

STABILIZATION OF RETAINING WALL ALONG TAILRACE CHANNEL OF HODENPYL DAM

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ABSTRACT

A cantilever wall located along the tailrace channel of the Hodenpyl Hydroelectric Dam was undergoing significant lateral displacement. An unsuccessful repair attempt was carried out in 1996 using conventional strand tiebacks. Remediation of the movements was accomplished in 2002 by installing additional tiebacks through the wall. The tieback system selected for this project was Single Bore Multiple Anchors (SBMA), bonded into high-plasticity clays behind the potential slip surface. The SBMA system provided the desired tieback capacities in the clay with a reduced potential for long-term creep. This was the first application of post-grouted SBMA technology in the United States. The limited monitoring data collected after remediation suggests that the SBMA system has performed remarkably well.

To expedite remediation of the wall, the design had to be completed in phases and adjusted according to the monitoring data obtained until the start of construction. This paper presents a description of the investigation and analyses performed for design of the remediation. It also describes briefly the SBMA system and the results obtained as interpreted from the wall monitoring performed up to this date. A companion paper by Bruce et al. (2004) describes in more detail the SBMA design and construction details for this project.

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INTRODUCTION

The Hodenpyl Hydroelectric Dam is located on the Manistee River in Michigan. The facility, constructed between 1923 and 1925, consists of an earthen embankment running roughly in the north-south direction. The powerhouse is located on the southern end of the embankment and discharges the water to a tailrace channel excavated in natural soils. Unlike most dams, the tailrace channel is nearly parallel to the core of the dam. Cantilever retaining walls of varying height were originally constructed on the east and west sides of the tailrace channel. The east wall is approximately 250 feet long and 30 to 50 feet high (see Figure 1).



FIG. 1. View of the tailrace channel and east retaining wall. Note the existing tiebacks installed in 1996. The sheetpiles were also added in 1996 as a facing and do not penetrate below the footing

The east wall was first repaired in 1996. The wall had undergone visible lateral displacements. A repair attempt was carried out using conventional strand tiebacks. Subsequent monitoring of the wall revealed that lateral displacement of the wall continued to develop, and that additional stabilization measures were required.

Design of the additional stabilization was performed in stages. Initially, a geotechnical investigation was performed to assess the potential causes for movement while collection of movement data continued. Inclometers and piezometers were installed to determine the geometry of the sliding mass, and variation of the groundwater table behind the wall. Several potential mechanisms that could cause the observed movements were identified. It was concluded that a global slide encompassing the existing wall and tiebacks was the most likely cause for the movements.

Based on the results from these analyses, a preliminary remediation design was completed that was used as part of the bid package. These analyses also aided in establishing additional measures to enhance the existing monitoring program and to verify the preliminary design assumptions. Construction drawings were furnished to the bidders along with a set of well-defined performance specifications. The bidders were required to provide a final design to match or exceed the established performance requirements.

Pre-selection and final selection of contractors took place concurrently with monitoring of the wall and redesign of the remediation. After the contract was awarded, final adjustments to the remediation design were introduced based on interpretation of the latest results from the extended monitoring program. It was understood, however, that movements of the wall might continue and that additional remediation measures might be necessary in the future. As designed, the stabilization was expected to improve the present conditions of the wall while additional monitoring information was collected.

This approach presented several advantages. It reduced costs, as design was completed for the most likely slide mechanism, while some risk related to unknown conditions was accepted and managed. It shortened the total time required for procurement and construction, as procurement was started before final design was completed. Finally, it involved the owner and contractor in the decision process while making them aware of the importance of wall monitoring and testing of the proposed solution.

Because the slip surface was relatively deep, stabilization of the wall required tiebacks that developed relatively large capacities within the high-plasticity clay predominant at the site. The solution adopted for this project consisted of the use of post grouted Single Bore Multiple Anchors (SBMA), bonded behind the potential slip surface. This tieback system was selected due to the need to obtain the desired capacities in the high-plasticity clay with reduced potential for long-term creep.

The proposed stabilization was successful and reduced significantly the rate of movement of the wall in the months following tieback installation. This paper describes the approach followed during the geotechnical study and design of the stabilization. The paper also includes an evaluation of the performance of the SBMA system based on monitoring and inclinometer data before and after stabilization. Details regarding the design, installation, and testing of the SBMA system are given in a companion paper by Bruce et al. (2004).

