HIGH CAPACITY AND FULLY REMOVABLE SOIL ANCHORS

Anthony D. Barley, Single Bore Multiple Anchor Ltd., Harrogate, U.K.
Donald A. Bruce, Geosystems, L.P., Venetia, PA, U.S.A.
Mary Ellen C. Bruce, geotechnica, s.a., Inc., Venetia, PA, U.S.A.
J. Christopher Lang, Lang Tendons, Inc., Toughkenamon, PA, U.S.A.
Horst Aschenbroich, Con-Tech Systems Ltd., Delta, BC, Canada

Over 60,000 multiple anchors have been used internationally since their introduction in the early 1990s, including 1000 in the United States. The multiple anchor system comprises a "multiple" of "unit" anchors installed within a single borehole – each unit anchor being staggered within the borehole length to mobilize its own capacity independently of the other unit anchors. These systems offer higher capacity than conventional anchors with identical bond lengths due to superior load transfer efficiency. The use of higher capacity anchors may allow reduction in the number of anchors required on a project, which results in time and cost benefits to the anchor installer, contractor, and the owner. Fully removable temporary multiple anchors are available, and have been used with consistent success. Three case histories are discussed highlighting the use of these systems.

INTRODUCTION

The advantages of using anchor/tiebacks for the temporary retention of vertical faces of deep and underground construction were first realized in the 1960s. Their usage grew greatly after successful anchoring in soil and weak rocks was achieved. The major benefit provided by these anchored systems was the open excavation area created by eliminating horizontal or raked struts, which generally inhibit rapid construction within the site area.

In the majority of instances the constructed retaining walls can be relatively stiff but the spacing of anchor tiebacks both horizontally and vertically is frequently controlled by the anchor/tieback working capacity rather than full exploitation of the wall stiffness.

With regard to environmental aspects, anchor tiebacks although installed for temporary usage generally provide a permanent "contamination" of the ground in which they are founded. This zone is frequently below adjacent structures or streets and highways and the existence of the remaining steel anchor/tieback members may jeopardize any further underground construction in that zone.

DEVELOPMENTS IN ANCHOR TECHNOLOGY

Significant advances in anchor technology have been achieved in the past 30 years, resulting in increased anchor capacities and fully removable anchor systems that accommodate some of the constraints imposed by urban construction. The following examples are provided.

Increase in Anchor Capacity

Working capacities of anchor/tiebacks in soils and weak rock have been gradually increased due to changes in anchor physical dimensions and installation techniques, and increased understanding of load transfer mechanisms. Some of the significant enhancements of the technology that have provided these increased capacities include:

- Increased bore diameter (100 to 300 mm range).
- Use of underreaming systems (500 to 700 mm underreaming tools available).
- Use of end-of-casing pressure grouting (typically up to 10 bar).
- Use of post-grouting systems with grouting repeatability (up to 60 bar).
- Availability of more refined grouting plants.
- Development of more powerful drilling rigs to allow high production and reduction of breakdowns.
- Availability of more experienced personnel with an understanding of construction techniques and load transfer mechanisms.
- Development of fixed length geometries that optimize efficiency of load transfer.

These developments have resulted in an increase in working capacity for normal anchors from the 25 to 60 tonnes typically available in the 1960s (Littlejohn, 1970), to the 50 to 100 tonnes now typically obtainable.

