Two Important Recent Developments in Ground Anchor Technology
Dos Avances Importantes Recientes en la Tecnología de Anclajes de Tierra

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Abstract
Two important developments in ground anchor technology have taken place since the middle 1980s, namely the use of epoxy protected prestressing strand for tendons, and the invention of the Single Bore Multiple Anchor (SBMA) system. The former has helped to improve standards of corrosion protection and make them more cost effective, the latter has permitted markedly higher anchor loads to be developed in weak rocks and soils. The popularity of epoxy protected strand, however, has recently been impacted in the U.S. by concerns relating to the adhesion of the epoxy to the steel surface, although recent research would suggest that the problem has been resolved. Conversely, it is only within the last few years that SBMA technology has been employed in the U.S. This paper provides therefore a timely review of the current state of practice as related to each of these highly significant developments.

Resumen
Dos avances importantes en la tecnología de anclajes de tierra han ocurrido desde mediados de los años 80. Estos avances son el uso de cables para tendones pretensados y protegidos por epóxico y la invención del sistema de anclaje múltiple de barreno sencillo (SBMA por sus siglas en inglés). El primero de los avances mencionados ha ayudado a mejorar estándares de la protección contra la corrosión y a hacer los anclajes más efectivos económicamente, el último ha permitido que cargas de anclaje significativamente más altas sean movilizadas en rocas débiles y suelos. La popularidad del cable protegido por epóxico, sin embargo, ha sido afectado recientemente en los Estados Unidos por preocupaciones referentes a la adherencia del epóxico a la superficie de acero, aunque investigaciones recientes sugerirían que el problema ha sido resuelto. No obstante, es solamente dentro de los últimos años que la tecnología de SBMA se ha empleado en los EE.UU. Este artículo proporciona una revisión oportuna del estado actual de la práctica con respecto a cada uno de estos avances altamente significativos.

1 INTRODUCTION

Prestressed rock and soil anchors have been used around the world since 1934, and in the United States for over 40 years. Incremental developments in the technology have occurred mainly through the efforts of specialty contractors and post tensioning specialists, responding to the challenges imposed by difficult ground conditions, and high anchor capacities. Less frequent but major advances arise out of concepts and experiences shared in conferences, codes and standards. In this regard, the conference held at the Institution of Civil Engineers, in London, 1997, and the publication in the U.S. of the Recommendations of the Post Tensioning Institute (1996) are particularly significant.

In the last few years in the United States, two issues have had particular impact on the anchor industry: the use of epoxy protected strand tendons, and the development of the Single Bore Multiple Anchor (SBMA).

Epoxy protected strand has been used since the 1980s providing anchor specialists with a cost effective and technically acceptable system to enhance resistance to tendon corrosion. However, concern has been raised recently regarding the ability of the material to ensure satisfactory short and long term load holding capability as well. The results of a recent industry-wide survey are reviewed.

Regarding load transfer mechanisms in ground anchors, a mass of field experimental data exist which prove that most anchor designs, when based on a conventional tendon bond length, are extremely inefficient: load carrying capacity is not proportional to bond length. However, by anchoring the strands of the tendon at different positions within the bond zone a far superior performance results, providing a much more cost effective system, and thus the option of reducing ground anchor costs significantly on any given project. The fundamentals of the SBMA system are described in the second major section of this paper.

2 EPOXY PROTECTED STRAND

2.1 Background

The process of applying fusion bonded epoxy coating to 15-mm diameter, 7-wire prestressing strand appears to have been developed commercially in 1981, following earlier experiences with epoxy coated reinforcing bar. According to Bonomo (1994), the product was first commercially used in 1983 to post-tension a precast concrete floating dock in Portsmouth, VA. Until 1985, epoxy protected strand was used only in structural/building related projects. Early examples of its use include the Bayview cable stay bridge in Quincy, IL, 1984 and post tensioned pier caps on I-495 in Rochester, NY, 1988.