SOIL CHARACTERISTICS

Figure 2 shows a cross section of the east tailrace wall. The section depicts the soil strata identified from the site exploration. The soils behind the wall consisted of a layer of poorly graded sand, underlain by an interval of overconsolidated clay. The clay typically contained a 10- to 30-percent fraction of fine to coarse sand and traces of gravel-size particles. Sporadic lenses and/or seams of sand were also detected at some locations within the clay mass. The results of the laboratory testing revealed that the plasticity of the clay materials increased with depth. An approximate and

somewhat arbitrary boundary between low and high plasticity clay is represented in the figure.

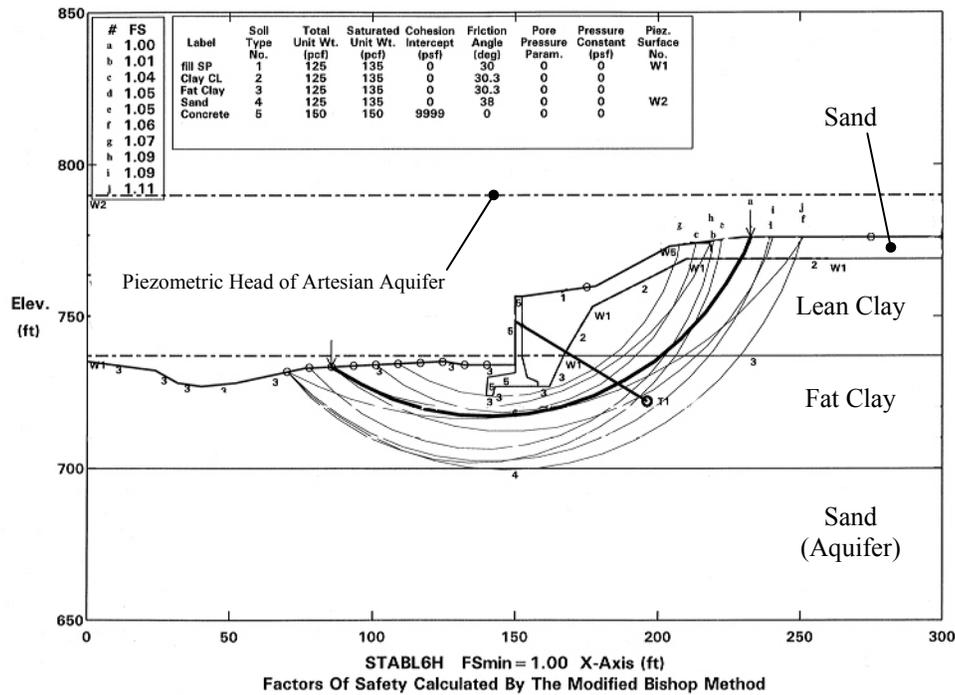


FIG. 2. Typical Section through East Tailrace Wall looking Downstream. Preliminary Stability Analyses Results are shown.

The clay stratum was underlain by a confined aquifer consisting of fine to coarse sands. The hydrostatic head of the aquifer was not known accurately. However, based on readings from nearby piezometers, an elevation of 790 ft (237 m) for the piezometric surface was estimated conservatively.

A number of tests were performed on disturbed and undisturbed specimens of the clay. In particular, ring shear tests on remoulded specimens were performed to determine the residual friction angle of the clay (ASTM D6467-99). Table 1 summarizes the interpreted property values of the clay, which were used for the preliminary stability analyses described in the next section. It is interesting to note the relatively large value of residual friction angle obtained for the clay. This is likely due to the sand content of the tested specimen. It must also be noted that the strength parameters obtained for lean and fat clay specimens were similar.

The properties of the sand strata used for the preliminary stability analyses were estimated based on correlations with the Standard Penetration Test (SPT) blowcount (Mc Gregor and Duncan 1998). They are also listed in Table 1.

ASSESSING THE MECHANISM OF WALL MOVEMENT

Several preliminary analyses were performed to ascertain the potential cause or causes for the observed movements. These analyses considered several potential mechanisms of movement of the wall. Progressive sliding and/or overturning of the

wall were analyzed. Potential failure or creep of the tiebacks installed during the first remediation attempt was a concern, given the characteristics of the clay at the site. Finally, global failure along a slip surface passing below the bottom of the wall footing was also considered a potential failure mechanism.

