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Final Report

CONSTRUCTION AND MONITORING OF POST-TENSIONED MASONRY SOUND WALLS

David B. Woodham, P.E.

DEPARTMENT OF TRANSPORTATION
RESEARCH

December 2001

COLORADO DEPARTMENT OF TRANSPORTATION
RESEARCH BRANCH

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16. Abstract
Prestressed masonry offers a competitive alternative to conventionally reinforced masonry and reinforced concrete in certain applications. While prestressed masonry is a commonly accepted form of construction in Europe, it has seen very little use in the U.S. This is mostly due to the lack of building code provisions for building officials, design guidance for design professionals, commercially available hardware, and construction experience for contractors (Schultz and Scolforo, 1991).

The purpose of this project was to document the installation of a post-tensioned concrete masonry sound wall constructed as part of a widening and sound wall project along US 36 near Denver, Colorado. In addition, the wall was instrumented at the time of construction to monitor the loss in prestress in the steel tendons over time due to concrete masonry creep and shrinkage and steel relaxation. Tendon tension was monitored for one year to obtain values for the accumulated losses. Accurate losses in post-tensioned concrete masonry are important for economical design. Currently, there is limited data to support an accurate prediction of prestress loss in concrete masonry

Implementation
Because of the limited experience from this project, study panel members did not deem a full implementation of this construction method was justifiable. However, further experimentation with pre-stressed masonry sound walls will be explored on further CDOT projects in the future to confirm findings from this research work.

17. Key Words
Post-tensioned, Masonry wall, Pre-stress Loss, Bond Beam, Creep, Grout

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by

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December 2001

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EXECUTIVE SUMMARY

Prestressed masonry offers a competitive alternative to conventionally reinforced masonry and reinforced concrete in certain applications. While prestressed masonry is a commonly accepted form of construction in Europe, it has seen very little use in the U.S. This is mostly due to the lack of building code provisions for building officials, design guidance for design professionals, commercially available hardware, and construction experience for contractors (Schultz and Scolforo, 1991).

The purpose of this project was to document the installation of a post-tensioned concrete masonry sound wall constructed as part of a widening and sound wall project along US 36 near Denver, Colorado. In addition, the wall was instrumented at the time of construction to monitor the loss in prestress in the steel tendons over time due to concrete masonry creep and shrinkage and steel relaxation. Tendon tension was monitored for one year to obtain values for the accumulated losses. Accurate losses in post-tensioned concrete masonry are important for economical design. Currently, there is limited data to support an accurate prediction of prestress loss in concrete masonry.

Laboratory tests were also conducted to confirm the safety factors associated with the tendon anchorages.

Total loss of prestress averaged 25.5% for the 7 tendons monitored over the one-year period. Initial losses, due to the tensioning of adjacent tendons averaged 5.3%.

This report describes the design, construction, and monitoring of the post-tensioned sound wall. In addition, the results of laboratory tests are presented.

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1.0 INTRODUCTION

This report documents the construction and monitoring of a post-tensioned concrete masonry sound wall built along the US 36 corridor in Westminster, Colorado. The research project was funded by the Colorado Department of Transportation (CDOT) and conducted jointly by Atkinson-Noland & Associates and Dr. Trey Hamilton of the University of Wyoming. The research project began in August of 2000 with the casting of the concrete grade beams supporting the wall. The post-tension anchorages were installed in the plastic concrete of the grade beam. The sound wall was completed in late September and tensioning of the tendons was done on October 2, 2000. A data acquisition system was installed to monitor and record strains in the tendons and was operated for one year after the initial tensioning.

1.1 Background

The sound wall was constructed of nominal 8-inch split face block with two courses of fluted accent block near the top of the wall. The wall is cantilevered 12 feet 5 inches from the continuous footing. The adjacent wall was conventionally built with 2 #6 reinforcing bars at 24-inch centers and included a horizontally reinforced bond beam every 48 inches.

2.0 PROJECT OBJECTIVES

The main purposes of this research were to demonstrate the post-tensioning technology in a structure and to determine the actual loss of prestress force in tendons due to creep and shrinkage of the concrete masonry and relaxation of the steel tendon. In addition, laboratory tests of the anchorages were done to evaluate the adequacy of a typical anchorage using a concrete masonry unit (CMU) bond beam. During tensioning of the actual wall, tendon strains were monitored to evaluate the distribution and losses of post-tensioning force within each tendon.