It was logical that epoxy protected strand should become considered for strand tendons for ground anchors: it removed the necessity for a separate tendon protective encapsulating sheath, allowed hole diameters to be minimized, and simplified the grouting operations. Such construction efficiencies have the potential to offset the higher material costs of such strand. Its first use in an anchoring application was to stabilize the foundation of a private residence in Malibu, CA, in 1985, while the first *major* anchoring project was a permanent tieback wall at the Los Angeles City Library in 1989. This followed a smaller similar earth retention project in Phoenix, AZ, in 1988. However, little interest seems to have been generated within the ground anchor community during this period, and high capacity, permanent anchors for high dams continued to be installed using only grout as the sole barrier to potential corrosion of the tendon in the bond length (Bruce, 1993).

In 1990, the U.S. Bureau of Reclamation specified the material for use in the tendons of Stewart Mountain Dam, AZ. This highly successful project was later widely promoted by all participating parties and industry was quick to take advantage, as shown in the rapid growth in similar projects in the years thereafter (Figure 1). This popularity was underpinned by the publication in 1992 of ASTM 882/A882M-92 "Standard Specification for Epoxy Coated Seven Wire Prestressing Steel Strand", Bonomo's practice review paper of 1994, and the acknowledgement in the Post Tensioning Institute's (PTI) Recommendations (1996) that such strand could provide an acceptable ("Class I") level of tendon protection. All these sources made cautionary statements about the special relaxation, creep, and wedge seating characteristics of the epoxy protected strand so that proper performance comparisons could be made with bare strand tendons during both short and long term evaluation periods.

However, in 1999, during the initial stressing of high capacity tendons at Wirtz Dam, TX, several instances of strand slipping through the wedges were recorded – up to 48 hours after successful initial lock off, together with observations of epoxy delamination from the strand.

Closer examination of the strand on this project also revealed an unacceptably high frequency of "holidays" (Frithiof and Krumm, 2000). Questions were raised regarding the uniformity of the thickness and adhesion of the epoxy coating, and so its ability to behave satisfactorily in the short term during stressing and Lock Off, and to satisfy the long term corrosion protection goals. These problems precipitated detailed forensic investigations by the various parties involved in the Wirtz Dam project and the findings elevated the issue to one of general discussion in the anchor industry.

This situation led to the formation in 2000 of an Epoxy Coated Strand Task Force, under the auspices of ADSC: The International Association

