Post GroutedSingle Bore Multiple Anchors at Hodenpyl Dam, Michigan

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ABSTRACT

Despite the installation of a row of anchors in 1996, the right downstream retaining wall of Hodenpyl Dam, MI, continued to move inward and downstream. The remediation design called for installation of additional anchors. However, there were concerns about creep-induced relaxation of the anchor load over time given the existence of high-plasticity clays at the site. The solution was the installation of post grouted multi-anchors along the base of the retaining wall (Single Bore Multiple Anchors – SBMAs).

SBMAs utilize several "unit" anchors within the same borehole, each with its own short efficient bond length positioned at staggered intervals along the bond zone. This staggered arrangement allows each unit load component to be transferred to the soil in a controlled manner over a discrete length of the borehole, thereby producing a very efficient load transfer mechanism. A larger factor of safety against creep is therefore attainable using SBMAs as compared to that provided by conventional tendons.

One sacrificial anchor and 13 production anchors were installed. An innovative testing setup and program were developed to allow extended creep testing of the sacrificial anchor followed by load testing to 2.8 times the design load without anchor failure. This paper describes the design and construction of the SBMAs, the load testing setup, and results of extended creep load testing.

1. INTRODUCTION

Hodenpyl Dam, owned and operated by Consumers Electric Company of Cadillac, MI, is located in Wexford and Manistee Counties, MI, and is one of a series of dams

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along the Manistee River. Investigation and analysis of the wall movement was conducted by Schnabel Engineering, Inc. (West Chester, PA) and Applied Engineering and Geosciences, Inc. (Greensboro, NC). The details of these studies (including descriptions of soil properties and design methodologies) are presented in a companion paper by Gómez et al. (2004). A total of 13 restressable, regroutable anchors were specified to improve the stability of the wall. The philosophy behind this design was to provide an immediate improvement of the wall stability while controlling construction costs. A detailed monitoring/action plan was also specified which would allow to determine whether subsequent treatments were necessary.

Figure 1. Downstream face of Hodenpyl Dam, showing right downstream retaining wall on left.

2. ANCHOR DESIGN

2.1 System Design Criteria

The specified working load for each tieback was 135 kips. Anchor geometry requirements dictated a minimum free length of 50 feet; a minimum bond length of 40 feet; a minimum drill hole diameter of 5 inches; and an anchor inclination of 20° (or less). The specified elevation of anchor entry was El. 734.2 feet. Bar tendons were recommended originally since these elements were initially assumed to be easier to regrout and restress. Class I corrosion protection (PTI, 1996) was required for the permanent anchors.

The expected anchor bond zone materials (between approximately El. 718 and 693 ft) consisted of a clay stratum generally stiff to very stiff, moist. Geotechnical properties of these materials are described in detail in the companion paper (Gomez et al., 2004). The clay stratum was underlain by a sand aquifer.

2.2 Single Bore Multiple Anchor (SBMA) System

2.2.1 SBMA Concept

Although the anchor requirements presented above may have been satisfied by using a conventional multi-strand tendon with a 40-foot bond length, Single Bore Multiple Anchors (SBMAs) were proposed by the contractor as an alternate to conventional tendons to provide a more efficient and uniform mode load transfer and therefore enhanced performance (i.e., reduced potential for creep).

A typical SBMA (Figure 2) consists of a multiple of unit anchors (single or double strand) with varying lengths installed in a borehole (4- to 8-inch diameter) such that their respective load transfer lengths are located at predetermined positions within the total fixed length.

