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Concerning Pressure-Grouted Soil Anchors

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Until recently, anchored sheet piling walls were almost exclusively provided with long horizontal anchors that had anchor walls, slabs, deadmen, or pile clusters at their ends. These were anchored in the passive zone of the soil wedge behind the classical rupture wedge of soil. A relatively new method in foundation engineering for back-tying of excavation walls is the pressure-grouted soil anchorage. This new kind of soil anchorage system has now become an important element in current foundation-engineering practice. It has gained increased significance and popularity, and its use continues to increase. This paper describes some of the basic principles involved in the tie-back anchorage or wall-anchor-soil system, reviews a basic type of soil anchor, and presents a method for stability analysis of a pressure-grouted soil anchorage system.

Anchored sheet piling walls have been constructed, almost without exception, with long horizontal anchors that have anchor walls, slabs, deadmen, or pile clusters at their ends. These were anchored in the classical Coulomb's passive zone of the soil wedge behind the classical rupture wedge of soil.

The pressure-grouted soil anchorage—a relatively new method in foundation engineering for back-tying of excavation walls—has become an important element in current foundation-engineering practice. This paper describes some of the basic principles involved in the tie-back anchorage system, reviews a basic type of soil anchor, and presents a method for stability analysis of a pressure-grouted soil anchorage system.

PRESSURE-GROUTED SOIL ANCHORS

Definition

The pressure-grouted soil anchor or tie-back is a special and important substructure anchoring element. It may be a steel rod, or a steel cable, or a multistrand of high-tension steel wires. Such an anchor is designed to be installed either horizontally or at an inclination to the horizontal. Its purpose is to anchor, in one or several tiers, various temporary or permanent earth-retaining and foundation structures to resist lateral, vertical, inclined, and hydrostatic uplift forces.

A pressure-grouted soil anchor works in tension. The integrally performing wall, anchor, and soil form the so-called wall-anchor-soil system, frequently referred to as the tie-back system.

Uses of Soil Anchors

Pressure-grouted soil anchors are used as both temporary and permanent support systems for sheeted excavations in sandy as well as clayey soils (1, 2, 3, 4, 5, 6, 7, 8, 9, 10). Tie-backs also stabilize river and canal banks, shore-walls, and earth slopes. In addition, they are used at construction sites where there is a lack of space between the building and the property lines. They are also used to transmit to the ground tensile forces from guy wires of suspension bridges and tentlike (or stressed-cable) structures whose roofs are supported by a stressed-cable network and to transmit to the ground hydrostatic uplift forces acting on the bases of submerged foundations.

Types of Soil Anchors

The multitude of pressure-grouted soil anchors on the market and in the state of development prohibit a complete listing and description of them here. Almost every foundation-engineering firm in the business of soil anchorage has its own trademarked or patented soil anchor design. The design and method of installation of soil anchors vary widely. Therefore, only the basic principle of the working of a pressure-grouted soil anchor will be described here. The type of soil anchor to use will be determined by the nature of the construction site, the soil geotechnical properties, the load, the method of installation of the anchors, and other factors.

Anchors can be classified as rock anchors or soil anchors. Soil anchors are subdivided into those installed in noncohesive soils (gravel, sand) and those installed in cohesive soils (clays). There are long and short anchors, shallow and deep anchors, and temporary and permanent anchors. There are horizontal, vertical, and inclined soil anchors. The height of the wall to be supported and hence the number of tiers (levels) will dictate the system—single tier, double tier, or multiple tier (or several tier)—to be used for anchorage. The double-tier anchorage system usually has upper and lower anchors. Each of the above anchors has its place and use in foundation and hydraulic structures engineering.

Requirements Imposed on Soil Anchors

Some of the requirements (11) imposed on pressure-grouted soil anchors are listed below.