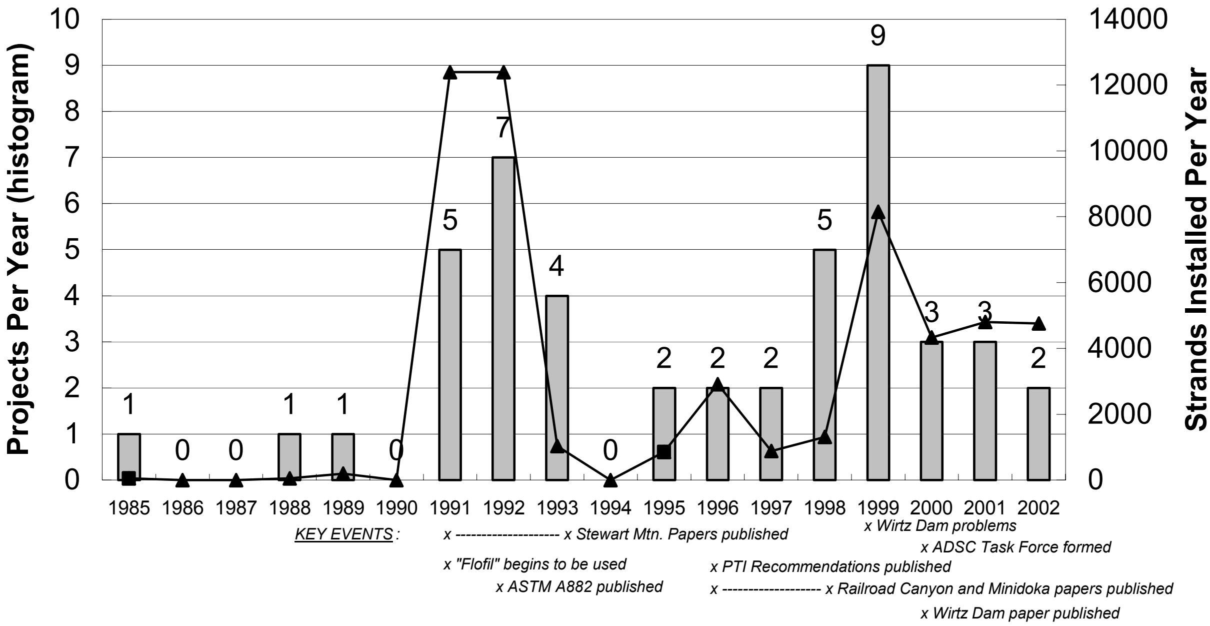


Figure 1. Epoxy protected strand usage for prestressed anchor applications, North America.

of Foundation Drilling. The impetus for this came primarily from the post tensioning companies who assemble the tendons, provide the top anchorage hardware and jacks, and supply stressing expertise. One of the main goals set by the chairman of this Task Force, Christopher Lang, was to write a supplement to the PTI Recommendations of 1996, dealing specifically and solely with issues relating to epoxy coated strand in ground anchors. This is scheduled to complete by mid 2003. A further goal of the ADSC Task Force has been to collect published and unpublished data regarding the historical size and value of the epoxy coated anchor tendon market over the years. This was published 2002-2003. At the same time, the ASTM A882 Committee has also been active in revising the standard to improve controls over the quality and consistency of the production processes.

2.2 History and Usage

Based on a survey of suppliers, owners, consultants, and contractors, supplemented by published data and the proceedings of successive Task Force meetings, the authors generated the data shown in Figure 1. During the period from first usage in 1985 to early 2002 there would appear to have been 47 projects (some being consecutive, but separate contracts on the same structure), of which 33 were related to dam or hydro schemes. During the period from 1990 to 2001, it is estimated that between 100 and 120 dams and hydro facilities were repaired by prestressed rock anchors in North America, at a total price of $200 to 300 million. Therefore it would seem that, overall, around 30% of the projects involved epoxy protected strand with an estimated 25% of each project's price being linked directly to the provision of the tendon and its hardware (i.e., $15 to 23 million). Figure 1 does illustrate, however, a smaller but relatively constant use of epoxy coated strand, following its peak of 9 projects in 1999. Outside North America, usage appears common to date only in Japan where a total of 700 projects had been completed from 1995 to 2000 (over 60,000 lin. m of strand), 43 involving dam stabilization. A few applications (for bridges) have also been reported in Korea and the Philippines.

2.3 Synopsis of Published Data

The following conclusions may be drawn from a review of the data published in case histories (ADSC, 2002-2003):

1. "Excessive" creep (relative to contemporary PTI Recommendations (1996) for bare strand) was first recognized as a phenomenon in 1991, but was rationalized in the laboratory test data first published in 1994 (Bonomo).

2. Strand slippage through the wedges after lock-off has invariably been found to be due to one or a combination of factors including
   - Non-alignment of strands and stressing equipment, and improper stressing procedures.
   - Grout, corrosion, or dirt in the wedges and/or anchor head.
   - Use of inappropriate wedge designs.
   - Variations in the thickness and adhesion of the epoxy coating (especially since 1999).
3. Slippage was typically recorded on the first few anchors installed and stressed on any particular project, often by crews previously inexperienced in its use.
4. The actual number of strands recorded to have slipped after Lock Off is numerically a very small percentage of the total installed and otherwise successfully performing (less than 0.2%). However, the technical, contractual, and financial impacts arising from these isolated occurrences have been disproportionately high, and have created unease about the use of the product in certain circles.