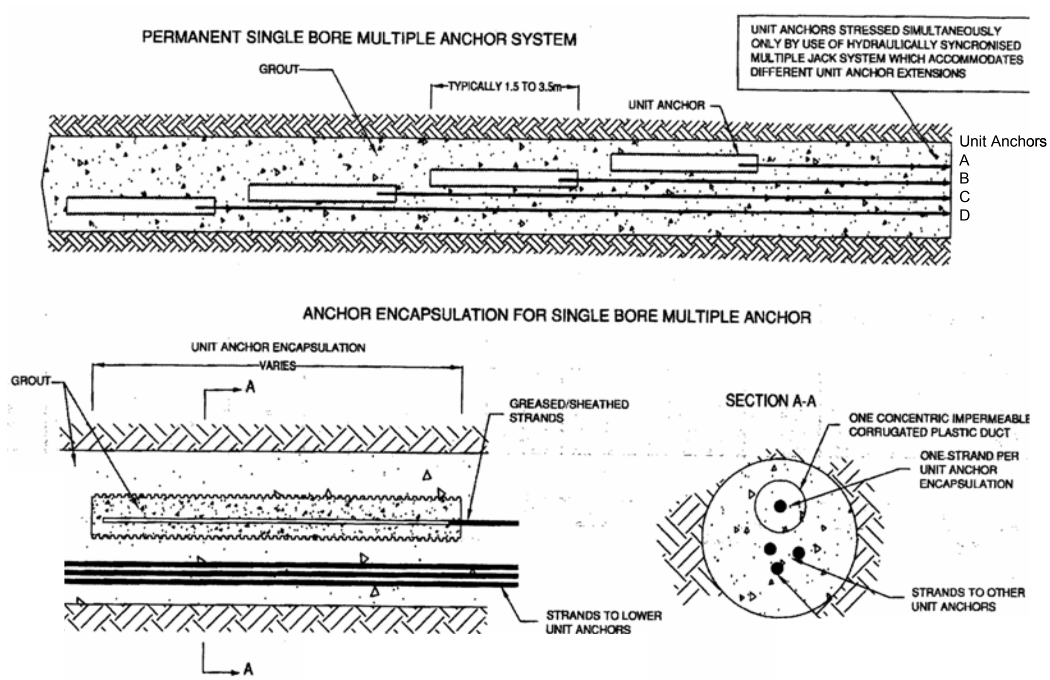


Figure 2. Elevations and cross section of a typical 4-unit SBMA.

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 (Littlejohn and Bruce, 1977; Barley, 2000). In the majority of conventional anchors, after initial loading, the bond stress is concentrated at 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 time, the bond stress reduces to a residual value at that location, and movement occurs: the capacity in that section of the anchor decreases, and the load is transferred distally. As load on the tendon is further increased, the bond stress concentration zone progresses farther along the fixed anchor. Just prior to ultimate pull-out, the load is concentrated at the distal end of the fixed length. Figure 3 depicts this load transfer phenomenon, referred to as "progressive debonding." The area under the bond stress distribution line is representative of the ultimate load in the anchor. It can be seen that the load does not increase uniformly with increasing length.

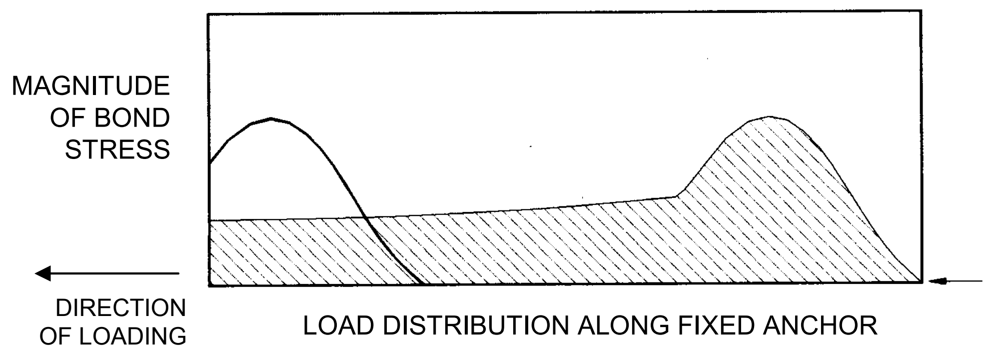


Figure 3. Load distribution and progressive debonding in conventional anchors.