TABLE 1. Soil Properties used for Preliminary Stability Analyses

Material (1)	Properties (2)
Stratum 1 Surface Sand Layer and Wall Backfill (SP)	Total Unit Weight, $\gamma_{tot} = 125$ pcf Saturated Unit Weight, $\gamma_{sat} = 135$ pcf Effective Friction Angle, $\phi' = 30^\circ$
Stratum 2 Clay (CL)	Total Unit Weight, $\gamma_{tot} = 125$ pcf Saturated Unit Weight, $\gamma_{sat} = 135$ pcf Residual Friction Angle, $\phi'_{res} = 30^\circ$ to 33°
Stratum 3 Fat Clay (CH)	Total Unit Weight, $\gamma_{tot} = 125$ pcf Saturated Unit Weight, $\gamma_{sat} = 135$ pcf Residual Friction Angle, $\phi'_{res} = 30^\circ$ to 33°
Stratum 4 Sand (SP) (Aquifer)	Total Unit Weight, $\gamma_{tot} = 125$ pcf Saturated Unit Weight, $\gamma_{sat} = 135$ pcf Effective Friction Angle, $\phi' = 38^\circ$

The results of these preliminary analyses suggested that the most likely cause of the observed movements was a global failure mechanism. To analyze this mechanism, the clay was assigned an effective friction angle corresponding to the residual condition. The intention of these analyses was to model the long-term behavior of the clay assuming that large displacements had already occurred along the slip surface. Although it was presumed that the magnitude of movement along the slip surface had reached several inches at the time, there was no supporting data on cumulative movement. However, the assumption of a fully developed residual condition along the slip surface was considered reasonable given the magnitude of wall movements observed and the response of the remoulded specimens during ring shear testing.

The analyses were performed in terms of effective stresses. To model pore pressures within the clay, it was assumed that a linear piezometric gradient existed across the clay interval. This assumption, although not entirely accurate, was found to provide reasonable results for this case.

Circular slip surfaces were analyzed in terms of effective stresses using the Bishop's modified procedure in the program PCSTABL. The analyses suggested that the critical slip surface passed below the wall footing and intercepted the bond zone of the existing tiebacks, as illustrated in Figure 2. A factor of safety of one against

circular failure was obtained for a residual friction angle of 30 to 31 degrees, which were the lowest expected values according to the laboratory test results.

During this preliminary phase, only limited horizontal displacement data of the top of the wall were available. The results of these preliminary analyses were used to develop an improved monitoring program to confirm the assumed mechanism of wall displacement. The analyses were also the basis for development of preliminary design and testing requirements for use by contractors during the bid process.

Two inclinometers were installed behind the wall that extended beyond the potential slip surface. The survey program in place at that time was extended to include vertical and horizontal movements of the base of the wall and the soil slope above the wall. For final design, more refined analytical techniques were used that took into account the data from the instrumentation and the extended survey.

INSTRUMENTATION DATA

Approximately six months after the preliminary analyses were completed, the initial analytical assumptions were revised to account for additional data provided by the inclinometers and the extended survey.

The inclinometer readings suggested that sliding was taking place along a surface passing approximately 10 ft below the bottom of the wall footing. In addition, it appears that the sliding mass rotated as a 'rigid body' about a point located directly above the wall. The results of the inclinometer readings were consistent with the surveying data. Inclinometer and surveying data along other sections of the wall suggested that most of the movements were occurring toward the downstream end of the wall, and that the thickness of the materials involved in the movement varied along the wall. Therefore, it was concluded that the movements were taking place along a spoon- or wedge-shaped surface.

BACK ANALYSES OF WALL STABILITY

The stability of the wall was re-analyzed considering the surveying data and the location of the slip surface revealed by the inclinometers, as illustrated in Figure 3. These analyses were performed for final design of the remediation solution. The procedure followed consisted of establishing slip surfaces and back calculating the strength parameters of the clay to obtain a factor of safety of one. The shape and location of the slip surfaces was estimated based, primarily, on the inclinometer data.

Two mechanisms of sliding were analyzed. A circular slip surface using Bishop's modified method was first considered as illustrated in Figure 3. In the figure it can be observed that the circular slip surface daylighted behind the crest of the slope. This condition was not confirmed by field observations, which indicated that most of the surface movement appeared to occur on the slope itself. Therefore, composite or block slide mechanisms were also analyzed using the modified Janbu method, where the extent of the block behind the wall was limited to match field observations. The composite slide mechanism is not represented in the figure. Further details on stability analysis techniques can be found in Duncan (1996).