1. Because of the great differences among soil types, the use and installation of soil anchors require knowledge both of soil conditions in situ and of soil geotechnical properties.
2. Generally, the tie-back must develop its anchorage within the stable soil behind the failure wedge that contributes to the active pressure on the earth-retaining wall.
3. The grouted anchor must extend far enough into the soil to develop the resistance by shear to avoid general failure of the anchorage system.
4. Prevention of strains in the high-tension anchor steel that do not exceed tolerable deformations of the earth-retaining structures means that the grouted soil anchors should be prestressed to 80 or 90 percent of the working (service) load.
5. The pressure-grouted soil anchor should have an adequate load-bearing capacity as determined by tensile tests in situ. The ultimate bearing capacity of the grouted soil anchors should be determined by testing them to failure or to a predetermined maximum load.
6. The anchor should have a positive load transfer from the steel tension element (rod) to the cement grout and then to the soil.
7. In dealing with flexible earth-retaining structures, one should frequently reckon with the soil lateral pressure redistribution phenomenon along the height of the wall.
8. Anchors should be protected against corrosion.

Sizing of Soil Anchors

Generally, the sizing of a soil anchor is a very complex problem. Design of an anchor should encompass all properties of the materials involved and the force play involved.

INSTALLATION

Methods of anchor installation vary widely according to soil types and properties encountered. The technique employed for installation of soil anchors is obviously the most economical (12). Generally, however, soil anchors are installed a sufficient distance back of the Coulomb's potential rupture surface in the backfill soil. The installation work commences by drilling a hole in the soil of the vertical bank of the excavation. To prevent the caving in of the walls of the hole, a metal casing is introduced; then the steel anchor elements—tendons—are inserted. Through the hole, a cement grout is injected under pressure around a certain length of the rear-end part of the anchor shaft.

Upon grouting under pressure, an expanded, extruded body of cement grout in contact with the soil forms around the shaft. The cement suspension (grout) forms a bond between the anchor steel shaft (rod) and the surrounding soil. After the grout has set, the head of this pressure-grouted soil anchor is connected in tension to the earth-retaining structure to be anchored.

In noncohesive soils, the horizontal wall motion caused by lateral earth pressure in anchored systems can usually be measured in millimeters. Hence, generally they are not dangerous. However, in a cohesive soil, depending on its state of consistency and plastic behavior, considerable wall-deflection deformations are possible, especially in a deep excavation of great length and width when creep may set in.

The ultimate bearing capacity of the grouted soil anchors is determined by testing them to failure (pull-out test) in situ. During the test, the stress-strain relationship of the anchor is monitored. The load is applied in strain increments that give a smooth stress-strain curve. Observations of creep or anchor movement at constant loading are made.

However, in the final analysis, the bearing capacity of a soil-grout-anchor system depends not only on the type of soil and its shear strength but also on the size, shape, and extent of the body of the grouted soil around the steel anchor shaft. The exact form of the grouted area to use in advance calculations of the soil anchor capacity is not yet known. The same comment applies to the shape of the torn off or ruptured body of soil brought about by an anchor pull at soil failure in shear. Likewise, the forms of the stress distribution diagrams for grout under normal and shear stresses are not yet known.

Also, the modes of force transfer from the steel tension rod to the body of the grout and from the grout to the adjacent soil depend on the type and make of the anchor, the quality of the grouting operation, and other obscure factors not yet fully known or clearly understood. Also, the problem of the effect of the least advantageous position of the surcharge p_o on the ground surface determining the possible resisting force for short soil anchors has not been solved.

STABILITY

In designing pressure-grouted soil anchorage systems, the following questions arise: How long should the grouted anchor be? How deep (z) (Figure 1) should the anchor proper be embedded below the ground surface? How long should the total length of the anchor for overall, external stability be?

The first two questions pertain to the anchor-soil system's internal stability. Thus, the system should be tested for its safety or external (overall) stability against groundbreak and its stability against sliding on the forced, deep-seated rupture surface, or for the system's internal stability.

By overall or external stability is understood the stability of a tie-back wall-soil system against groundbreak, i.e., failure in shear of the soil mass retained by the wall. In this system, it is assumed that the anchored retaining wall itself is stable and able to resist earth and water pressures.

By internal stability is understood the forced sliding wedge stability failure. The stability analysis involves evaluation of the driving and resisting forces acting on a designated free body.

Stability Against Groundbreak

In this external stability test of the wall-soil supporting system, the excavation retaining wall is connected rigidly to the backfill as a monolithic body by means of the soil anchors. Upon soil rupture, this monolithic body, sliding down as a unit over an assumed rupture surface that is usually a circularly curved cylindrical rupture surface, brings about the collapse of the soil-anchor-wall system. The stability analysis of the groundbreak may be performed by using the usual analytical methods discussed in soil mechanics.