Inefficiency of load transfer in conventional anchors is due in part to non-uniform load distribution along the bond length. It is fully acknowledged by researchers who have investigated grout/ground load transfer that the distribution of stress along the fixed anchor is non-uniform due to general incompatibility between elastic moduli of the anchor tendon, anchor grout, and the ground (Ostermayer, 1975; Littlejohn and Bruce, 1977; Fujita et al., 1978; Shields et al., 1987; Casanovas, 1989; Ludwig and Weatherby, 1989; Mecsi, 1995 and 1997; Briaud et al., 1998). In the vast majority of conventional anchors, after initial loading, the bond stress is concentrated over the proximal end of the fixed anchor, while the distal end of the fixed length remains unstressed. As load is increased, the ultimate bond stress at the proximal end of the fixed length along either (or both) the steel/grout interface or the grout/ground interface is exceeded. At that moment, the bond stress reduces to a residual value at that location, the capacity at that location of the anchor is reached, and movement occurs. Subsequently, the capacity in that section of the anchor decreases, and the load is transferred towards the distal end of the fixed length. As load on the anchor is further increased, the bond stress concentration zone progresses further along the fixed anchor. Just prior to pull-out, the load is concentrated at the distal end of the fixed length. Figure 1a depicts this load transfer phenomenon, referred to as "progressive debonding." The area under the bond stress distribution line represents the ultimate load in the anchor. It can be seen that the load does not increase uniformly with increasing length. The effects of this phenomenon were understood and diagrammatically quantified as early as 1975. General research suggested that little increase in anchor capacity was achieved in fixed lengths in excess of 23 feet (7 m).

Although the debonding problem and the severity of its effects have been known for years, it was not until the development of the single bore multiple anchor system (SBMA) around 1988, that a method was devised to eliminate the detrimental effects of progressive debonding. The SBMA system utilizes a "multiple" of "unit" anchors installed in one borehole: the fixed length of each unit anchor being staggered within the borehole length to mobilize its own capacity independently of the other unit anchors. The load is transferred equally between each unit anchor and the grout over a multiple of short lengths throughout the bond zone, thereby allowing the same load to be carried by each unit anchor simultaneously. A comparison of load distribution along an SBMA and a conventional anchor is depicted in Figure 1b.

The enhanced load transfer in the SBMA practically eliminates or reduces to negligible proportions the occurrence of progressive debonding, and thereby substantially increases the efficiency of the anchor.

To quantify the effect of progressive debonding, data were evaluated from over 60 investigatory anchors with different fixed lengths installed and tested in a range of soil conditions (clays, silty clays, and sandy clays, boulder clay and glacial till) (Barley 1995, and 1997; Barley and Windsor, 2000). From this research, the concept of an "efficiency factor" was developed, which suggests the following simple mathematical expression to reduce the ultimate bond stress (τ_{ult}) by accounting for the occurrence of progressive debonding:

$$T_{ult} = \pi \, d \, L \, f_{eff} \, \tau_{ult}$$

Where,

T_{ult} = ultimate anchor capacity
d = borehole diameter
L = fixed length or unit fixed length
f_{eff} = efficiency factor, which itself is a function of L
τ_{ult} = ultimate bond stress of a short fixed length

Efficiency factors from these investigatory anchors were plotted versus fixed length as shown in Figure 2.

The best fit curve is represented by the following equation:

$$f_{eff} = 1.6 \, L^{-0.57}$$

where, L = fixed length or unit fixed length (in meters)

As an example, assuming a conventional anchor with a 40-foot length (13 m), the efficiency factor is