2.1 Approach

The study included laboratory testing of the bond beam anchorages and design of the post-tensioned wall using the Masonry Standards Joint Committee (MSJC), *Building Code Requirements for Masonry Structures (ACI 530-99/ASCE 5-99/TMS 402-99).* The construction of the post-tensioned wall was monitored and documented as the wall was built. Lastly, a data acquisition system was installed to monitor strains in the tendons.

2.1.1 Personnel

The post-tensioned wall and adjoining reinforced masonry wall were constructed by J & J Masonry of Henderson, Colorado. The instrumentation package for monitoring the long-term strains in the post-tensioning tendons was developed by CDOT's Research Branch. The University of Wyoming designed and conducted the laboratory research and assisted in the design of the post-tensioned wall. Atkinson-Noland & Associates designed the post-tensioned wall and monitored construction of the wall. Data acquisition, over the one-year monitoring period, was done by CDOT's Research Branch.

2.1.2 Test Locations

The test area was a short section of sound wall located in the southeast quadrant of the intersection of Federal Boulevard (U.S. 287) and the Denver/Boulder Turnpike (U.S. 36) in Westminster, Colorado. Figure 1 shows the location of the sound wall.

3.0 RESULTS

3.1 Laboratory Testing

Anchorage testing was conducted to evaluate the adequacy of the bond beam top anchorages. In order to test the anchorages, a small 4 foot by 4 foot wallette was built that contained a bond beam at the bottom and top course. Each bond beam was horizontally reinforced with two #4 bars to provide an anchorage for two 11/16-inch diameter tendons. The tendons were installed vertically at 24-inch centers using standard Dur-o-Wal anchorage plates. Load-indicating washers were installed at the top anchorage to indicate when the maximum rod tension had been reached. As the tendons were tensioned, deflection readings were taken on the face of the masonry immediately below the anchorage and at intervals between the two tendon anchorages (see Figure 2). Measurements were taken with a Demec gage with resolution of 0.0001 inch. The displacement readings were plotted along with calculated values for the displacement (Figure 3). The displacement calculations follow the classical solution by Timoshenko for a beam on an elastic foundation and agree well with the measured displacements assuming typical concrete masonry material properties.

3.2 Design

The design of the wall was in conformance with the report from the Masonry Standards Joint Committee (MSJC), *Building Code Requirements for Masonry Structures (ACI 530-99/ASCE 5-99/TMS 402-99).* The sound wall design is governed by wind loading and in accordance with AASHTO guidelines, a value of 27 pounds per square foot was used as the design wind load. The final design utilizes 11/16-inch diameter tendons (Dur-o-Wal D/A790T Sure-Stress) spaced at 24 inches on center. The tendons have an average yield stress of 100,000 psi and an average ultimate strength of 122,000 psi. Each tendon is initially tensioned to 26.1 kip. After predicted losses of 25% of the post-tensioned force, the force at service loads is assumed to be 19.6 kip.

3.3 Construction

The concrete grade beams at the base of the CMU wall were cast on August 11, 2000. Immediately after the pour, the anchorage assemblies (Dur-o-Wal D/A-790F Sure-Stress) were inserted in the fresh concrete and vibrated to ensure consolidation around the anchorage. The anchorage assembly, consisting of the anchorage and a 36-inch tendon, were aligned to a string line to ensure that the tendons would be located along the center line of the wall. Figure 4 shows the layout of the tendons in the grade beam prior to building the wall.

The lower portion of the wall was constructed the week of August 21, 2000 and the vibrating wire strain gages were installed late during the same week. The vibrating wire strain gages were preinstalled on 36-inch sections of tendons by Geokon, Inc. Eight tendons were instrumented and leads from the strain gages were routed down the cell to the bottom of the wall where the wire exited the wall. Electrical conduit was run from each instrumented cell to an instrument cabinet to protect the wiring. The electrical cabinet housed a Campbell Scientific CR-10 data recorder, 8-channel multiplexer, vibrating wire interface for the CR-10, and a 12 Volt deep-cycle battery to power the system. The data recorder was programmed to record both the strain and temperature of each tendon once per hour.