Stability in Deep-Seated Rupture Surface

This stability test serves mainly to establish the necessary length of the grouted part of the anchor. Here one would start out with the assumption that the anchor yields with its surrounding soil and that therefore the wall inclines or yields toward the inside of the excavation and tends to slide down along a forced, deep-seated rupture surface FM (Figure 1). Notice that, in this analysis, the length of the anchor proper is chosen approximately, and then by a method of trial and adjustment the available stability of the soil-anchor system is ascertained.

The driving force, F_D, or anchor pull of the anchor (available force in the anchor, or $A_{available}$) is the one determined from the analysis of overall anchored sheet piling before the stability analysis of the deep-seated rupture test. The necessary force, F_R (resisting force, also called the possible force, or $A_{possible}$), for equilibrium of the grouted soil anchor with the driving force is mobilized by the shear resistance between the contact surface of the grouted length of the soil anchor and the adjacent soil (Figure 1) and is determined from the force polygon formed by the forces acting on the free body of the soil, which rests on the deep-seated rupture surface.

The actual bearing capacity or pull-out resistance of the grouted soil anchor is usually determined by a pulling test of the anchor at the construction site.

The internal stability rests on the stability of the soil and its resistance to sliding of the free body over the forced deep-seated rupture surface in soil. This surface is forced by the grouted soil anchor pressure, and its form is assumed to be a plane. Results of analyses with curved deep-seated rupture surfaces (F-Y-M) do not reveal any significant advantage over the plane ones. The deep-seated rupture surface passes through the foot-point, F, of the sheet piling wall. Therefore, the embedment depth, JF, of the sheet piling and the inclination of the anchor and its length have a great influence on the stability of the soil-anchor-wall system of the excavation in its immediate vicinity, especially behind the wall outside of the excavation.

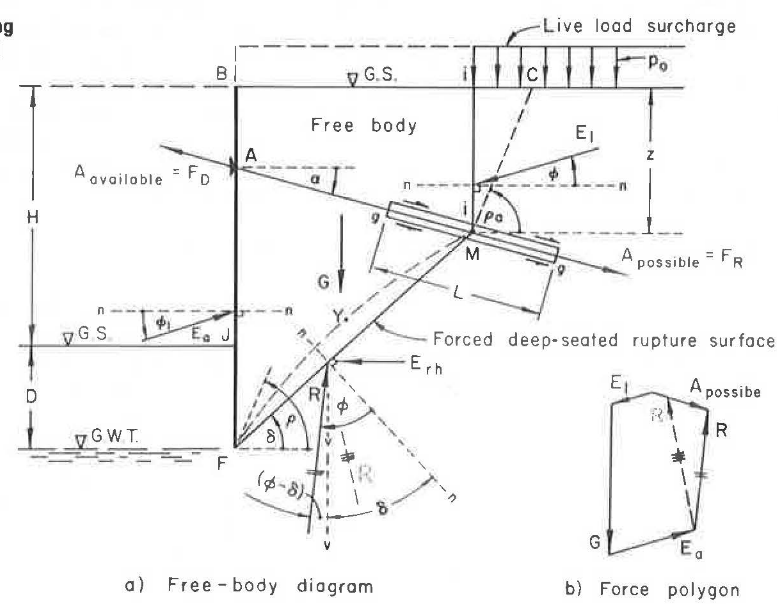
Analysis of Internal Stability

This analysis with respect to $A_{possible}$, also called the resisting anchor force, F_R, may be based on the equilibrium condition of the free-body diagram FBiMF, shown in Figure 1, in a manner similar to the method of calculation of horizontal anchors (13).

The following forces act on the free body:

- G = self-weight of the free body, FBiMF (a gravity force);
- E_a = active earth pressure (shown as reaction to the free body at an angle of wall friction ϕ_1), the magnitude of which may be calculated as for flexible sheet piling walls;
- R = soil reaction from below as the combined effect from all the other forces acting on the free body (at an angle of internal friction of soil ϕ), against the deep-seated rupture surface (to be scaled off from the force polygon in Figure 1);

Figure 1. Tie-back system for analyzing internal stability of free-end supported sheet piling wall.