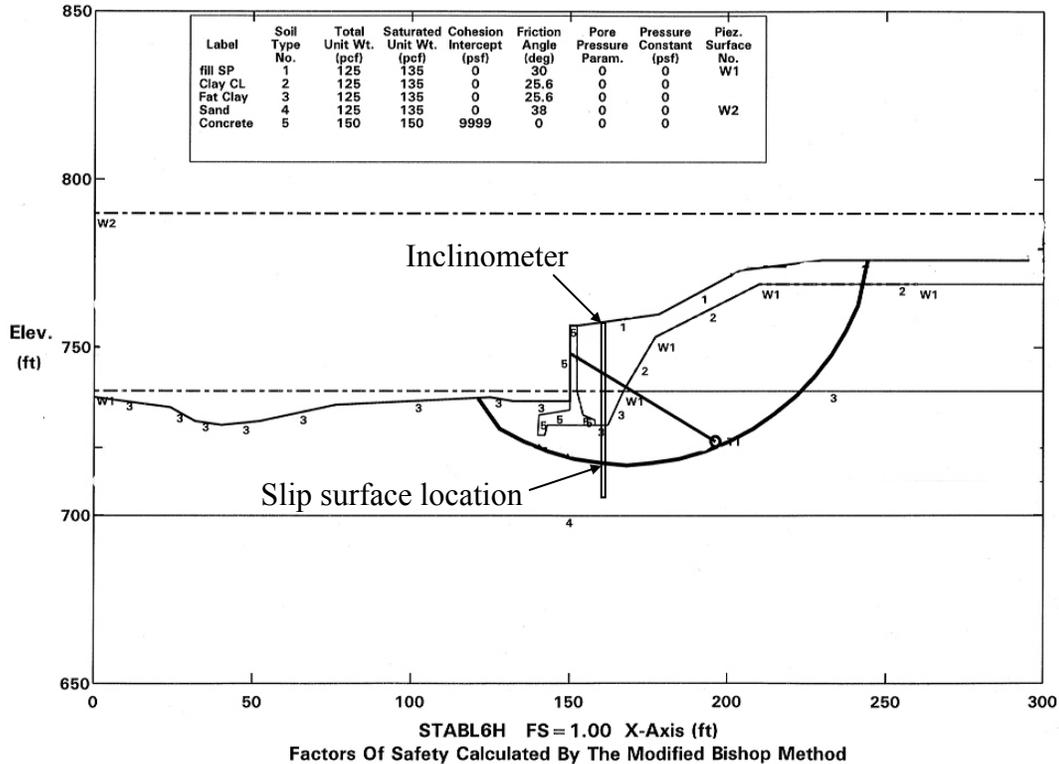


FIG. 3. Results of Back Analysis of the East Tailrace Wall.

Although the existing tiebacks were included in the analyses, their contribution to stability was negligible as the sliding mass typically encompassed them entirely.

As indicated previously, the friction angle of the clay was adjusted until a factor of safety of one was obtained. Table 2 contains the soil strength parameters estimated from the back analyses. It is seen that the estimated friction angle value for the clay is lower than those presented in Table 1. It is possible that the sand fraction of the specimens subject to shear testing may have been higher than the average sand fraction within the clay interval; thus, the specimens may not have been representative of the stratum. It is also possible that the slip surface developed through a 'weak' layer or through isolated 'weak' spots within the clay. Finally, it is possible that some of the sand seams within the clay may have been connected to the underlying artesian aquifer; therefore, the pore pressures close to the base of the wall would be significantly larger than estimated in the analyses. This last possibility was not supported by field observations during exploration or tieback installation.

REMEDICATION

Initially, the preferred alternative for remediation consisted of installing a row of caissons along the toe of the wall and in contact with the wall footing. The main advantage of this solution was avoiding the installation of tiebacks bonded into clay, which required consideration of the potential for creep and consequent load relaxation. In addition, local contractors were more experienced and better equipped