The tendons were tensioned October 2, 2000. The tensioning began at the north end of the test wall with gage #1 and proceeded to the south (gage #8). The instrumented tendons, installed at 4 ft. centers (every other tendon), were tensioned first and the intermediate (non-instrumented) tendons were tensioned in a secondary operation. Figure 5 shows the tensioning equipment consisting of steel shims, a tubular steel beam, an open cylinder hydraulic ram, and hydraulic pump. The tendon force is distributed into the bond beam upon final tensioning by 4 by 6 inch cast bearing plates (Dur-o-Wal D/A 790BP Sure-Stress).

One strain gage was damaged during tensioning when a connector failed due to inadequate thread engagement with the tendon. The tendon was rethreaded fully into the connector and tensioned to the design value; however, the sudden release in strain during the initial tensioning damaged the one vibrating wire strain gage.

3.4 Initial Losses

Losses were incurred during the initial tensioning as tendons adjacent to previously tensioned tendons were then stressed. Note that instrumented tendons were installed at 4 ft. centers with intermediate non-instrumented tendons between. The tendons were numbered from north (1) to south (8) along the wall. Table 1 shows the results of the initial stressing operation. The values in the table are the output of the data acquisition system and are proportional to the strain in the tendon. The first column shows the tendon that is being stressed and each row is the change in stress in other tendons due to the influence of the tensioned tendon.

The loss of stress is due to the elastic shortening of the wall that occurred when each instrumented tendon was tensioned. The values range from 2.2% to 4.7% with the exception of the large reading of 13.9% at tendon five. This large loss is not consistent with the remaining data and is probably due to error.

Table 1. Strain history of individual tendons when other instrumented tendons were tensioned.

Stressed Tendon	Final Stress in Tendon No.							
	1	2	3	4	5	6	7	8
1	9618					*		
2	9491	10298				*		
3	9457	10131	9560			*		
4	9432	10055	9212	11609		*		
5	9426	10047	9156	11370	11606	*		
6	9411	10020	9112	11399	10015	*		
7	9407	10019	9114	11299	9991	*	9979	
8	9405	10018	9112	11301	9992	*	9620	9787
Net Loss	2.2%	2.7%	4.7%	2.7%	13.9%		3.6%	-----

*Gage 6 failed during tensioning.

Table 2 shows the total loss after the non-instrumented tendons were stressed and represent the losses that might occur on a wall with tendons at 2-foot centers. The effect of stressing the tendon in the left column can be observed on the neighboring tendons which gives an indication of the zone of influence for each tendon.

Table 2. Instrumented tendon strain history when adjacent (intermediate) tendons were tensioned (values in table are from the data acquisition system and are proportional to strain).

Stressed Tendon	Final Stress in Tendon No.							
	1	2	3	4	5	6	7	8
North of 1	9372	9994	9105	11299	9975	*	9603	9753
Between 1 & 2	9222	9886	9078	11286	9971	*	9584	9743
Between 2 & 3	9204	9792	8997	11269	9967	*	9582	9734
Between 3 & 4	9192	9758	8911	**	9942	*	9578	9720
Between 4 & 5	9185	9763	8884	11064	9914	*	9563	9708
Between 5 & 6						*		
Between 6 & 7	9178	9757	8882	11065	9813	*	9448	9664
Between 7 & 8	9176	**	8880	11064	9808	*	9324	9530
South of 8	9174	**	8876	11061	9804	*	9293	9396
Net Loss	2.1%	2.4%	2.6%	2.1%	1.7%		3.2%	3.7%

*Gage 6 failed during tensioning.
** A stable reading could not be obtained at this tendon.

Table 3 shows the summation of the losses for tendons on 4-foot and 2-foot centers. Theoretically the losses for tendons spaced at 2-foot centers should be twice as large as those for 4-foot centers since twice the prestress will induce twice the deformation of the wall. The last row shows the ratio of prestress loss for the 4-foot on center tensioning compared to the 2-foot on center tensioning.

Table 3. Instantaneous prestress loss as a percentage of the initial measured stress.