Data collected and analyzed over a 10-year period were used to develop a simple mathematical expression to reduce τ_{ult} by accounting for the occurrence of progressive debonding (Barley, 1995):

$$\tau_{ult} \propto f_{eff} \times L$$

where, f_{eff} = efficiency factor, which itself is a function of L
L = fixed length (in meters)

Efficiency factors were back-analyzed from data collected from eight projects where anchors of different fixed lengths were tested to failure in clays, silty clays, and sandy clays, boulder clay and glacial till. The analysis of the data and comparison of curves from other researchers were described by Barley and Windsor (2000). These efficiency factors were plotted versus fixed length, and the best fit curve is represented by the following equation:

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

For a conventional tendon with a 40-foot (13-m) length, the efficiency factor is

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

For an SBMA with four fixed anchor lengths of 3 m (total fixed length = 40 feet), the efficiency factor for each 10-foot unit anchor is:

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

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).

SBMAs were developed to transfer load to the grout over a series of short lengths at staggered intervals along the borehole, and to carry the same load on each tendon simultaneously – thereby reducing or eliminating the occurrence of progressive debonding and substantially increasing the efficiency of the overall anchor. A comparison of load distribution along an SBMA and a conventional anchor is depicted in Figure 4.

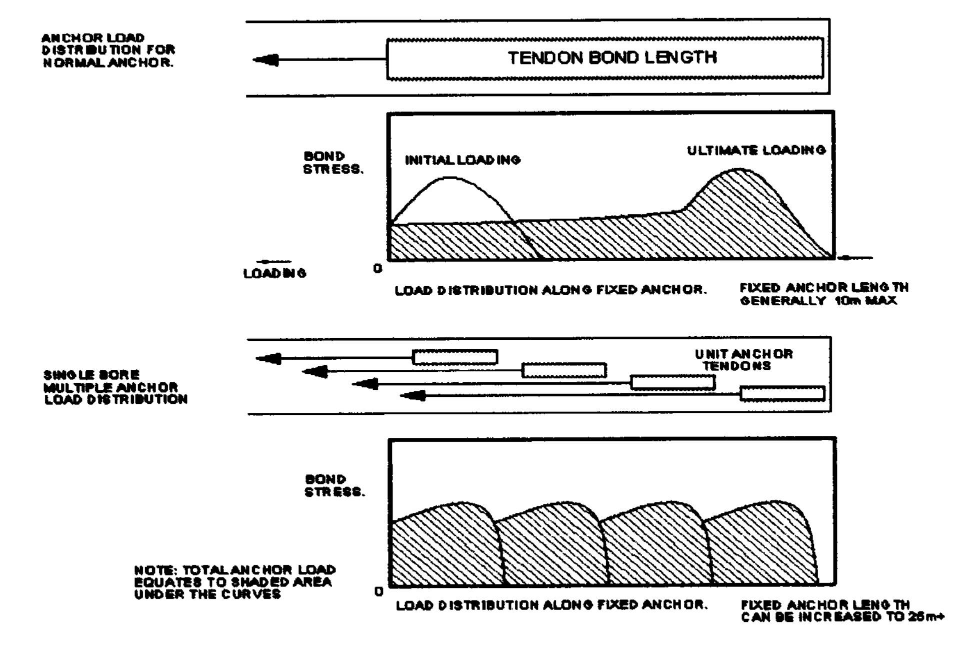


Figure 4. Comparison of load distribution along a conventional anchor and an SBMA (Barley, 2000).

2.2.2 <u>SBMA Design</u>

As shown in Figure 2, the encapsulation of each unit anchor consists of a 10-foot-long, 2-inch-diameter corrugated PVC duct grouted prior to delivery. The spacing of the encapsulations in the borehole defines the fixed length for each unit anchor; i.e., the fixed length = the encapsulation length plus the distance between adjacent encapsulations. A computer program developed by Single Bore Multiple Anchor Ltd. was used to design fixed lengths of unit anchors in a range of soil conditions. This program relates bond stress at the grout/soil interface to either N-values, undrained shear strength (c_u), or undrained shear strength plus an enhancement of bond stress due to post grouting. The latter program was used for the Hodenpyl anchor design. Table 1 lists the unit anchor lengths and SBMA geometry generated by this program.