2.4 Recommendations for Future Practice

The authors firmly believe that there are effective remedies for the problems reported to date, and that if these remedies are routinely implemented, epoxy tendons will perform to the same levels of short and long term expectations as normally achieved by bare strand tendons. In particular, the following recommendations are made:

- <u>Epoxy Protected Strand itself</u>: must be manufactured to acceptable and constant standards of quality, consistent with its known application. This especially requires assurance of appropriate thickness and adhesion. Reliable, non-ambiguous data are required on samples of representative length to confirm the creep performance at different stress levels. All manufacturers' data should to be reaffirmed at regular intervals, and especially if significant manufacturing process changes have occurred.
- <u>Tendon Installation and Grouting</u>: strands should be correctly spaced in the free lengths, and first stage grouting must not be conducted within at least 10.7 m of the anchor head.
- <u>Stressing Preparation and Execution</u>: all lock-off components (wedges and wedge plates) must be free of grout, rust or any other dirt debris prior to stressing, and must be properly lubricated. Wedges should be placed only before lock off, and must be of a design specific for epoxy strand. Removal of the epoxy coating must not be permitted. All components must be correctly aligned.
- <u>Anchor Acceptance</u>: when assessing performance at Lock-Off, utilize relevant "correction factors" to account for the creep losses due to the intrinsic properties of the epoxy protected strand itself.

3 SINGLE BORE MULTIPLE ANCHORS (SBMA)

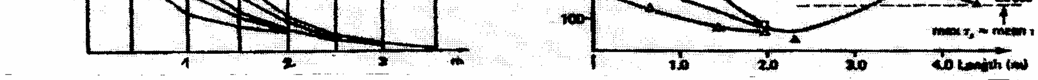
3.1 Progressive Debonding and Non-Uniform Load Distribution

It has been acknowledged by numerous researchers for over 60 years that when tensile load is applied to a steel or composite member in concrete, in grout or as an anchor, whether founded in rock or soil, that load distribution is non-uniform.

In 1940 Gilkey et al. demonstrated the occurrence of progressive debonding between steel and concrete when a tensile load was applied (Figure 2a). Berrardi (1967) also illustrated the concentration of load at the proximal end of a tendon founded in rock (Figure 2b). Ostermayer's research in the early 1970's into the performance of anchors founded in clays, sands and gravels highlighted the non-uniform distribution of bond stress and the progression of load concentration along the length of long fixed anchors (Figure 2c).

Ostermayer (1974) and Fujita et al. (1978) each concluded that high bond stresses could be mobilized at the grout/ground interface over a short length, 1 to 2 m, and even when fixed lengths greater than 6 to 7 m were used, little real increase in overall pull-out capacity could be achieved.

Yet despite this knowledge of non-uniformity of bond distribution along the fixed anchor, and despite length limits being recommended, the anchor industry has largely continued to gain



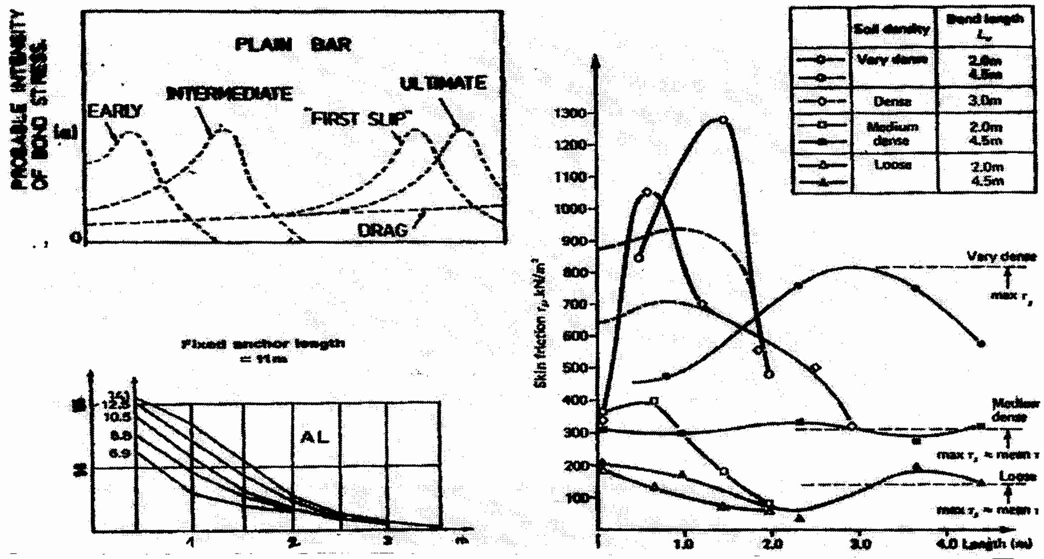


Figure 2. Non-uniform distribution of load or bond along fixed lengths due to progressive debonding: In concrete (Figure (a) after Gilkey et al., 1940); in rock anchor (Figure (b) after Berrardi, 1967); in soil anchors (Figure (c) after Ostermayer, 1974).

progressively higher load capacities by simply (but inefficiently) increasing fixed anchor lengths to as much as 15 m.