Tendon Spacing	Tendon No.							
	1	2	3	4	5	6	7	8
4 ft	2.2%	2.7%	4.7%	2.7%	13.9%	*	3.6%	-
2 ft	4.3%	5.1%	7.3%	4.8%	15.6%	*	6.8%	3.7%
Ratio 2/4	1.96	1.88	1.55	1.78	0.89	*	1.89	-

The results from tendon 5 are considered an outlier in accordance with the guidelines of ASTM E 178, *Standard Practice for Dealing With Outlying Observations* and are not included in subsequent calculations. Initial losses averaged 5.3% with a standard deviation of 1.4% leading to a relatively high coefficient of variation of 26%.

3.5 Long-term Losses

Strains in the tendons were monitored for a period of one year after tensioning to obtain realistic values for post-tensioned losses. The values obtained after one year of monitoring show loss of prestress from the initial condition from 14% to 25%

Table 4. Summary of losses over one-year monitoring period.
Measurements taken with GEOKON manual readout device (GK403).

Date	**Gage 1 (uε)**	**Gage 2 (uε)**	**Gage 3 (uε)**	**Gage 4 (uε)**	**Gage 5 (uε)**	**Gage 7 (uε)**	**Gage 8 (uε)**
(10/2/2000)	3954	4188	3825	4897	4225	4004	4044
(10/17/2001)	3413	3327	3312	3796	3312	2994	3060
Loss (uε)	541	861	513	1101	913	1010	984
Loss (%)	14	21	13	23	22	25	24

4.0 DISCUSSION

From the beginning of the monitoring period, the measured strains contained some signal variation or "noise." A longer grounding rod was installed on January 19, 2001 and seemed to eliminate some of the noise in the system. However, periodic high strain readings still appeared on all gages in the data.

The noise may have been due in part to the high strains induced in the tendon. The tendons were initially tensioned to 26.1 kip, corresponding to nearly 2400 microstrain for an 11/16-inch diameter tendon. Since the vibrating wire strain gage requires initial tension in order that the wire is not slack, the initial (no load) reading was set near 900 to 1000 microstrain. The stated range of the vibrating wire strain gage is 2500 microstrain implying that the instrumentation was operating at or beyond the stated range.

As seen in Figure 6, the strains tendancies are as expected; however, several rises in strain are evident in the plot. The reason for the temporary increases in strain is unknown. Vibrating wire strain gages typically are very stable and the output from them exhibits little if any signal drift.

A large variation in the loss of prestress occurred in the 7 tendons. The average long-term loss was 20.2% with a standard deviation of 4.8% leading to a coefficient of variation of 20.7%. Tendons 1 and 3 had long-term losses of 14% and 13% respectively while the remaining tendon's long-term losses ranged from 21% to 25%. It is unclear why there are two apparent groups in the data. Short-term losses (those occurring during tensioning) averaged 5.3% but also had a large variation.

As can be seen in Figure 6, the loss in strain is becoming less as time progresses. In most time step methods (e.g. *Recommendations for Estimating Prestress Losses* reported by the PCI Committee on Prestress Losses) 70 to 80% of the ultimate losses occur within the first year. It is expected that further losses will occur.

Accurate cost comparisons between post-tensioned and conventional masonry wall systems are difficult for several reasons. The contractor had no previous experience with post-tensioned masonry and the relatively short length (40 feet) of the test panel did not provide the economy of scale that a larger panel would have. The cost for the hardware for the 40 by 12 foot test panel was approximately $1,450.00 or about $3.00 per square foot. Conventional reinforced and grouted cells (12 feet high at 24-inch centers) cost roughly $1.50 per square foot of wall area. Productivity increases, due to the use of post-tensioning, have to offset the remaing $1.50 per square foot of wall area to make the two systems comparable in cost.

5.0 CONCLUSIONS AND RECOMMENDATIONS

The construction of a post-tensioned concrete masonry sound wall was documented under this study to evaluate this type of construction for future sound walls and to document the loss of prestress in this relatively new type of construction. The findings apply to concrete masonry post-tensioned with threaded high strength steel bars similar to the Dur-o-Wal Sure Stress system used in this project. The losses for strand tendons used to post-tension concrete will most likely be different.

Initial prestress losses were recorded during tensioning. These losses were due to the additional compression on the masonry as adjacent tendons were tensioned. Losses were found to range from 4.3% to 7.3% neglecting one value which is believed to be erroneous.