$$f_{eff} = 1.6 \times (13 \text{ m})^{-0.57} = 0.37$$

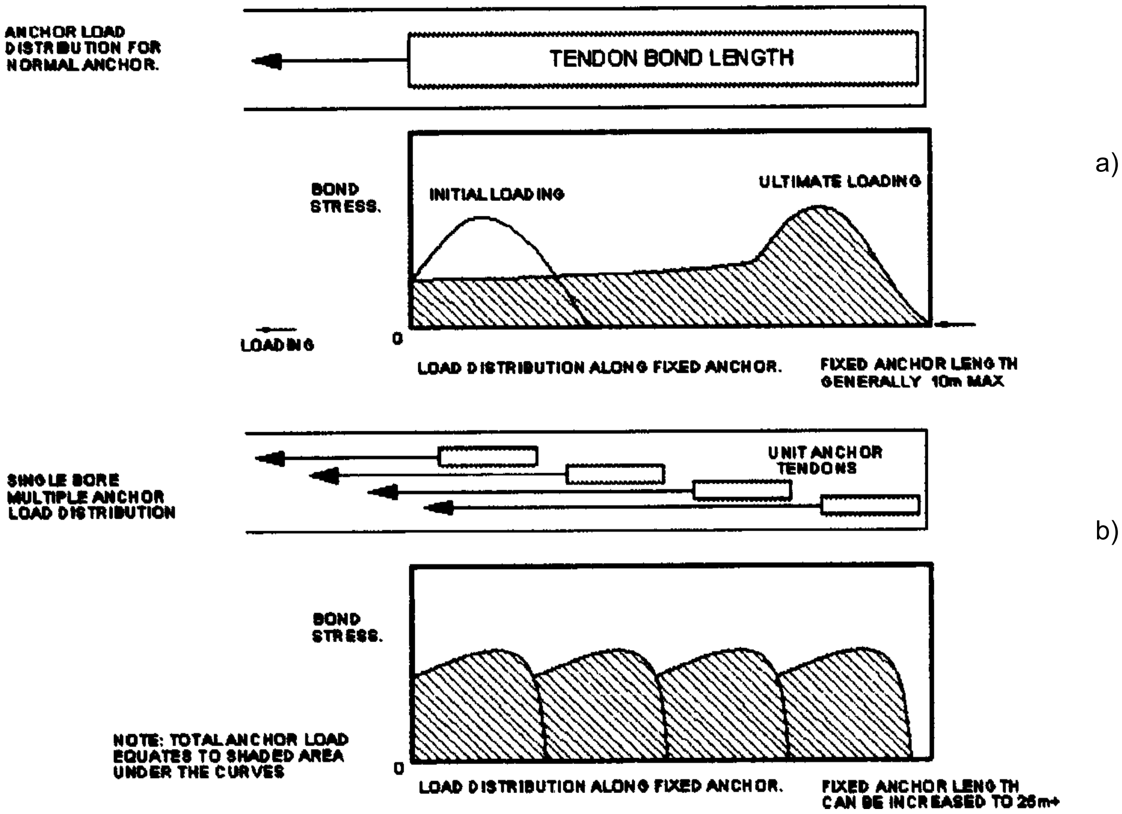

Figure 1. Load transfer mechanisms in a) a conventional anchor and b) an SBMA with equal overall fixed lengths.

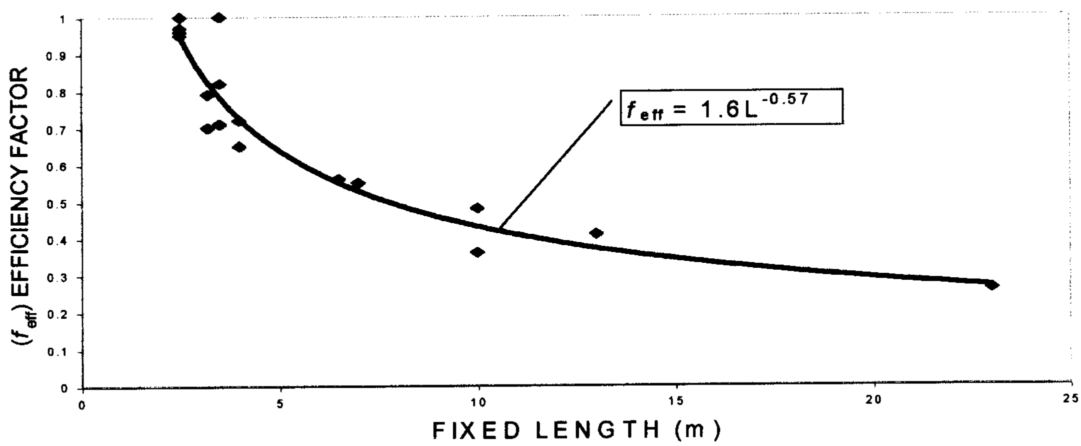

Figure 2. Efficiency factor versus fixed length (Barley, 1995). (Best fit curve shown.)

