained samples in dry state.

Although the maximum pullout force was observed on a 200.0 mm diameter plate in all soil types, when the values were examined in terms of pullout strength, as shown in Fig. 7, the maximum strength was observed on a plate of 150.0 mm diameter. Since this passive strength originates from an overburden pressure of soil located above the plate, the maximum bearing capacity is also obtained on this diameter.

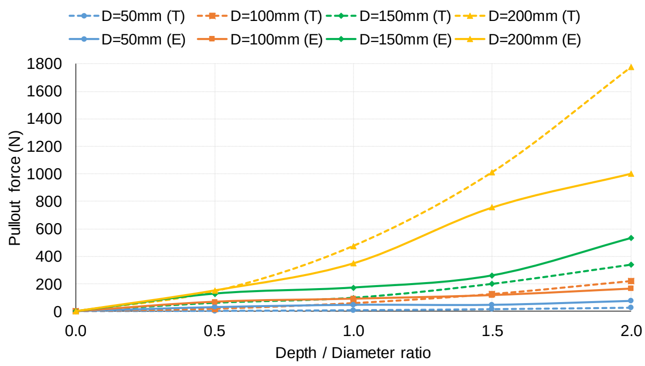
The pullout forces of a case performed in a laboratory were calculated according to the theoretical approach (Eq. 2-3) taking into account only the internal friction angle values of the soil samples in a dry cohesionless state. The compared graphs of the theoretical (T) and experimental (E) pullout strength results based on the depth/diameter ratio are given in Fig. 8. It can easily be seen at the curves that maximum pullout forces within experiments are greater than theoretical ones up to a 15.00 mm plate diameter in all of the focused depth/diameter ratios. When considering both the created cone diameter and the capacity increment, this ratio can be taken around 1.50 for related dry soils. This behavior is directly related with the embedment ratio of plate anchors in granular soils and problematic cases can be solved by using large ratio to eliminate grain size effect within scaled laboratory tests according to Athani *et al.* (2017). In addition, considering the differences between theoretical and experimental curves, with an increasing depth/diameter ratio, the shear wedge diameter decreases after increasing up to a critical angle between the anchor plate and the conical shear surface. This critical ratio changes according to the internal parameters of the soil that creates the soil strength. Therefore, the maximum pullout force of the anchor is limited by the strength of the anchored soil predominantly.

3.4 Failure modes

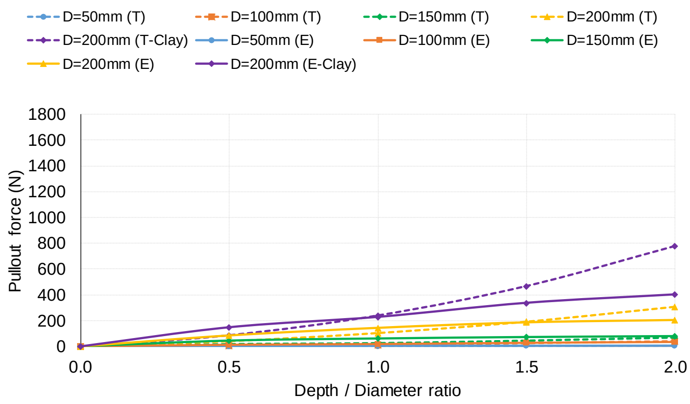
The angle 'β' was taken as 5.00° which is located between the shear wedge surface and axial direction of anchor, since thin layered dry soils did not have enough strength to create a wider angle. Therefore, the proposed



(a) Loose sand



(b) Dense sand



(c) Silt & clay

Fig. 8 Comparative theoretical (T) and experimental (E) maximum pullout force curves

equations can be evaluated within laboratory experiments. It is expected that anchors possibly have higher capacity in strong soils caused by an increment of angle related to the amount of high passive soil resistance and surface friction as well. This failure plane angle of anchored soils may varies from 22.00º to 30.00º for cement-stabilized sand (Consoli et al. 2013) and can rise up to the 53.00º in gravel formations (Hsu and Chang 2007). Since the formation of the shear plane in the umbrella anchor arises from the anchorage end to the root surface, the passive behavior of the conical shaped soil mass spreads over the load to quite a wide area in case of stronger soil existence.