Long-term losses range from 13% to 25% not including the initial losses. The average long-term loss was 20.2% with a standard deviation of 4.8%.

Total losses including initial and long-term averaged 25.5% for the 7 monitored tendons with a standard deviation of 4.7% resulting in a coefficient of variation of 18.6%.

As a result of the monitoring performed on this study, the proposed Masonry Standards Joint Committee (MSJC) commentary of 30-35% looks both reasonable and not overly conservative. Because of the variability measured in this study, a slight overestimation (2 standard deviations) of the prestress loss seems reasonable. This results in closer tendon spacing and increased cost of post-tensioning hardware. It is recommended to continue periodic monitoring of the tendons in the concrete masonry to quantify losses in subsequent years.

It appears that the use of post-tensioned masonry could have cost savings if the cost of the post-tension hardware is reasonable. The time saved by not having to grout vertical cells (typically in multiple lifts of 5 feet or less) provides the main labor savings. One horizontal bond beam is required below the upper anchorage to distribute load laterally into the wall. On the other hand, the use of post-tensioning requires a level of precision that many masons are unfamiliar with. Most tolerances are critical for this method of construction, all connections must be fully engaged, and stressing the tendons must be done with care and attention to detail.

In some cases, it may be preferable to wait to post-tension a wall to allow for some of the initial shrinkage of the concrete masonry to occur. If losses are to be minimized, re-stressing the tendons may be valuable to reduce the 5.3% average initial losses.

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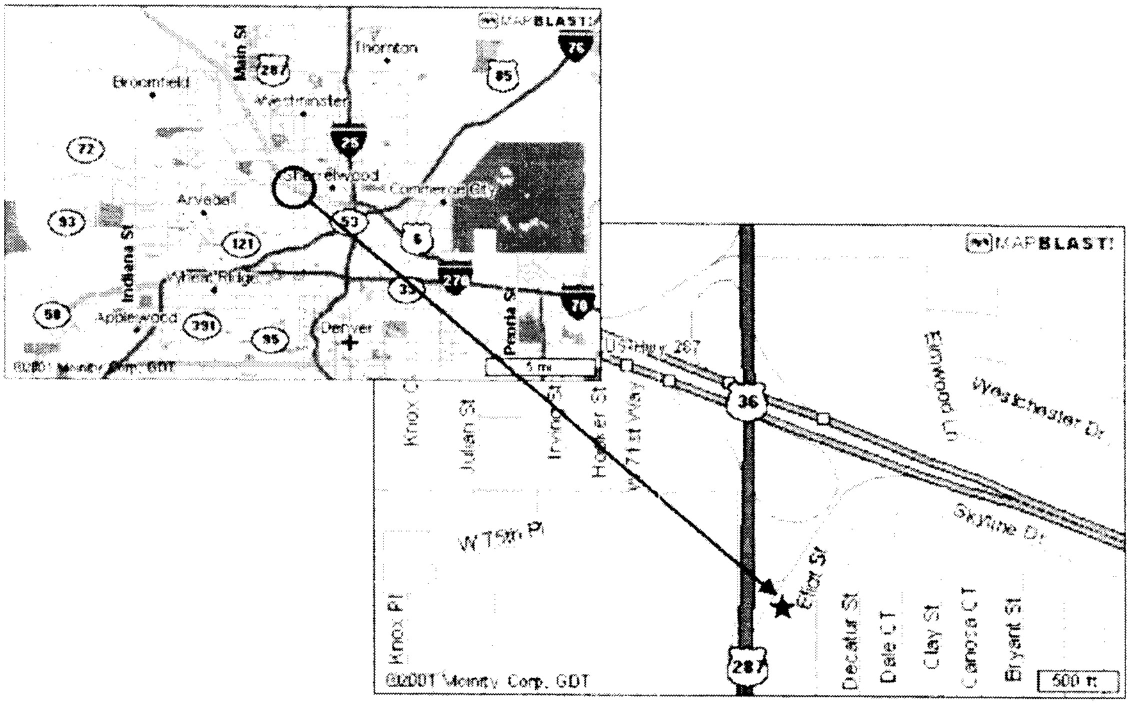


Figure 1. Location of post-tensioned test section in northwest Denver.