Table 1. Summary of unit anchor lengths and SBMA geometry.

Unit Anchor	Free Length (ft)	Fixed Length* (ft)	Total Tendon Length (ft)**
A	55	11.5	71.5
B	66.5	10	81.5
C	76.5	10	91.5
D	86.5	10	101.5

* Total tendon length = 5-foot tail + free length + fixed length
Overall SBMA = 101.5 feet long.

Design parameters for the SBMAs for this project are summarized in Table 2. In addition to the design of the physical components of the anchors, a very important part of the design process was the installation and testing of a sacrificial anchor as discussed in Section 3, the performance of which provided site-specific information to confirm the design assumptions of the production anchors.

3. SACRIFICIAL ANCHOR INSTALLATION AND TESTING

A sacrificial anchor was required by the Owner and his Engineer. This anchor was installed using identical construction methods and materials and bonded in the same soils as those proposed during production with the following exceptions a) the sacrificial anchor was installed vertically, as opposed to being inclined at an angle of 20° below horizontal; b) three 10-foot-long unit encapsulations were installed as opposed to four (to avoid penetrating the underlying sand aquifer); and c) the upper two unit anchors contained two strands in each encapsulation to allow load testing to very high grout/ground bond stress (described in Section 3.3).

3.1 Anchor Installation

The borehole was installed through a steel-reinforced concrete pad. Rotary drilling with end-of-casing water flush was performed using a diesel/hydraulic rig. A 7-inch o.d. N80 steel casing (0.45-inch thick wall) was advanced to the full depth of hole. The complete tendon comprising the three unit anchors [Top (A), Middle (B), Bottom (C)], the Primary grouting pipe, and the post grouting pipe (tube à manchette) was assembled in the field and installed through the casing. The drill casing was then withdrawn as the borehole was grouted via the primary grout pipe. The 1½-inch tube à manchette had sleeves at 3-foot intervals along the length of the four bond lengths. The grout was delivered to each sleeve through a double-packer placed at the corresponding sleeve location. Two post-grouting events (primary and secondary) were performed for each SBMA anchor. Within 24 hours of initial grouting, water was applied to each sleeve at pressures of 1000 to 2000 psi to fracture the initial casing grout. Neat cement grout was then injected at a target volume and pressure of 2 ft^3 per sleeve and 50 psi, respectively. After the refusal criteria for each sleeve were obtained, the double packer was advanced to the next sleeve in the post-grouting sequence. The secondary sleeve grouting followed the primary sleeve grouting by 24 hours.

Table 2. Summary of SBMA design parameters for Hodenpyl Dam.

Grout/Ground Bond • Factor of Safety on grout/ground bond = 3 • Post grouting enhancement factor (based on two phases of post grouting) = 2 • Ultimate grout/ground bond strength (τ_{ult}) = 3 ksf x 2 (post grouting) = 6 ksf • Primary Grout − Type I/II cement; Master Builders XR100 admixture, high speed, high shear mixer − Water/cement ratio (by weight of cement) = 0.45 − Unconfined compressive strength (28 days) > 4000 psi • Post Grout − Type I/II cement, high speed, high shear mixer − Water/cement ratio (by weight of cement) < 0.55 − Target volume = 15 gallons/sleeve; maximum pressure = 800 psi • Encapsulation Grout (SBMA) − Type II cement − Water/cement ratio (by weight of cement) = 0.475
Grout/Steel Bond (within encapsulation) • Verified by recent in-house testing performed by tendon supplier • Maximum test load was reached over a bond length of 10 feet without pullout.
Tendon • 4-strand anchor tendons • Strand within the 10-foot fixed length encapsulation contained three evenly spaced nodes (localized areas of untwisted strand that provide increased mechanical interlock) • Guaranteed Ultimate Tensile Strength (GUTS) = 58.6 kips; therefore, maximum test load = 80% GUTS = 46.8 kips.
Corrosion Protection • Tendons and top anchorage (bearing plate, anchor head, wedge plate, and wedges) meet Class I (PTI, 1996) • Encapsulation = 2-inch i.d. 10-foot long corrugated duct

3.2 Load Test Set Up

The jack arrangement for a three-unit SBMA includes three hydraulic rams that are synchronized by coupling to the same hydraulic powerpack, so that the same load is applied simultaneously to each unit anchor. The jacking arrangement is shown in Figure 5. A primary gauge and a reference gauge were calibrated with one of the jacks. The ram extensions were recorded using a stiff steel rule, and during creep testing by using a vernier caliper. Measurements were corrected for reaction pad movement measured by dial gauges mounted on an independent reference beam.