TABLE 2. Soil Properties estimated from Back Analyses

Material (1)	Properties (2)
Stratum 1 Surface Sand Layer and Wall Backfill (SP)	Total Unit Weight, $\gamma_{tot} = 125$ pcf Saturated Unit Weight, $\gamma_{sat} = 135$ pcf Effective Friction Angle, $\phi' = 30^\circ$
Stratum 2 Clay (CL)	Total Unit Weight, $\gamma_{tot} = 125$ pcf Saturated Unit Weight, $\gamma_{sat} = 135$ pcf Residual Friction Angle, $\phi'_{res} = 25^\circ$ to 27°
Stratum 3 Fat Clay (CH)	Total Unit Weight, $\gamma_{tot} = 125$ pcf Saturated Unit Weight, $\gamma_{sat} = 135$ pcf Residual Friction Angle, $\phi'_{res} = 25^\circ$ to 27°
Stratum 4 Sand (SP) (Aquifer)	Total Unit Weight, $\gamma_{tot} = 125$ pcf Saturated Unit Weight, $\gamma_{sat} = 135$ pcf Effective Friction Angle, $\phi' = 38^\circ$

in drilled shaft installation techniques. However, this alternative was discarded for two reasons. Firstly, the thickness of the materials involved in the movement was, as established from the inclinometer data, greater than previously estimated. Therefore, the design of the caissons would need to be revised to account for shear and moment magnitudes larger than initially estimated. Secondly, the costs of the caisson remediation were relatively high. Consequently, remediation using tiebacks was considered a viable alternative, provided that an adequate tieback system was used and validated through careful field testing.

Stabilization using tiebacks presented several challenges. The tiebacks should develop their capacity within the high plasticity clays below the wall foundation. Creep was a concern given the relatively large capacities needed. In addition, the tiebacks should not penetrate the underlying confined aquifer. The length and orientation of the tiebacks would then be controlled by the presence of the aquifer below, the existing tiebacks above, and the location of the slip surface.

Figure 4 illustrates the results of one of the stability analyses performed to establish the remediation requirements. Analyses were performed using the same slip surfaces and procedures used for the back analyses described in the previous section. For clarity, only the circular slip surface is represented in the figure. The analyses were performed using the corresponding soil properties listed in Table 2.

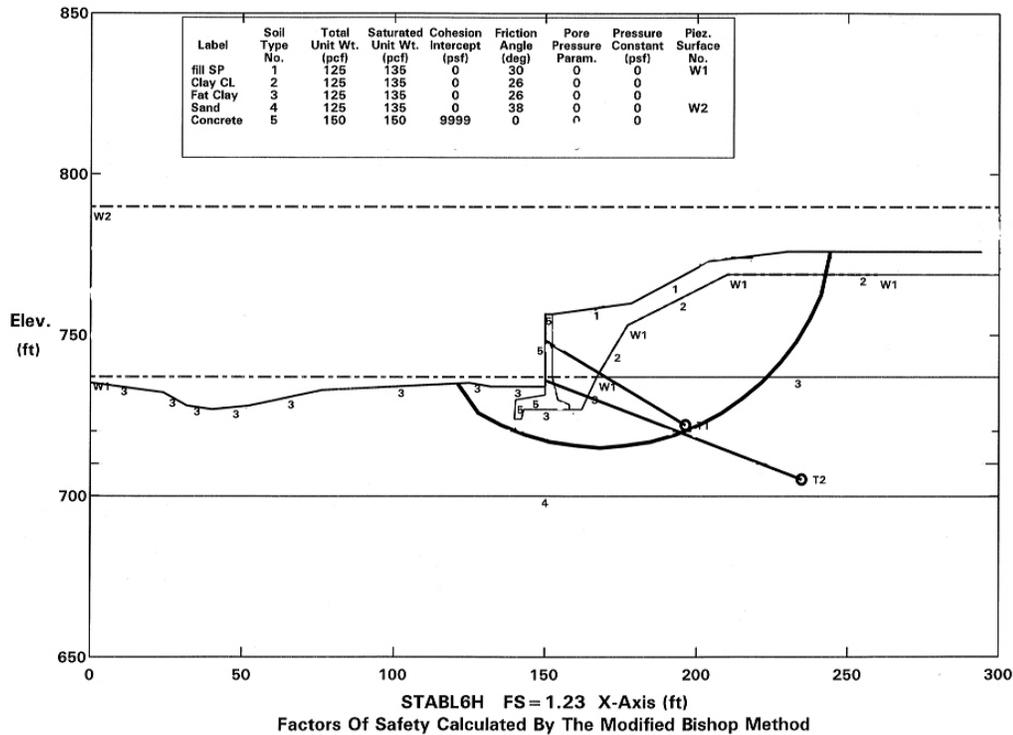


FIG. 4. Stability Analysis of the East Tailrace Wall for Remediation Design.