An SBMA with four fixed anchor lengths of 10 feet (i.e., overall fixed length of 40 feet), the efficiency factor for each 10-foot unit anchor (3 m) is:

$$f_{eff} = 1.6 \times (3\ m)^{-0.57} = 0.86$$

i.e., an SBMA with 4 unit anchors will be 2.3 times more efficient than a conventional anchor with a single 40-foot fixed length (0.86 / 0.37 = 2.3).

This advanced design approach allows the fixed length of each unit anchor to be tailored for the soil conditions encountered at a particular depth. Hence a multiple of unit anchors may efficiently utilize various unit fixed length of 8 to 10 feet (2.5 to 3 m) with corresponding efficiency factors ranging from 0.80 to 0.95.

Approximately 60,000 unit anchors have been installed (approximately 1000 in the United States). About 68 investigation anchors have been loaded to failure, and ultimate capacities of 200 to 500 tonnes achieved in soils (Simpson, 2001). The working capacities of SBMAs range typically from 80 to 200 tonnes, which is two to three times that of conventional anchor systems installed using the same construction techniques albeit with longer overall fixed lengths.

Removable Anchor Systems

The use of removable steel tensile members for temporary anchor applications has been developed since the mid 1970s. Two basic types of systems are available:

- one that allows the removal of only the steel member from the free (debonded) length; and
- one that allows the removal of the steel member from the entire length of the anchor.

Methods of removing the steel member from only the free length have been applied for many years by either unscrewing an anchor bar from the debonded length, or by providing some sort of a weakness in the strands at the debonded/bonded length junction. Although simple in principle, the implementation of this system has been difficult, and as a result, much supposedly “removable” free length steel has been left in place over the past 30 years. A limited number of specialist tendon suppliers and contractors now have “proven” removable systems available (Herbst, 1997).

The removal of both free and fixed length steel has until recently been extremely difficult to achieve. Loading the tendon to overcome grout/ground interface stress, which has typically been designed to factor of safety against bond failure in excess of 1.5, is practically impossible. Therefore, the limited number of removable systems available attempt to destroy or crack the grout column, thereby reducing tendon/grout bond capacity prior to pull out. Rates of success of tendon removal using these methods vary considerably.

For low capacity anchors (less than 20 tonnes) the use of an auger type system incorporated in the tensile member is readily available and generally successful (“Chance” system). A recently developed method that allows complete removal of the fixed and free lengths of multiple strand tendons has been more consistently successful. This system, developed from the concept of the recovery of a climbing rope during rappelling, utilizes a looped strand, sheathed and greased over its entire length (Photograph 1).

Load is transferred from the loop to a saddle and a short compression member within the corrugated sheath which in turn transfers the load to grout and the ground. The tails of the strand stick out of the borehole. The total elimination of bond between the steel strand and the grout facilitates the removal of the entire length of strand. This concept was adapted to SBMAs by incorporating a series of loops with saddles positioned at staggered depths in the borehole (Stockhammer and Trummer, 1995; Barley et al., 1999). During use, both tails are loaded simultaneously. During removal, one tail is loaded, and the strand slides around the saddle and pulls out of the borehole. Photograph 2 shows an extracted strand. The helical formation results from the friction along the saddle during pullout.

Photograph 1. Looped strands of removable SBMAs.

Photograph 2. Extracted strand of a removal anchor.

THE BENEFITS OF ENHANCED ANCHOR TECHNOLOGY

Benefits of Increased Anchor Capacity

The cost of the installation of an anchor is generally controlled by:

- Time to set up and start drilling
- Drilling time through structure or materials (wall or fill)
- Drilling time for free length of anchor
- Drilling time for fixed length of anchor
- Tendon material costs
- Grouting time and materials costs
- Anchor head material
- Stressing time

The SBMA achieves time and cost savings by providing two times the working load of a normal anchor, thereby halving the number of anchor. The net savings are not necessarily halved, but are on the order of 20%. The drilling and installation time is practically halved while the total tendon and anchor head costs are of the same order as the original scheme. Stressing time is increased for a multiple anchor, although the total time is undoubtedly less than that required to stress twice the number of conventional anchors. Cost savings may be shared generally between the anchor installer, the contractor, and the owner.