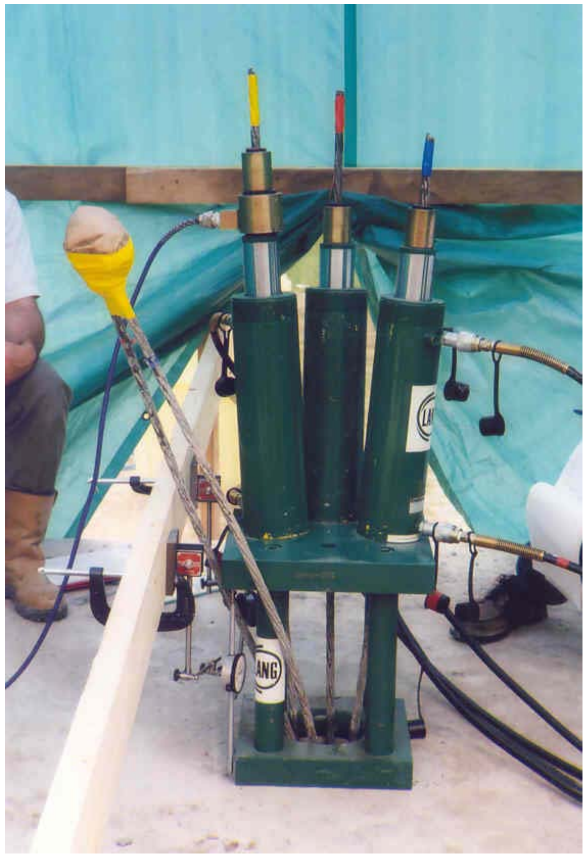


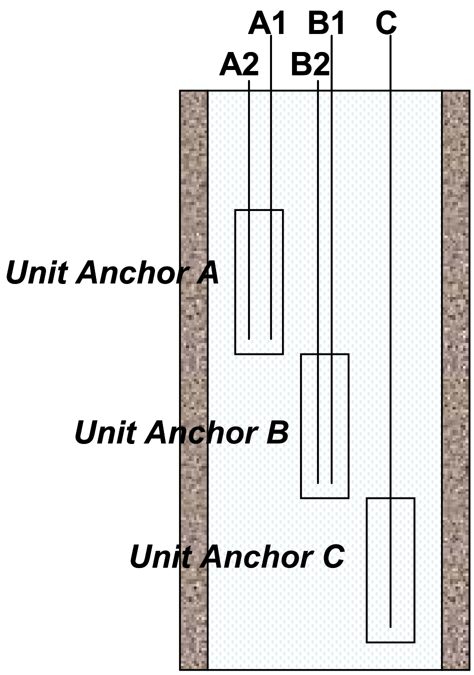
Figure 5. Sacrificial test anchor stressing jack.

3.3 Load Test Sequence

In addition to the Performance and Extended Creep Testing as detailed in the project specifications, load testing to high bond capacity was attempted on the sacrificial anchor. The stressing sequence for these tests is detailed in Figure 6.

The "Performance and Extended Creep Tests" included a Performance Test performed in general accordance with PTI (1996) to a maximum load of 1.33 x Design Load (≡ 44.9 kips), with Extended Creep Testing involving additional load holding periods at each load maxima (i.e., to 300 minutes). To obtain still longer-term creep measurement, the load-hold period for the sacrificial anchor was extended overnight (total load-hold time 810 minutes) at maximum load.