After consultation with the Owner, the target factor of safety was established at 1.2 to 1.25. Such a factor of safety could be achieved using one row of tiebacks with reasonably attainable capacity requirements. At that time, it was important to provide additional and immediate support for the wall rather than designing a final remediation solution, which would have required the acquisition and analysis of more monitoring data for a longer period, and installation of additional instrumentation. A well-defined monitoring/action plan after construction was established in order to assess the effectiveness of the remediation. The plan included threshold displacement values for performing further analyses and development of additional remedial measures if necessary.

The tiebacks forces required for the desired factor of safety were thus determined for the different slip mechanisms and types of analyses. The tiebacks would be installed at an inclination of 20 degrees from horizontal. The free length was established at approximately 15 m (50 ft). A maximum bond length of 12 m (40 ft) was required to avoid penetration into the aquifer. The tiebacks would have a minimum capacity of 600 kN (135 kip), and would be installed at a center-to-center spacing of 1.8 m (6 ft).

A set of remediation plans and performance specifications was prepared as part of the bid package. The specifications called for tiebacks with the length and capacity requirements determined from the stability analyses. In addition, the tiebacks should be retensionable in case creep-induced relaxation of the tieback load occurred over time. The contract specification required the contractor to be responsible for the design of an adequate tieback system that met these requirements.

SINGLE BORE MULTIPLE ANCHOR (SBMA) SYSTEM

In conventional tiebacks, the bonded portion is a single unit where all the tieback strands are encased together within the grout. Upon tensioning of the tieback, the resulting load transfer distribution along each of the strands is dependent on the magnitude of the load, the response of the grout-soil and strand-grout interfaces, and the stiffness of the strand. Conventional tiebacks have been used extensively and successfully for many years. However, the load transfer distribution along the bond zone is often non-uniform and the efficiency of the conventional tieback is reduced (see Barley and Windsor 2000). Furthermore, the length of the bond zone in traditional tiebacks is often limited to a 3 to 10 m (10 to 33 ft) range, as greater bond zone lengths do not increase significantly the tieback capacity.

The SBMA technology was developed to reduce these limitations. In this system, the bond length comprises a set of shorter and staggered individual unit anchors, each of which is fitted with one or more strands and is tensioned using an independent jack (see Figure 5). A more detailed description of the SBMA system is presented in a companion paper by Bruce et al. (2004).

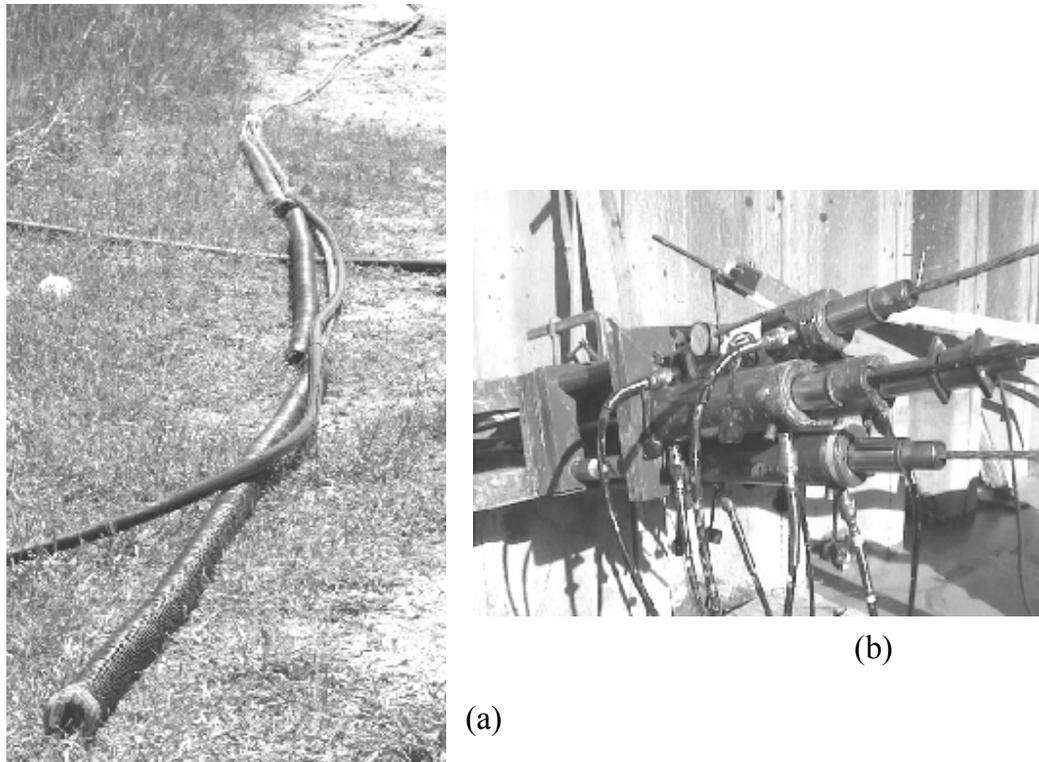


FIG. 5. (a) String of SBMA units almost ready for installation; (b) Performance testing of a production SBMA. Note the multiple jacks for stressing of each strand.