Fewer anchors also provide time savings due to a reduction in the number of wall penetration points (less ducts, reinforcement penetration or holes to be burned) and a reduction in the risk of operations in locations where high ground water level is present. Fewer rows of anchors reduce disruption during excavation and reduce the number of waling levels. Perhaps the most significant benefit is the reduction of the overall construction period, which may be as much as 40% and is generally to the advantage of the Contractor and Owner.

Benefits of Removable Anchor Systems

Row(s) of temporary anchor tendons left in place can inhibit future construction especially in urban areas. Conventional piling rigs, diaphragm walling rigs, or boring rigs can easily penetrate existing grout and plastic components (saddle from removable systems), although abandoned steel components may prove impenetrable. In many of the world's larger cities, the use of temporary anchors for soil/wall retention is only tolerated if removal of the steel tendons can be guaranteed (e.g., Edinburgh, London, Hong Kong, Singapore, and Berlin).

CASE HISTORIES

Although many projects have achieved these time and cost savings since the introduction of the system in the early 1990s, three international projects provide suitable illustration.

Excavation for Central Station, Hong Kong

At Central Station in Hong Kong, a 20-m deep excavation 120 m long and 75 m wide was retained using up to 5 levels of 200-tonne working capacity multiple anchors (probably the highest capacity soil anchors ever installed). The general contractor would not have considered an anchor solution if such working capacities could not be achieved (Barley et al., 1999). Closely-spaced horizontal struts were used as retention in the adjacent section (Photograph 3). Structures constructed in the open-space excavation were completed 3 months earlier than those in the adjacent strutted section.

Deep Excavation, Singapore

In Singapore, a vertical bored pile wall is currently being retained by 150-tonne working load anchors (Barley and Kiat, 2002) (Photograph 4). The use of these high capacity anchors allowed the contractor to reduce the number of anchors in half with a considerable overall time saving. The performance of the anchors and the integrity of the corrosion protection system were demonstrated in test anchors and gun barrel tests prior to production.

Slope Stabilization, Natchez, MS

In Natchez, MS, slope stabilization and retention projects have been undertaken to arrest slope erosion along the Mississippi River. Stabilization of the slope has been difficult due to the need to achieve adequate bond stresses in the ultra-sensitive fine-grained loess soil at the retention level. A trial multiple anchor was installed, and an anchor system of adequate capacity for permanent soil retention was provided (Photograph 5) (Fairweather, 1997).

Photograph 3. 200-tonne working capacity multiple anchors at Central Station in Hong Kong.

Photograph 4. 150-tonne working load anchors allowed the original number of 80-tonne anchors to be reduced by half.

Photograph 5. High capacity SBMAs in difficult “loess” soils in Natchez, MS.

SUMMARY

Significant time and cost benefits have been realized through the use of high capacity single bore multiple anchors (SBMAs). Advancements in anchor technology and installation techniques have resulted in working capacities of up to 200 tonnes. These high anchor capacities achievable in soil and weak rocks have allowed the number of anchors required on specific projects to be reduced by half, which correlates to a cost savings of approximately 20% on the anchor installation.

Removable multiple anchors are available that employ a loop and saddle arrangement to permit the extraction of the strand from within the corrugated sheath after usage. The removal of the steel allows future construction to progress unencumbered by the abandoned tendons. Additional information on high capacity and removable multiple anchors is available on-line at www.SBMAsystems.com and www.theanchorman.com.

REFERENCES

BARLEY, A., and S.C. KIAT. (2002). “Slope Stabilisation by Soil Nails and Replacement by bored pile wall and Multiple Anchors” *Ground Engineering*, February.