The Ultimate Load Test was performed in two parts. In Part 1, the previously unstressed strands (A2 and B2) were subjected to a cyclic loading/unloading sequence identical to that imposed upon the stressed strands (A1 and B1) (although without the load hold periods) to 1.33 x Design Load. This extra cycling was performed to impart similar stress histories into the strands so that, when these strands were subjected to further stressing, the pairs of A and B strands would each exhibit similar behavior. In Part 2, the maximum test load of 2 x 80% x 58.6 kips = 93.8 kips/unit anchor was applied. This test load therefore equaled 2.78 x Design Load (93.8 kips / 33.75 kips = 2.78).



Performance and Extended Creep Testing
Strands A1, B1 and C stressed as detailed in specifications for Performance and Extended Creep tests to 1.33 x Design Load. The second strands of Unit Anchors A and B remain unloaded throughout this testing).

Ultimate Load Testing
Upon completion of specified Performance and Extended Creep testing, the jacks were removed and re-installed to grip all four strands in Unit Anchors A and B (i.e., A1, A2, B1, and B2). A second load test was performed on these units, and the maximum test load was 2 x 80% x 58.6 kips/unit anchor (GUTS) = 93.8 kips/unit anchor. Test load applied to Unit Anchors A and B (and therefore the stress applied to their corresponding grout/soil interfaces) is doubled.

Figure 6. Stressing sequence for sacrificial anchor.

3.4 Performance and Extended Creep Test Results

Part 1

- The behavior of each unit anchor was extremely linear and repeatable, i.e., the plots of successive load cycles exhibit similar slopes and shapes. Figure 7 shows typical total movement versus load for the C Strand (A and B strands were similar but at different slope gradients due to different elastic lengths).
- Elastic and permanent movements for each unit anchor are shown in Figure 8. The plots of elastic movements are extremely linear and therefore indicate virtually no progressive debonding into the unit fixed anchor. As expected, the slopes of the curves decrease with increasing free stressing length, since at a given load, greater movement will be generated by a strand with a longer free stressing length.
- The permanent movements recorded at the maximum test load ranged from 0.2 to 0.35 inch. The readings were occasionally erratic due to the low Alignment Load. At the higher loads, the data are consistent and logical.

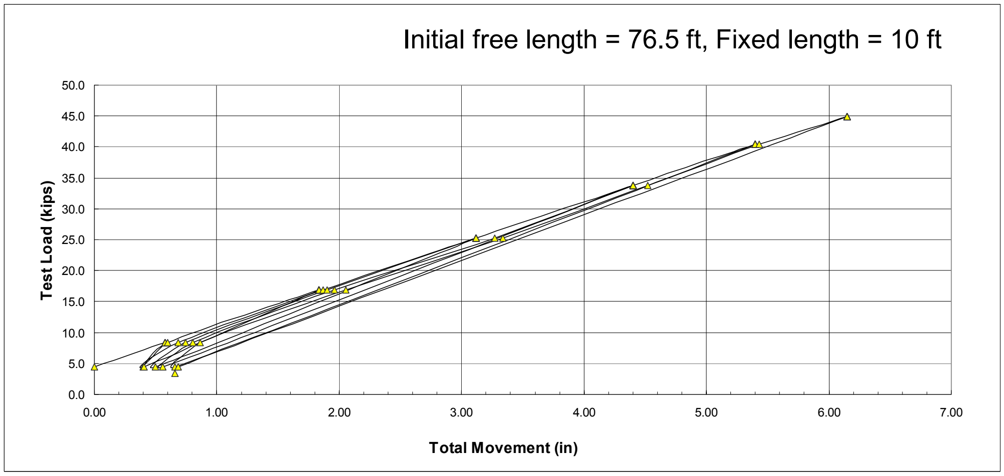
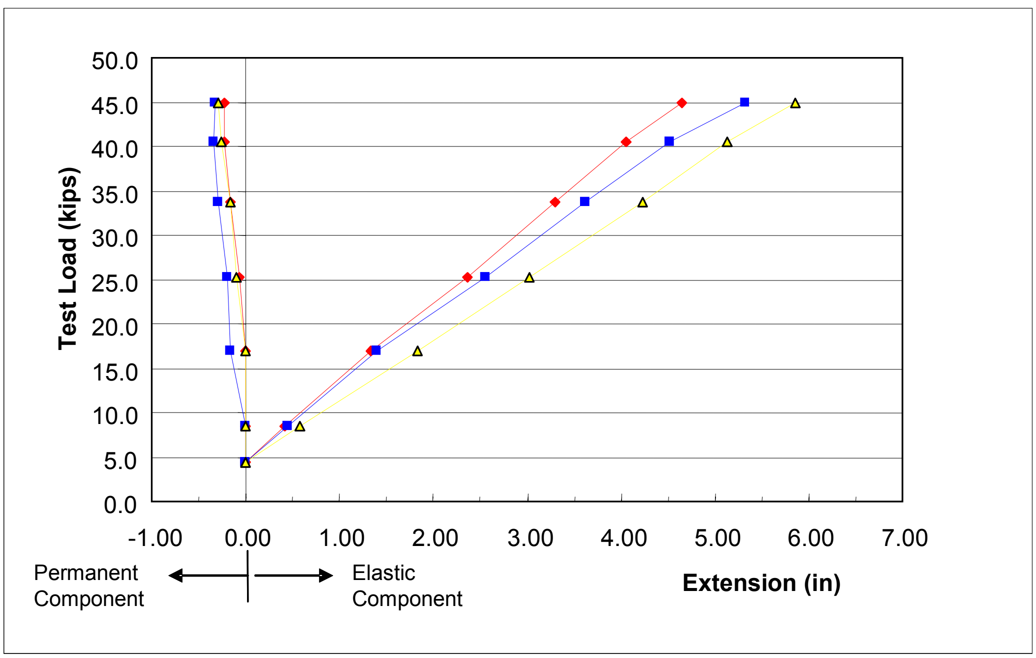