4. Details of umbrella anchor

Despite the fact that a theoretical background is established in the umbrella anchor approach, and is evaluated by experiments, a composite root part details play a vital role during practical application by providing a foreseen high capacity. Otherwise, the anchor cable is pulled away from the root zone before the load is transferred to the slope covering and the system will not work. Within this purpose, miscellaneous anchor details have been designed. Greater efficiency and easy implementation are the most significant factors in a final decision for the proposed umbrella anchor detail, while an increase in anchor capacity ensures a shortening in anchor length and a decrease in the number of anchors. Therefore, this device will provide considerable time saving and financial gain.

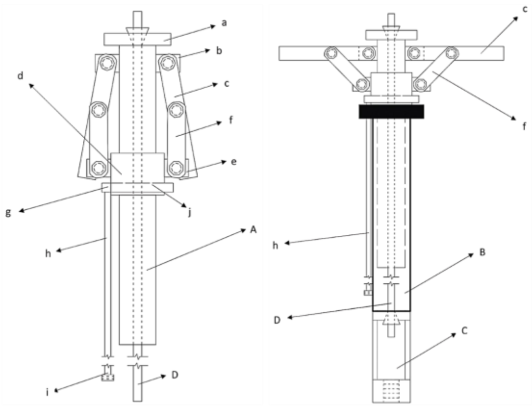


Fig. 9 Umbrella anchor details in unlocked and locked positions, respectively; A. Anchor body, a. Anchor cap, b. Upper connection brackets, c. Cutter vanes, d. Open-close ring, e. Lower connection brackets, f. Support elements, g. Grouting ring, h. Grouting pipe, i. Grouting coupling, j. Nozzle orifices, B. Guide tube, C. Cable locking apparatus, D. Anchor cable (Evirgen *et al.* 2017)

Firstly, the unlocked vanes are designed as a single pulley system and a spherical pulley system. The required number of cables are assembled on the each vane's endpoint for single pulley one within the purpose of ensuring the opening procedure. Then, these cables are combined in a central tendon and pulled through the anchor body. In the next step, a spherical pulley with special cable channels is

Table 2 Properties of natural soils

Layer	Depth (m)	Unit Weight (kN/m^3)	Cohesion (kN/m^2)	Bearing Capacity (kN/m^2)
Silty Clay - 1	0.0 - 4.0	19.00	60.00	120.00
Silty Clay - 2	4.0 - 7.0	17.00	20.00	40.00
Silty Clay - 3	7.0 - 10.0	19.00	85.00	170.00

proposed to eliminate the local stress concentrations on the pin connections. A metal helmet is mounted on the end of anchor which provides the ease of installation during application stage. However, these connection details severely force the cutter vanes or connection members. Therefore, free-hinged vanes with support elements and an open-close ring mechanism are proposed that can easily move the vanes inside the hole.

Secondly, following the provision of concave or convex cast iron usage, the vane geometry is designed with industrial steel profiles. The front sides of the vanes are designed wider to steel mesh connection in order to provide a suitable opening procedure as well as cutting of the soil. This system includes an external guide tube than can be seated inside the socket on the anchor body. On the other hand, some difficulties has been encountered such as the properly seating requirement of steel cable inside the socket and the heaviness or tearing problems of cast iron. Thirdly, a grout injection system is arranged. Finally, a vane-opening system is proposed consisting of a guide tube and rope locking apparatus. These mentioned umbrella anchor details of final design in both unlocked (closed) and locked (open) positions are shown in Fig. 9. Capital letters indicate the main parts, while lower case letters illustrate the subcomponents mounted on the main parts within mentioned figure.

The intended uses of main members are given below.

• The anchor body produced from a hollow steel section is the main element that the cutter vanes and all other parts are assembled together on.

• The cutter vanes provide both fixing of the anchor inside the soil and the formation of a high strength composite element with the grouting. The main task of the vanes is an interlocking to the soil in the horizontal position and, simultaneously, an opening for the stretcher element.

• An open-close ring allows the vanes to open by support elements when it comes to the required position, two locks become a part of an activity within the aim of prevent the reclosing.

• The grommet shaped interior grouting ring is a steel pipe that has nozzle orifices for the purpose of injecting the required amount of water-cement mixture to the anchor root zone.

• The guide tube makes movement of the entire anchorage mechanism inside the center of the anchor hole during penetration. While the cable-locking apparatus is pulling the anchor cable, a guide tube serves the support function. Next, the guide tube contacts the open-close ring and deployment of the vanes commences.