E_l = active earth pressure on the substitute (fictitious or imaginary wall i-i (i-M) (Figure 1), acting at an angle of internal friction of soil ϕ (E_l is to be calculated as Coulomb's active earth pressure on a massive wall);

p_o = eventual surcharge load (live load) on the ground surface; and

F_R = $A_{possible}$, the possible or required anchor-resisting force for equilibrium condition as a function of G, E_a, R, E_l, and p_o (to be scaled off from the force polygon). Furthermore, the required resisting force F_R depends on anchor size, soil strength, and bond between anchor and soil.

All other symbols are shown in Figure 1. The static system, the free-body diagram, and the force polygon are shown in Figures 1 and 2.

Safety Factor

From equilibrium conditions of forces acting on the free body, one constructs a force polygon (14). From the force polygon, one scales off the magnitude of the maximum value of $A_{possible}$ (F_R). Knowing the magnitude of the available anchor pull $A_{available}$ (F_D), the degree of the internal stability of the system, i.e., the factor of safety η, is computed as

$$\eta = F_R/F_D = A_{possible}/A_{available} \qquad (1)$$

Expressed in terms of horizontal components,

$$\eta = F_{Rh}/F_{Dh} = A_{h\ possible}/A_{h\ available} \qquad (2)$$

The quantity $F_{Rh} = A_{h\ possible}$ can also be computed from the force polygon as set forth. The force geometric relationships in the force polygon are shown in Figure 2. From here, the magnitude of $F_{Rh} = A_{h\ possible}$ calculates as follows:

$$A_{h\ possible} = E_{ah} - E_{lh} + E_{Lh} - A_{h\ possible} \cdot \tan\alpha \cdot \tan(\phi - \delta) \qquad (3)$$

or

$$A_{h\ possible} = E_{ah} - E_{lh} + E_{Lh} \times 1/[1 + \tan\alpha \cdot \tan(\phi - \delta)] \qquad (4)$$

or

$$A_{h\ possible} = C_{A_h}(E_{ah} - E_h + E_{Lh}) \qquad (5)$$

where

$$C_{A_h} = 1/[1 + \tan\alpha \cdot \tan(\phi - \delta)] \qquad (6)$$

is a coefficient, and

$$E_{Lh} = [G - (E_{ah} \cdot \tan\phi_l - E_{lh} \tan\phi)] \tan(\phi - \delta) \qquad (7)$$

or an auxiliary horizontal force component is an auxiliary mathematical quantity in the force polygon as in Figure 2.

In these equations, α is the angle of inclination of anchor with the horizontal and δ is the slope angle with the horizontal of the deep-seated plane rupture surface FM.

The C_{A_h}-coefficient can be computed, tabulated, and shown graphically as a function of (a) angle of inclination α of the anchor, (b) angle of internal friction of soil ϕ, (c) angle of wall friction ϕ_l, and (d) slope angle δ of the deep-seated rupture surface (see Table 1 and Figure 3).

The internal stability calculation should be repeated several times, each time assuming a different length and inclination of the anchor, until the position of the most dangerous deep-seated rupture surface has been found. The minimum required safety factor is $\eta_{min} \geq \eta_{allowable}$.

In practice, the factor of safety, $\eta_{allowable}$, in such calculations is usually taken by experience as

η = 1.50 for anchor slopes of v:h = 1:2;
η = 1.75 for anchor slopes of 1:1; and
η = 2.00 for anchor slopes of 2:1 and for vertical slopes.

For permanent anchorage, the safety factor chosen should be greater than that mentioned above.

Figure 2. Force relationships in force polygon.