Figure 7. Total movement vs. load for Unit Anchor C during the Performance and Extended Creep Test.



◆ Strand A1 (Initial free stressing length = 60.5 feet); ■ Strand B1 (Initial free stressing length = 70.5 feet); Δ Strand C (Initial free stressing length = 80.5 feet)

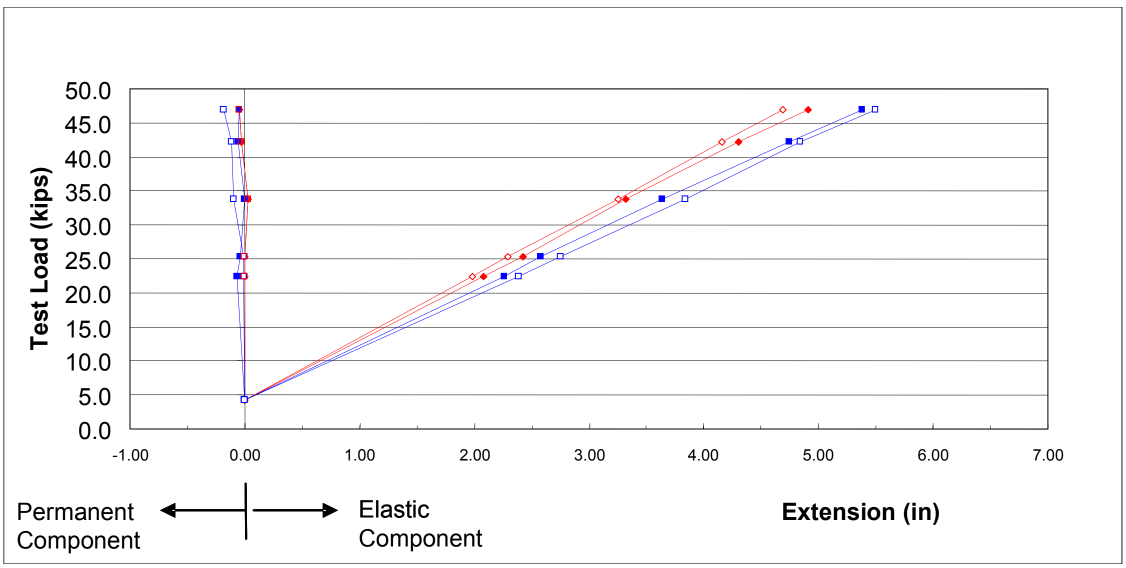
Figure 8. Elastic and permanent movements of Unit Anchors A, B, and C during the Performance Test.