3.2 Quantification of the Efficiency of Fixed Anchor Lengths

When anchor design formulae are used to evaluate ultimate anchor geotechnical capacity by equating it to the cylindrical area of the grouted fixed length multiplied by the ultimate bond stress of the grout/ground interface uniform load distribution is assumed and the existence of progressive debonding is neglected.

Although not translated into mathematical design formulae, Ostermayer's experimentally derived curves (1974) do allow evaluation of the capacity of anchors in granular materials and in post grouted and non-post grouted clays permitting debonding.

In 1989 Casanovas proposed a supplementary factor to allow the evaluation of the a*pparent* fixed length of the anchor in sands and in gravels, i.e., apparent fixed length of a 10-m fixed anchor would be 7.3 m in loose medium grained sand, or 3 m in very dense sand and gravel. ("Apparent" is the effective length over which useful bond can be utilized when accommodating debonding).

Probably the most extensive attempts to model both the construction technique and performance of an anchor allowing for debonding have been carried out by Mecsi (1995) who analyzed construction data and performance results from several hundred anchors. He also has indicated it was possible to establish from formulae the contributory part of a long fixed length.

In 1995, Barley proposed the simple quantification of the "efficiency" of an anchor based on the shape of the bond stress distribution curve (Figure 3a) and the evaluation of efficiency factors from his investigation work (Figure 4). This research from 1989 to 1995 involved the pull-out to failure of many anchors of varying fixed lengths founded in different but relatively homogeneous strata on eight construction sites. He defined the "efficiency" of the bond length (fixed length) of an anchor as the ultimate pull-out capacity of that bond length compared with the ultimate capacity of the same bond length that could be achieved *without* progressive debonding: if the ultimate bond capacity could be mobilized simultaneously over its entire fixed length an anchor would be 100% efficient.

In Figure 3a, "efficiency" is defined by the area under the actual bond stress distribution line divided by the area under the ultimate bond stress line extending over the full anchor length.