This system was particularly attractive for the Hodenpyl project. By using a bond length similar to that of a conventional anchor, the required individual tieback capacity could be achieved maintaining a relatively low bond stress along the grout-

soil interface of the SBMA elements, thus reducing the potential for long-term creep of the tiebacks.

The selected contractor proposed the use of post-grouted SBMA elements consisting of four unit anchors with bond lengths approximately 10 feet long. This was the first application of post-grouted tiebacks using the SBMA technology in the United States.

A sacrificial test anchor was installed and tested before the start of construction to verify the capacity and response of the proposed SBMA design (see Figure 6). Due to space restrictions, the sacrificial anchor was located on the embankment above the wall and was installed in a vertical position. To prevent drilling into the aquifer, a shorter bond length consisting of three 10-ft bond units was used for the sacrificial anchor. Two strands were used for each of the upper two units. This modification with respect to the production design was introduced for research purposes in order to attempt to induce bond failure of the upper bond units during a secondary test phase.

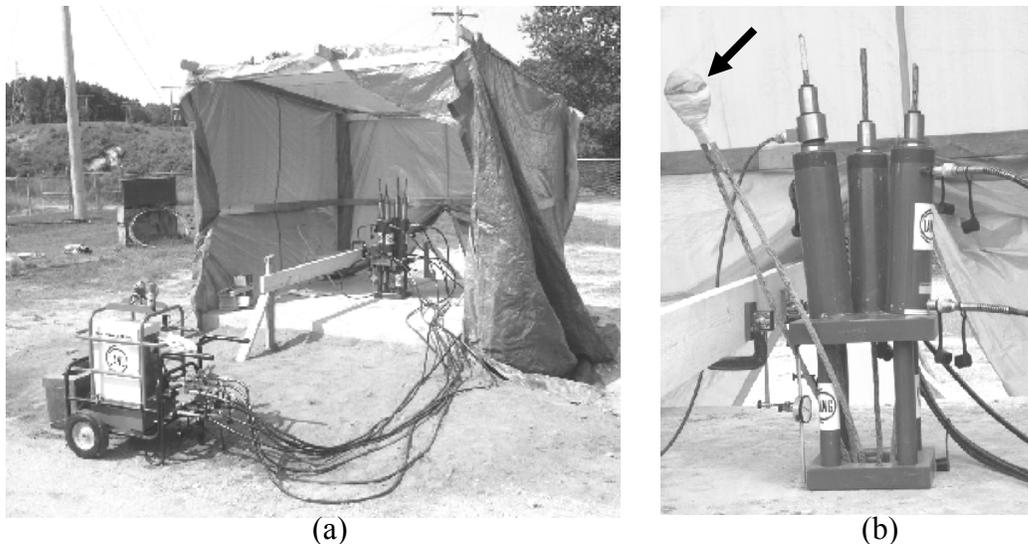


FIG. 6. (a) View of the setup for sacrificial anchor testing; (b) Detail of the stressing arrangement. Note the two additional strands not engaged during the first portion of the test.

In addition, two performance tests (PTI 1996) were carried out on production anchors. Details of procedures and results from the sacrificial and production anchor tests are presented in the companion paper by Bruce et al. (2004). The test results indicated that the required capacity of the tiebacks could be achieved and that creep would not be an issue. The tiebacks were installed from within a cofferdam constructed at the toe of the wall (see Figure 7). A barge was used to provide access for materials and equipment. The tiebacks were all installed in a period of approximately 15 working days without disruption to the plant operation. A waler beam was used to connect the anchorage to the facing of the wall (see Figure 8). All the anchorage elements of the tiebacks were encased within a grease-filled protective cover, which was large enough to house the excess strand length for eventual lift-off testing and retensioning, as shown in Figure 9.



FIG. 7. View of the site during installation of the SBMA elements. a sheet piling cofferdam provided a dry working area below the tailrace water level. Note service barge on the left.