BARLEY, A.D. (1995). “Theory and practice of the Single Bore Multiple Anchor system.” Anker in Theorie and Praxis. Proc. Int. Symposium Salzburg Okt. 1995. Balkema Rotterdam, Pp. 293-301.

BARLEY, A.D. (1997). “The single bore multiple anchor system” Proc. Intern. Conf. Ground Anchorages and Anchored Structures. London, pp. 65-75.

BARLEY, A.D. (2000). “Trial soil nails for tunnel face support in London Clay and the detected influence of tendon stiffness and bond length on load transfer.” Proceedings of the third International Geosystems, London, June.

BARLEY, A.D., and C.R. WINDSOR. (2000). “Recent advances in ground anchor and ground reinforcement technology with reference to the development of the art.” *GeoEng2000*, International Conference on Geotechnical and Geological Engineering, Melbourne, November 19-12, pp. 1048-1094.

BARLEY, A.D., W.D. PAYNE, and P.L. MCBARRON. (1999). “Six rows of high capacity removable anchors support deep soil mix cofferdam.” Proceedings 12 European Conference on Soil Mechanics and Geotechnical Engineering, Amsterdam, Geotechnical Engineering for Transportation

Infrastructure. (Eds. Barends, et al.) Rotterdam, pp. 1465-1471.

BRIAUD, J., W. POWERS, and D. WEATHERBY. (1998). "Should Grouted Anchors have Short Tendon Bond Lengths", Journal of Geotechnical and Geoenvironmental Engineering, ASCE, February and Discussion (September, 1999).

CASANOVAS. (1989). "Bond strength and bearing capacity of injected anchors: a new approach." Proceedings of the 12th Conference SMFE, Rio de Janeiro, Vol. 2.

FAIRWEATHER, V. (1997). "Ground Anchor Advance." *Civil Engineering,* December.

FUJITA, K., K. UEDA, and M. KUSABUKA. (1978). "A Method to Predict the Load Displacement Relationship of Ground Anchors." Revue Francaise de Geotechnique No. 3. 58-62

HERBST, T.F. (1997). "Removable ground anchors – Answer for urban excavations." Proceedings of the International Conference on Ground Anchorages and Anchored Structures," London, pp. 197-205.

LITTLEJOHN, G.S. (1970). "Anchorages in Soils- Some Empirical Design Rules," *The Consulting Engineer*, May.

LITTLEJOHN, G.S., and D.A. BRUCE. (1977). "Rock Anchors - State of the Art." Foundation Publications, Essex, England, 50 pp. (Previously published in Ground Engineering in 5 parts, 1975-1976.)

LUDWIG H.P., and D.E. WEATHERBY. (1989). "Behaviour of a Tieback in Cohesive Soil," 12th International Conference on Soil Mechanics and Foundation. Rio de Janeiro, Vol. 2.

MECSI, J. (1995). "Analysis of grouted soil anchors." Proceedings of International Symposium *Anchors in Theory and Practice*, Salzburg, October, Balkema, Rotterdam.

MECSI, J. (1997). "Some practical and theoretical aspects of grouted soil anchors. Institution of Civil Engineers Conference on Ground Anchors and Anchored Structures, London, March 1997, pp. 119-130.

OSTERMAYER, H. (1974). "Construction, carrying behaviour and creep characteristics of ground anchors." *Diaphragm Walls and Anchorages.* Proceedings, Institution of Civil Engineers, London, September 18-20, pp. 141-151.

SHIELDS, D.R., H. SCHNABEL, and D.E. WEATHERBY. (1978). "Load transfer in pressure injected anchors." Journal of the Geotechnical Engineering Division, September.

SIMPSON, D. (2001). "Dublin Port Weighs Anchors." European Foundations, Winter.

STOCKHAMMER, P., and F. TRUMMER. (1995). "Der Wiedergewinnbare Litzenanker System Keller. *Anchors in Theory and Practice*, Proceedings International Symposium, Salzburg, October. Balkema Rotterdam, pp. 373-376.