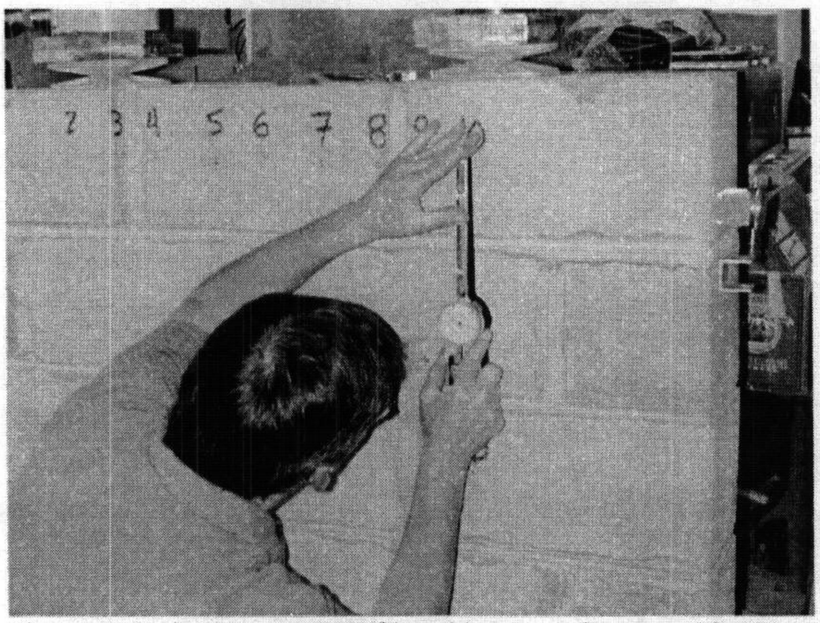


Figure 2. Laboratory tests of bond beam anchorage. The top course is a fully grouted, horizontally reinforced bond beam constructed with 8-inch concrete block. Strains were measured with a dial gage at 10 points between the two tendons (top of photograph).

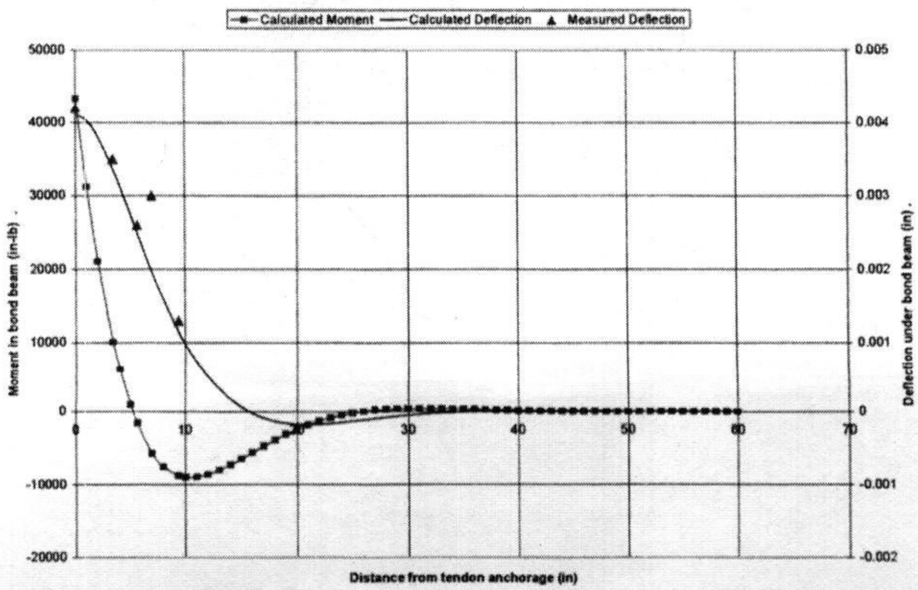


Figure 3. Calculated deflections based on a solution by Timoshenko for a beam on an elastic foundation.

Figure 4. Photograph of grade beam with tendon anchorages installed.