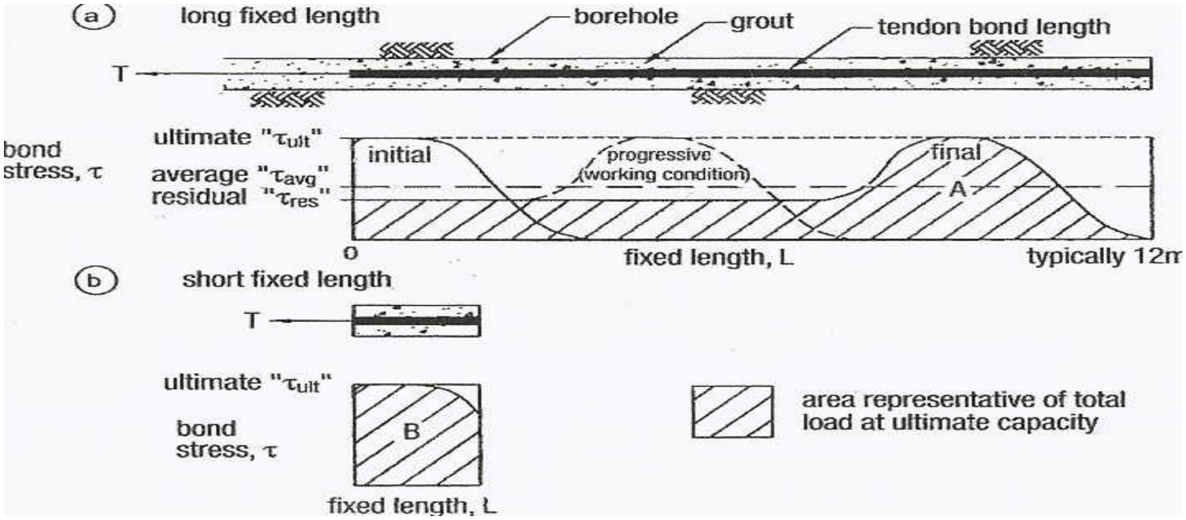


Figure 3. Progressive debonding and progress of load concentration along a long fixed anchor Figure (a) efficiency factor = area of shape A/Area under "τ_{ult}" line; Figure (b) efficiency of a short fixed anchor with negligible effect of debonding.

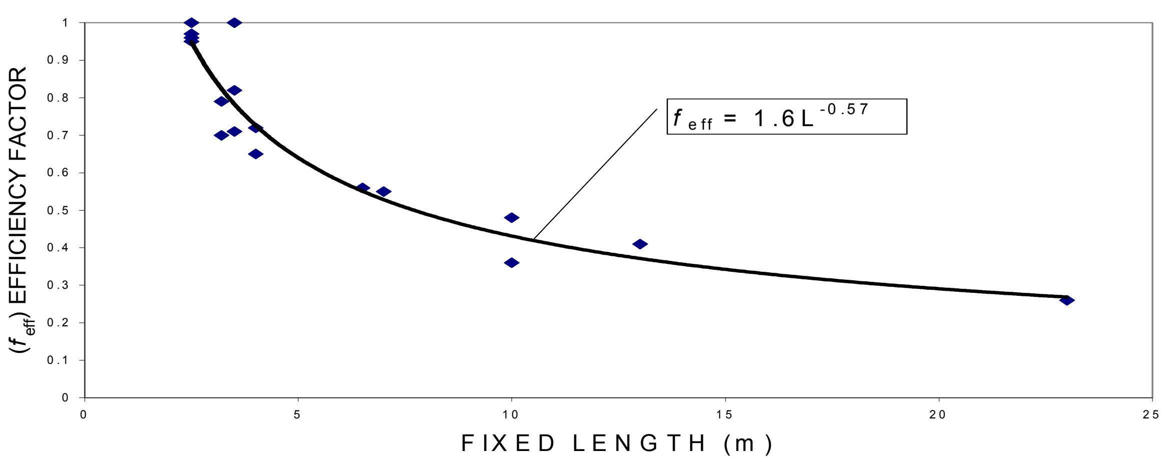


Figure 4. Distribution of anchor efficiency with fixed length, showing best fit curve (Barley, 1995).

The "efficiency" factor, f_{eff}, has been evaluated, from Barley's research (Figure 4). The best fit curve indicates

$f_{eff} = 1.6L^{-0.57}$ with L in meters

This factor indicates that an anchor less than 2.3 m long is 100% efficient and an anchor 12 m long is 38% efficient.

Thus, the original anchor design formula for pull out capacity

$T_{ult} = \pi \times d \times L \times \tau_{ult}$

may be amended to

$T_{ult} = \pi \times d \times L \times \tau_{avg}$

Where τ_{avg} = average bond stress mobilized in a bond zone of any length at ultimate load and $\tau_{avg} = \tau_{ult} \times f_{eff}$

and τ_{ult} = bond stress mobilized in a short bond zone at ultimate load.

Hence $\tau_{ult} = \pi \times d \times L \times \tau_{ult} \times f_{eff}$

The efficiency factor first established by Barley was mainly based on data from anchors founded in fine grained material; clays, silts and fine sands. However Barley chose to compare his "best fit" factor with those presented by Ostermayer in his boundary line curves (Barley & Windsor, 2000). The efficiency factor of $1.6L^{-0.57}$ indicates very close correlation with results from anchors in post grouted and non-post grouted stiff clays and from medium dense to very dense sands and gravels as presented by Ostermayer in (1974).