• The stretcher element is a fabric member assembled on the cutter vanes that ensures connection of the vanes to each

Fig. 10 Miniature prototypes of umbrella anchor; 3D output and steel prototype

Fig. 11 Life size productions in unlocked and locked positions

other, and is positioned in such manner to cover like umbrella fabric. After testing different materials, such as canvas fabric, carbon fiber fabric and steel mesh, it was determined that the most suitable fabric type was the aramid fabric used in the steel vest production.

A miniature prototype model of the umbrella anchor was printed by 3D printer. Detailed parts were inspected using both this output and the steel prototype before the production of full scaled ones. The functions of the mechanism operated successfully as is shown in Fig. 10.

5. Real sized production

It is necessary to evaluate the usability of umbrella anchor and to verify both experimental and theoretical results. Therefore, in total, 12 real sized anchors were produced in three different diameters, according to the design. The steel made anchor body has a 70.00 mm inner diameter, 76.00 mm outer diameter and 3.00 mm wall thickness. The length of the body tube was produced in sufficient lengths considering the opening-closing distance of the vanes. An anchor cap and upper connection brackets were welded to end of the body with a minimum 420.00 MPa yield strength and a minimum 500.00–640.00 MPa tensile strength argon welding.

For 500.00, 750.00 and 1000.00 mm diameter umbrella anchors, cutter vanes were manufactured from 10.00 mm thick laminated steel of 212.00 mm, 338.00 mm and 462.00 mm in length, respectively. One end of the each vane was assembled to the upper brackets by a mechanical connection with the other ends being cut at an angle of 45 degrees to provide ease of bolting to the soil. Support elements having half the length of the vanes were fixed to the lower connection brackets located on the open-close ring. Circular grouting rings made of 13.00 mm diameter hollow steel were fixed to each of the anchor heads. Grouting pipes were of 2.50, 4.50, 6.50 and 8.50 m lengths with the aim of pumping the grout material from the soil surface to the bottom of the borehole. The last production step was the careful assembly of the aramid fabric. The unlocked and locked positions of real sized anchors are shown in Fig 11.

6. In-situ application

6.1 Site conditions

The application site was located in the northern side of Eskisehir in Turkey. Three different silty clay layers were observed according to subsurface exploration carried out in the first ten meters of ground. The consistency limits of these weak layers change between soft to medium levels. The soil properties are given in Table 2. The ground water level was encountered at around -3.00 m. In total, twelve boreholes were drilled in a working area of approximately 2000 m^2. Three different diameter and four different depth values were applied to evaluate the anchors. A borehole pattern was settled upon sufficient spacing in order for capacities of adjacent ones to be unaffected.

6.2 Pre-evaluation tests

The seven wire steel strand are used with a diameter of 15.20 mm and a cross sectional area of 140.00 mm^2 has an 1860.00 MPa average tensile strength and a 5.00% extension value according to ASTM A416/A416M − 17a (2017), within cable tension tests. Therefore, a single cable capacity was taken as 26.00 tons during calculations. On the other hand, 60.00 bar and 20.00 bar outlet water pressures are observed with two units of nozzles 2.00 mm in diameter and four units of nozzles 3.50 mm in diameter, respectively (Fig. 12). In the field application, an injection of around 60.00 bar pressure by four units of nozzle orifices with cement was achieved; a water mixture having more viscosity.

6.3 Placement of anchors

Firstly, anchor holes of 2.00, 4.00, 6.00 and 8.00 m depth were drilled using a 180.00 mm diameter auger. By covering the inner parts of the holes with clay-based soil well failures were generally prevented. Otherwise, it would have been necessary to use casing or a bentonite mixture. A secured number of steel cables against the axial load were fixed by steel anchor wedges to the anchor head. Plastic separators were used to prevent the cables from touching each other. Although no cable protection pipe was used within the free zone in this study, the use of this apparatus becomes compulsory in the case of long-term anchoring. After the appropriate guide tube had been inserted, as shown in Fig. 13, the anchor in the closed position was lowered to the bottom of the borehole by crane mechanism.