FIG. 8. View of the wall at near completion of the installation of the SBMA elements near the bottom of the wall. The strands are to be saw-cut and covered. The old tieback installation is visible near top of photo.



FIG. 9. Detail showing the anchorage elements. The strands are about to be cut and covered with the grease-filled housing.

PERFORMANCE OF THE REMEDIATION

Figure 10 summarizes the survey data at selected locations along the wall. It is seen that displacements of the wall were steadily increasing before remediation. After a temporary and expected disturbance during installation of the tiebacks, the rate of movement decreased significantly.

The inclinometer data shows a similar trend. However, at the time this paper was written, some displacement at the slip surface continued to occur at a reduced rate. It is believed that this movement is due to redistribution of stresses within the clay mass.

At the time of preparation of this paper, the period elapsed since installation of the SBMA system was relatively short, especially considering the long-term nature of the movements. However, the preliminary conclusion is that the remediation was successful. Further monitoring data over the next two years will provide indication as to the long-term performance of the tiebacks and/or the accuracy of the model used to analyze the mechanism of movement of the wall.

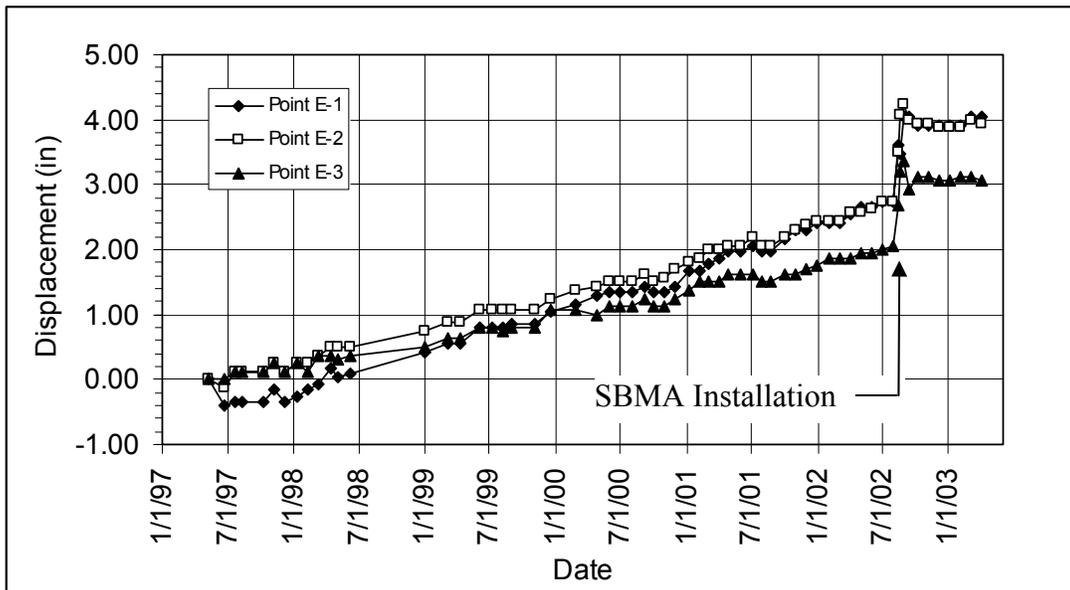


FIG. 10. Relative Displacement of the East Tailrace Wall (Values measured along the Cap of the Downstream End of the Wall).

CONCLUSIONS

Remediation of the East Tailrace Wall was successful on several levels. The philosophy followed for design allowed to reduce costs significantly and permitted an accelerated procurement and construction schedule. The factor of safety against a global slide was defined in concordance with the owner of the dam, and was intended to provide immediate improvement of the stability of the wall. In addition, a well-defined monitoring/action program was established to track the performance of the remediation over time.

The design called for restressable tiebacks, which would allow load adjustments if they were subject to relaxation due to creep or unanticipated movement patterns. Although it is entirely possible that no further remediation will be needed, the monitoring program would allow detection of additional movements that could be cause for concern. If additional and immediate remediation is required, the tiebacks could be restressed depending on the causes for the additional movement, while other stabilization measures are implemented as needed.

The SBMA system selected for this project performed remarkably well during the tests. Additionally, in spite of its sophistication, the installation of the system was simple and few issues developed during construction.

Finally, the project was completed as a team effort, where all the parties involved collaborated in accomplishing precise goals established during the design.

ACKNOWLEDGEMENTS

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