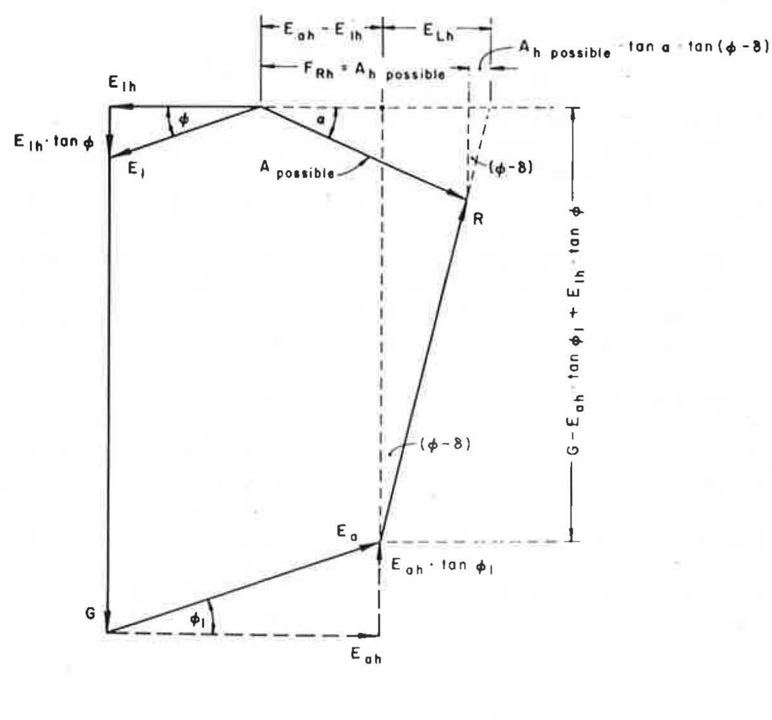
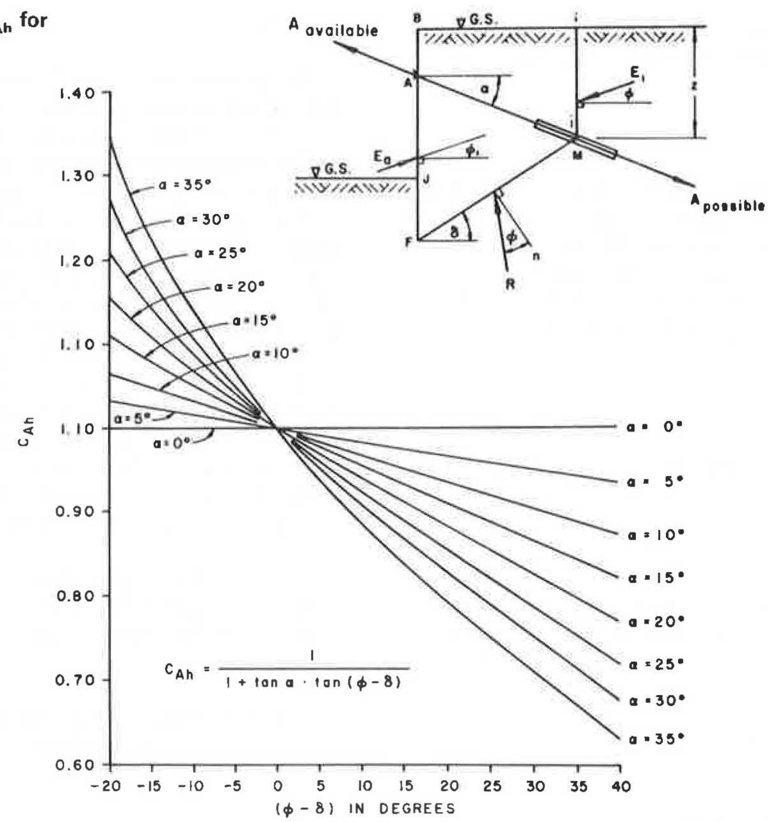


Table 1. Anchor coefficient $C_{Ah} = 1/[1 + \tan\alpha \cdot \tan(\phi - \delta)]$.