Fig. 12 Injection process of water-cement mixture

Fig. 13 Placing stages of anchor; Umbrella anchor with guide tube, opening process of vanes and final position in the hole

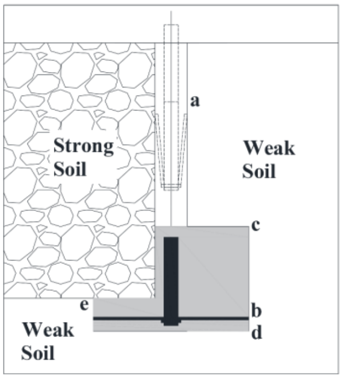


Fig. 14 An illustration regarding placement of anchor due to soil condition

Fig. 15 In-situ test setup; A: Anchor head, B: Circular locking plate, C: Hydraulic jack, D. Lvdt for cable displacement, E: Upper rigid plate, F: Load cell, G: Lower rigid plate, H: Lvdt for settlement, I: Transmission beams

In the second and most important stage, the cutter vanes were opened. This was because, in order to produce a composite root zone at the designed diameter, it was necessary to open the vanes completely and to make sufficient injection otherwise there is no difference from the application of a conventional one. By opening the vanes, the guide tube, cable-locking apparatus and cables worked together. After the guide tube had been fixed to the opening-close ring, the cable was pulled and the anchor moved up a little to open the cutter vanes, simultaneously.

By this process, while the guide tube was subjected to compression force, the cable-locking apparatus worked against the tension force. Since the concrete mass is to be formed in front of the anchor, the required amount of soil must be removed to fill with grout. Hence, in the third stage related soil is compressed in upward direction with the locked umbrella anchorage mechanism by the vanes and stretcher element. 0.5 m free space is generated for each anchor. This process is clearly explained in Fig. 14. After opening the vanes at level ‘b’, the locked anchor is moved between elevations ‘c’ and ‘d’ with the purpose of obtaining free space, when the creation of a large-sized concrete mass inside the weak soils is required. On the other hand, it may be necessary to choose thick steel sections, as it will be difficult to open the vanes in granular soil. If a strong rock layer is found after any weak soil, fixing the anchor immediately after this layer (location ‘e’) will provide the most effective solution in terms of capacity and deformation. The ultimate load capacity of the anchors can reach up to three times design value if the ground anchors are tied to the rock layers according to Liu *et al.* (2017).

Grouting is an essential step for anchorage support system. If low-pressure injection, known as ‘blasting’, is used to create the root zone, an umbrella anchor cannot be applied since there is inadequate concrete mass. Therefore, in the fourth stage a cement-water mixture is pumped into the empty space created in the previous step. The mixture was prepared in a 7.5 kW-1400 rpm mixer and then discharged to an agitator unit with 4.5 kW-1400 rpm.

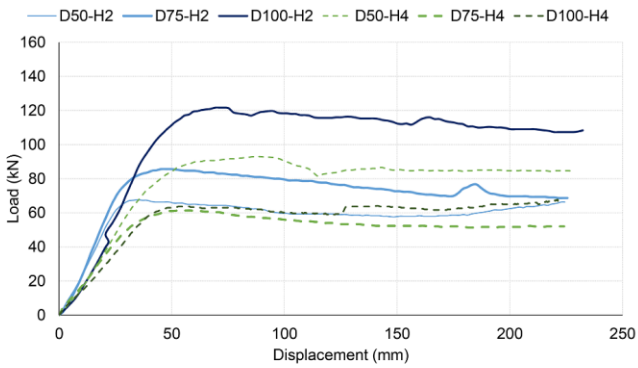
6.4 Test set up and instrumentation

Umbrella anchors were subjected to pullout tests after a 28 days setting time of the grout mixture. The test instruments were a 100-ton capacity TML load cell, a 30-ton capacity double-acting Enerpac piston and three displacement transducers. The test setup shown in Fig. 15 consisted of an anchor head, circular locking plate, hydraulic jack, upper rigid plate, load cell, lower rigid plate and load transmission beams from a top-to-bottom direction. Displacement values were collected of 300.00 mm capacity, 2 transducers for cable movement and 100.00 mm capacity transducer for settlement, simultaneously.