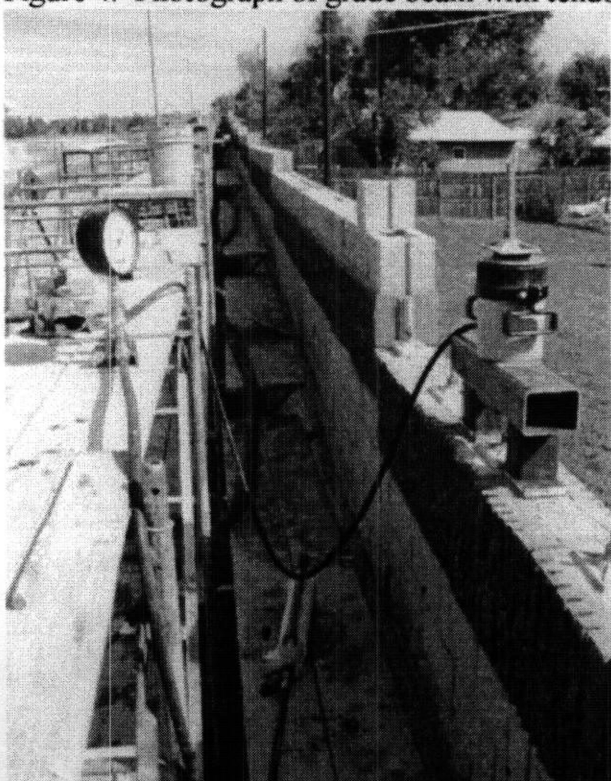


Figure 5. A hand hydraulic pump was used with a hydraulic ram to accurately tension the instrumented and intermediate tendons.

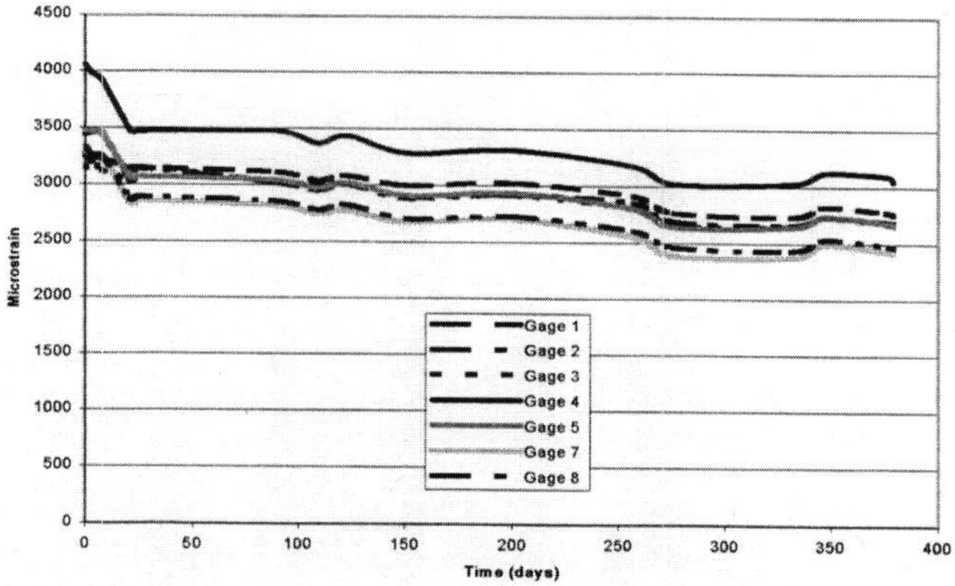


Figure 6. Long-term losses in 7 tendons measured over a period of one year.