- No creep was measured during the load-hold periods of the specified testing. During the additional optional load hold period, creep measurements were extremely low: 0.020 inch, 0.020 inch, and 0.082 inch, for the A1, B1, and C strands, respectively.

Part 2

- Figure 9 shows permanent and elastic movements to a maximum test load of 2.78 x Design Load on the upper two unit anchors. The plots from this loading were extremely linear and repeatable.
- Real permanent movements ranged from approximately 0.002 to 0.178 inch and were again somewhat erratic (similarly to those measured during the Performance and Extended Creep Test).
- There was no indication of impending failure at the maximum permissible test load, equivalent to 80% GUTS of the enhanced tendon capacity (i.e., 93.8 kips); therefore, no ultimate load was established.

With respect to the analysis of elastic movements, permanent movements (manipulated to compensate for the low Alignment Load effects), and creep, each unit SBMA proved entirely successful and compliant with the acceptance criteria.



◆ Strand A1 (Initial free stressing length = 60.5 feet); ■ Strand B1 (Initial free stressing length = 70.5 feet)

Figure 9. Elastic and permanent movements of strands of Unit Anchors A and B during the Ultimate Test. (Note: Each unit anchor has two strands; therefore the maximum ptest load on each unit anchor = 2 strands x 80% x 58.6 kips (GUTS) = 93.8 kips).

4. PRODUCTION ANCHOR INSTALLATION AND TESTING

4.1 Drilling and Tendon Installation

The 13 production anchors were installed between July 29 and August 23, 2002. Testing and lock off were conducted August 29 and 30, 2002. Anchors were installed sequentially from downstream to upstream starting with even numbered anchors (Anchors 2 through 12), followed immediately by odd numbered anchors (Anchors 1 through 13).

Anchor holes were drilled using rotary duplex with water flush and 7-inch casing with a 1-inch overcut from the casing shoe teeth, resulting in an 8- to 8½-inch hole diameter. Casing was advanced to the target tip elevation for each anchor.

4.2 Load Testing

Anchors 2 and 6 were subjected to Extended Creep Testing. As noted during sacrificial anchor testing, the permanent movement for each unit anchor appears to be artificially exaggerated due to low alignment loads and friction within the jack chair assembly. Remaining anchors were subjected to proof testing. Each anchor performed elastically at or above the required 80% of theoretical extension of the free length. Anchor 2 was the only anchor to show debonding, with magnitudes of 4.5 and 1.8 feet in Unit Anchors A and B, respectively. All other anchors had theoretical debonding values less than 0. Permanent movements at maximum test load were less than 1 inch for all anchors. No measurable creep at the maximum test load was recorded for any anchor.

4.3 Lock Off and Final Assembly

All unit anchors were locked off at 34 kips (136 k anchor load) using a monostrand jack. The strands were then trimmed to approximately 8 inches beyond the wedges. The trumpets were grouted, and the steel caps were installed as designed and filled with grease.

5. CONCLUSIONS AND FINAL REMARKS

Single Bore Multiple Anchors (SBMAs) incorporating a post-grouting program was used to satisfy the specified load requirements of the remedial anchors founded in a cohesive stratum. No load loss due to creep was encountered within a normal time period at 1.33 x design load. PTI and specified load carrying and movement acceptance criteria were met. This excellent anchor performance is considered due to the beneficial effects of a very concentrated post-grouting program, and the constructional and operational features of each unit SBMA. Analysis of the load-movement data confirmed no discernible debonding at any structural interface; very small and gradually increasing permanent movements with increasing load; and therefore, absolutely no evidence of impending failure at Test Load (i.e., at an average grout/ground bond of 135 kips/30 feet = 4.5 kips/ft).

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