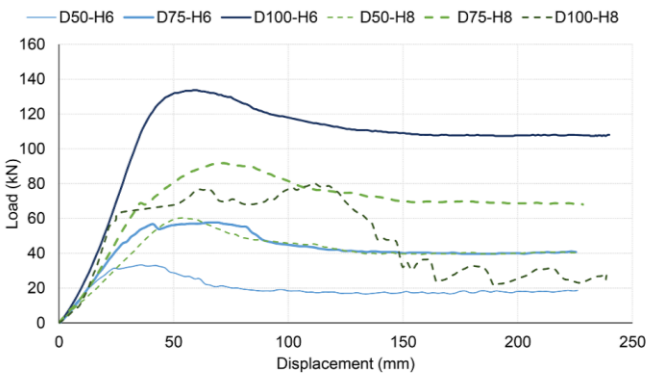
6.5 Analysis of field test results

The load-displacement curves of 12 pullout tests performed in the field application are given in Fig. 16. The letters ‘D’ and ‘H’ were used to define the diameter and depth parameters for curves as in the experimental tests. For example, the name ‘D50-H2’ refers to having a 500.00 mm diameter and a 2.00 m depth of anchor. No sudden drop was encountered after the pullout forces reached their ultimate value. This indicates that umbrella anchors behave according to the proposed working principle in terms of safety consideration. Otherwise, if the composite zone completely slips from the surrounding soil, a sudden and serious decrease in the load is an unavoidable result. Displacement values observed at the ultimate load are generally less than 50.00 mm, although they differ according to depth and diameter parameters. On the other hand, it may be said that the soil remaining on the upper part of the anchor has a partial strength increment due to compression.

The axial strength values were obtained by dividing the ultimate pullout forces into the circular composite area formed at the bottom end portion in accordance with the proposed working principle (Fig. 17). This value can be used in the structural design of the composite section and in the calculation of connection details with steel thicknesses. Considering the weak clayey soil behavior and the occurrence of ground water where the anchor is applied, capacity values of the 500.00 mm and 750.00 mm diameter anchors were applied at a depth of 6.00 m with the lowest bearing capacity due to the natural soil conditions. Even though the average displacement values observed at ultimate state at depths of 2.00 m and 6.00 m were about 50.00 mm, displacements at 4.00 m and 8.00 m deep applications increased up to 90.00 mm. If anchor diameter increases, the axial stress in the unit area decreases. On the other hand, if injection is not made at a sufficient level in weak clayey soils, there is no positive effect of diameter increment in terms of pullout capacity.



(a) 2.00-4.00 m depth



(b) 6.00-8.00 m depth

Fig. 16 Load-displacement curves of in-situ tests

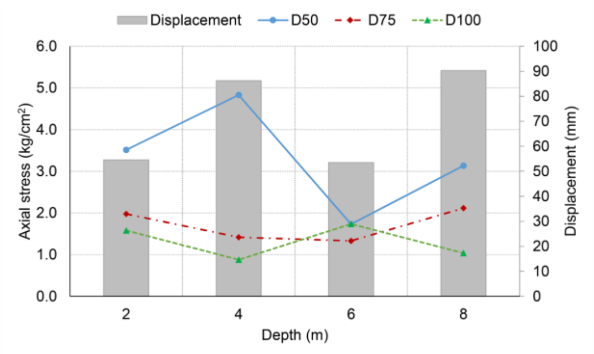


Fig. 17 Axial stress vs. depth graph with displacement value

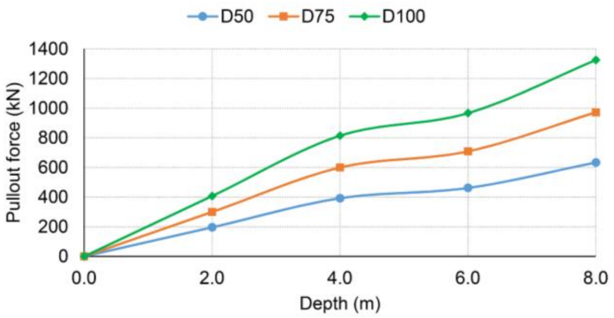


Fig. 18 Pullout force vs depth graph due to theoretical approach

Fig. 19 Certain failure modes of trial anchorages during the design phase; buckling of vanes and tearing of standard canvas, breaking of vanes and tearing of carbon fiber fabric, rupture of anchor cable and slipping of cable from composite mass; respectively

The pullout forces were calculated for in-situ application according to the proposed theoretical equations depending on the soil properties (Fig. 18). These values seem to be quite high. It can clearly be seen that the soil bearing capacities around 1.50 - 2.00 kg/cm^2 levels are reached as the upper limit in application. These results prove that the strength of soil is the primary factor that determines the pullout capacity of the umbrella anchor, if the cross-section and joint details are designed with sufficient rigidity. On the other hand, all of the soil mass inside the conical shape operates in a reverse direction to the anchor within vertical practice. However, these strength levels can be reached if optimum conditions are provided. It is expected that this problem will not be encountered when the umbrella anchor is applied at a close to horizontal angle in lateral support structures. This is because, only the component of the passive soil zone will resist along the same pulling direction. Increasing the volume and strength of the concrete mass in front of the anchor body will directly increase the pullout capacity. In addition, a factor of safety may be preferred as marginally higher than '1.00' for further calculations and high-pressure injection is recommended for practical application.