3.3 SINGLE BORE MULTIPLE ANCHOR

A Single Bore Multiple Anchor utilizes a number of short bond length “unit” anchors located at staggered depths in one borehole (Figure 5).The distribution of load in each unit anchor is highly efficient since over the short unit length the loss of efficiency due to debonding is negligible (Figure 3b). Four unit anchors each of length 3 m staggered in a 12.2 m grouted length would achieve more than twice the capacity of a conventional 12.2 m anchor in most stiff to very stiff soils. (Efficiency of a 3-m fixed length is 85% compared to the efficiency of a 12.3-m fixed anchor of 38%.)

Furthermore additional unit anchors can be added to an extended drilled bond zone length with each short unit anchor providing a proportional enhancement in anchor capacity. Total drilled bond lengths of 9.1 m to 18.3 m are now used in soils to achieve high anchor capacities (2000 to 4900 kN) that approach three times that of the conventional anchors which utilize long inefficient fixed lengths. Working loads of 890 to 2000 kN are now feasible routinely.

Due to the different free tendon lengths of the multiple of unit anchors, the incorporation of a multiple of hydraulically synchronized jacks, stressed simultaneously, is an essential part of the SBMA system during anchor testing.

Where preliminary trial anchors are deliberately over stranded and tested to failure each unit anchor yields its own value of ultimate bond capacity and hence more intensive data than conventional test anchors. The in situ testing of many of these multiple anchors with variable unit lengths has therefore recently extended the knowledge and understanding of the tendon/grout/ground bond mechanism. The SBMA system has been utilized in permanent anchors and temporary anchors (including those with removable tendons).

As an example of a recent U.S. project, a post-grouted SBMA project comprising one sacrificial anchor and 13 production anchors was installed to arrest inward and downstream movement of the right downstream retaining wall at Hodenpyl Dam, MI. A row of conventional tiebacks were installed previously and experienced continual load loss: a phenomenon common to conventional anchors in soft clay. An innovative testing setup and program were developed to allow extended creep testing of the sacrificial anchor followed by testing to 2.8 times by the design load (ultimate). The apparent debonding and creep were minimal on all anchors, even the sacrificial anchor which was tested to almost three times the design load.

4 FINAL REMARKS

The issues of corrosion protection and bond capacity are fundamental to the proper, cost effective, and safe design of ground anchors. Epoxy protection of individual strands is not per se a new development, but the industry study conducted recently is helping to broaden its usage by recommending appropriate construction and analytical procedures. The relatively high load transfer efficiency of short bond lengths is exploited in the SBMA system which is now in international use, including applications in North America. This system will be especially valuable in earth retention systems in urban areas.

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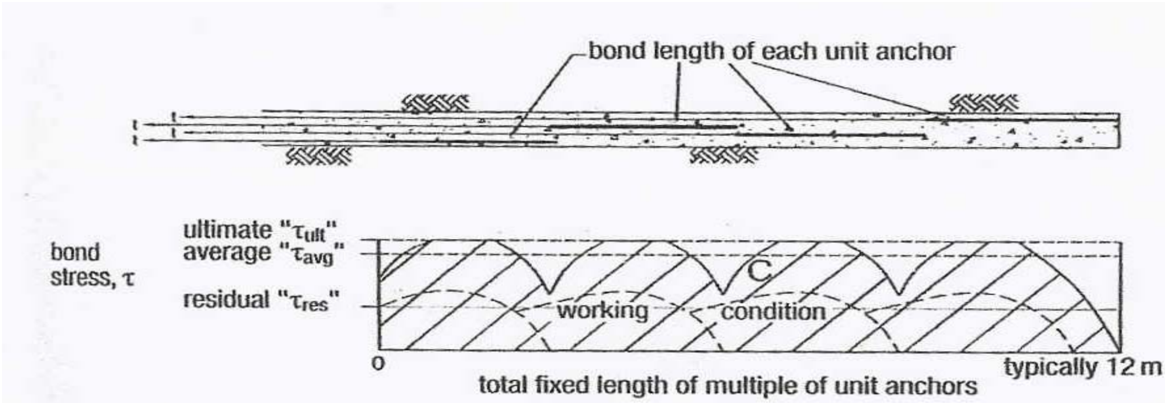

Figure 5. The Single Bore Multiple Anchor mobilizes a number of short efficient unit anchors located at staggered positions in the borehole.

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