$\phi - \delta$ (°)	$\alpha = 0°$	$\alpha = 5°$	$\alpha = 10°$	$\alpha = 15°$	$\alpha = 20°$	$\alpha = 25°$	$\alpha = 30°$	$\alpha = 35°$
-20	1.000	1.032	1.068	1.108	1.152	1.204	1.266	1.342
-15	1.000	1.024	1.049	1.077	1.108	1.142	1.183	1.230
-10	1.000	1.015	1.032	1.049	1.068	1.089	1.113	1.140
-5	1.000	1.007	1.015	1.024	1.032	1.042	1.053	1.065
0	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
+5	1.000	0.992	0.984	0.977	0.969	0.960	0.951	0.942
+10	1.000	0.984	0.969	0.954	0.939	0.924	0.907	0.890
+15	1.000	0.977	0.954	0.933	0.911	0.888	0.866	0.842
+20	1.000	0.969	0.939	0.911	0.883	0.854	0.826	0.796
+25	1.000	0.960	0.924	0.888	0.854	0.821	0.787	0.753
+30	1.000	0.951	0.907	0.866	0.826	0.787	0.750	0.712
+35	1.000	0.942	0.890	0.842	0.796	0.753	0.712	0.671
+40	1.000	0.931	0.871	0.816	0.766	0.718	0.673	0.629

Figure 3. Anchor coefficient C_{Ah} for calculating $A_{h\ possible}$.



The final conclusions about the anchor capacity must be based on pull-out tests in the field, of course, to assure the adequacy of the design. Inclined anchors contribute a downward force component on the sheet pile and/or soldier piles of sheeted excavation walls. Thus, to ensure stability of tie-back systems, there should be adequate sheet piling end-point bearing capacity of the soil; that is, there should be a sufficient embedment depth of the sheet piling in soil to counteract by skin friction the downward force component.

The basic concepts presented here are also valid for multiple-tier soil-anchor-wall systems.

SUMMARY AND CONCLUSIONS

Advantages of Tie-Back Soil Anchorage

These studies on soil anchors have led to the following conclusions. Pressure-grouted tie-back soil anchorage is becoming more common and popular because of its advantages over conventional bracing systems. Some of these advantages follow.

1. Soil behind the tie-back wall (outside the excavation) will usually settle less than soil behind a frontally braced earth-retaining wall.
2. Each anchor can be prestressed. Prestressing of soil anchors reduces the movement of adjacent soil mass and results in no or insignificant settlement of streets and buildings located adjacent to the excavation. Settlement measurements are useful so that countermeasures against it can be applied in time.
3. The excavation pit can be kept free of all bracing and strutting so that there is freedom in the pit for excavation and construction activities uncluttered and unobstructed by a forest of timber and steel. This reduces below-ground construction time and costs.
4. The construction and installation of the earth anchors can be accomplished without any noise pollution and without vibration harmful to adjacent structures.

5. Depending on the depth of excavation, soil anchors can be installed in one or several tiers. Tie-backs can be installed in soil zones inaccessible from above because the anchors can be installed from the inside of the excavation.

6. Each of the selected anchors can be tested to failure or to a predetermined maximum load; therefore their ultimate load-carrying capacity can be determined.

7. Defective anchors can be repaired.

8. Inadequate anchors can be replaced.

9. Pressure-grouted soil anchors have a relatively good fixity in the soil.

All in all, inclined pressure-grouted soil anchors may have economic advantages over conventionally braced or strutted retaining-wall systems, the former being generally competitive with the latter, which means savings in time and money.

Disadvantages of Pressure-Grouted Soil Anchors

One of the major disadvantages of soil anchors is the corrosion of the steel rods and cables.

How prone to corrosion anchor steel will be depends on the aggressiveness of the groundwater. However, this problem can be alleviated by using a special corrosion-resistant steel. Furthermore, the anchor steel can be protected against corrosion with a corrosion-protecting envelope (say, plastic or rubber sleeves or hoses) around the steel. These may become damaged and thus ineffective, however, if installation is defective (tearing against the threads of the casing pipe, for example). Hence, painstakingly careful handling and installation of the anticorrosion elements are very much in order.

Anchoring work also requires very careful drilling and preparing of the bore holes for installation of anchors at construction sites where there are various underground obstacles such as utilities (cables, pipes, sewer lines).

Therefore, grouted soil anchorages still present themselves as a very complex foundation-engineering problem, indeed. This is to say that the complex force play in and the nature of loading of the soil-anchor-wall system have not yet been completely clarified in detail. Expert judgment in designing soil anchorage is required of the engineer. Regardless of what was said above, experience indicates that the pressure-grouted soil tie-back anchorage system has been applied with reasonable success in many instances in terms of time and economy.

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