6.6 Failure modes

The ultimate pullout capacity occurs under optimum conditions when a shear wedge is formed at the estimated cone angle with respect to the theoretical approach. Capacity can be prevented by different structural failure modes due to geotechnical conditions and anchor characteristics before reaching these levels. Mechanical connection errors, material or workmanship defects, symmetry deterioration, problems during placement and injection processes can trigger certain collapse situations. If any of the following eleven different types of failure modes are realized, strength is limited by any component in the system, individual material strength or behavioral inadequacy (Fig 19). The main expectation of the design is to reach an ultimate tensile strength value by creating general shear failure given in a twelfth option.

1) Inadequate shear strength of vane connection bolts
2) Inadequate shear strength of support element connection bolts
3) Inadequate tension or compression strength of support members
4) Inadequate welding strength on the brackets
5) Inadequate bending resistance of the vanes
6) Inadequate resistance of guide tube against buckling and crushing
7) Inadequate material strength of open/close ring
8) Excess cable tensile strength condition
9) Slipping of the cable from the anchor head
10) Slipping of steel frame from concrete mass
11) Inadequate strength of stretcher element
12) General shear failure condition

7. Conclusions

Anchors are frequently used in geotechnical and geological fields, such as slope stability applications, deep excavation systems, support work in mining sites or tunnel lining and so on. If previous studies are examined, it can be seen that safer, more effective and more easily applicable anchors are required in the fast-growing geotechnical engineering sector. Accordingly, a unique umbrella anchor design was presented and evaluated considering the previous suggestions. Based on the results obtained from study, the following conclusions can be derived.

The proposed umbrella anchor focuses not only on the friction resistance capacity, but also on the axial capacity of the composite end structure and the friction capacity occurring around the shear wedge. In this approach, ultimate anchorage capacity calculations are proposed for both granular and cohesive soils depend on the size of wedge and internal parameters of soil. The approach is generally dominated by passive pressure of a conical shaped soil mass that locates in front of the composite end device. In order to achieve an ultimate capacity, it is necessary to create a general shear failure situation. Therefore, the proposed method allows for lower factor of safety values.

On the other hand, site conditions, overburden pressure, ground water properties, grout quality, volume of concrete mass and direction of anchor all directly affect the behavior of anchors. The proposed approach may be modified by using these factors.

The evaluations made in the experimental studies are related to dry soils within the purpose of worst-case simulation. It can be seen that as the depth/diameter ratio increases, the diameter of the shear cone formed in the direction of the pulling force increases up to a critical ratio. Then, stress gradually decreases. This ratio is calculated around 1.50 in dry soils. Maximum axial stresses occurred at the 150.00 mm anchor plates in each case. The strength of anchoring soil and related angle of the wedge (β) are the most important factors in terms of capacity. On the other hand, this anchor type is not applicable for dry cohesive soils when small anchor diameter was used and no grouted mass was created at the same time.

Real-size design, production and in-situ application of umbrella anchors have been successfully carried out. Stretcher element, interior grouting system, guide tube and cable locking apparatus are the unique parts of this system. The primary limiting factor is also the passive strength of soil layer in the field. No sudden drop was encountered according to load displacement curves after the pullout forces reached their ultimate value. This suggests that umbrella anchors behave according to offered working principles in terms of safety application. The displacement values observed at the ultimate load are generally less than 50.00 mm, although they differ according to depth and diameter parameters. If the umbrella anchor end can be fixed immediately behind strong soil, for instance rock or boulder, it can work more efficiently and the pulling capacity of the anchor will be greatly enhanced.

Comparisons of the theoretical approach to field and laboratory measurements prove that the assumptions, production stages and application presented in this paper are conservative up to the strength of related soil. If conventional anchor and umbrella anchor are compared, fewer and shorter anchors will be used to transfer the same load in a geotechnical structure. Therefore, it is clear that the umbrella anchorage method will provide an economical, fast and safe solution in geotechnical designs while emphasizing factor of safety.

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