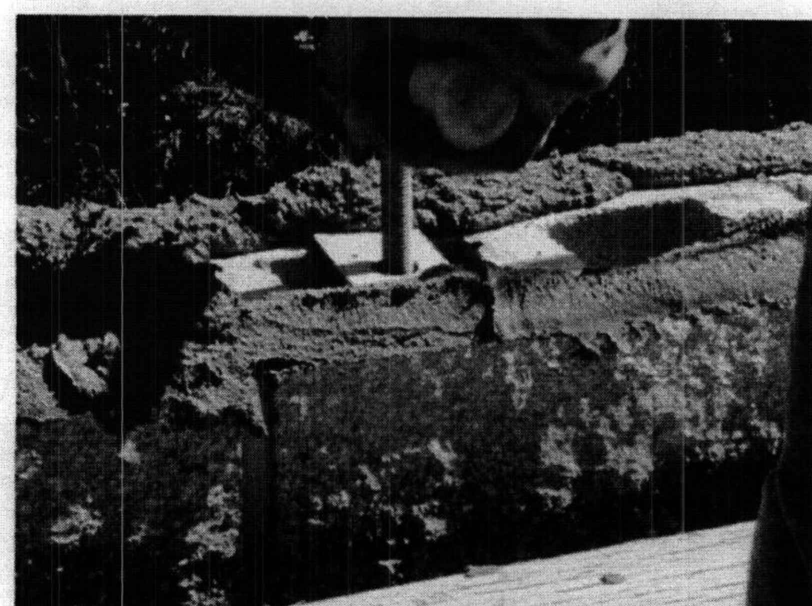


Figure 7. Photograph of the wall under construction. A tendon restraint plate can be seen in the center of the photograph.

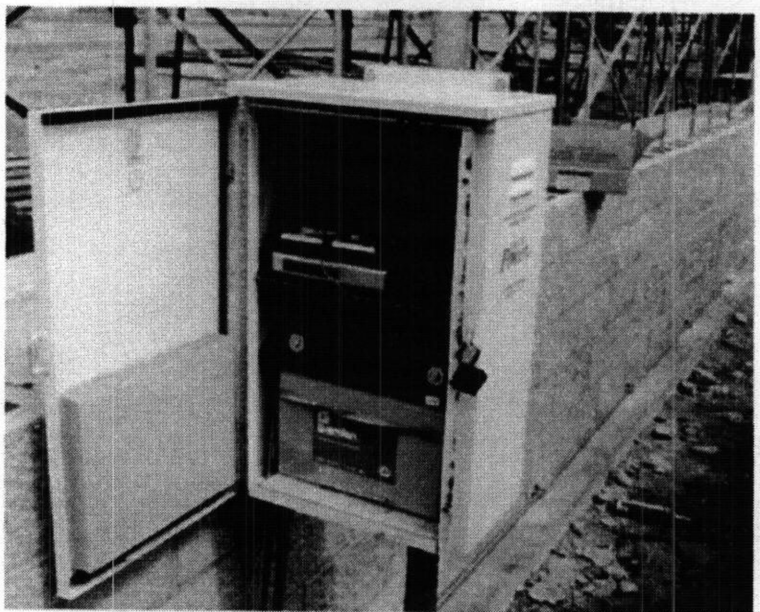


Figure 8. View of the instrument cabinet and the partially built post-tensioned wall in the background.

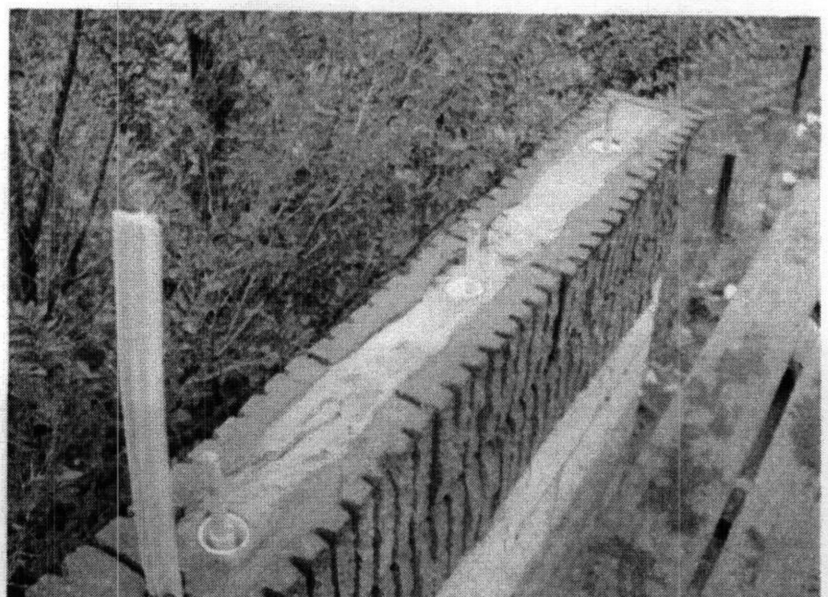
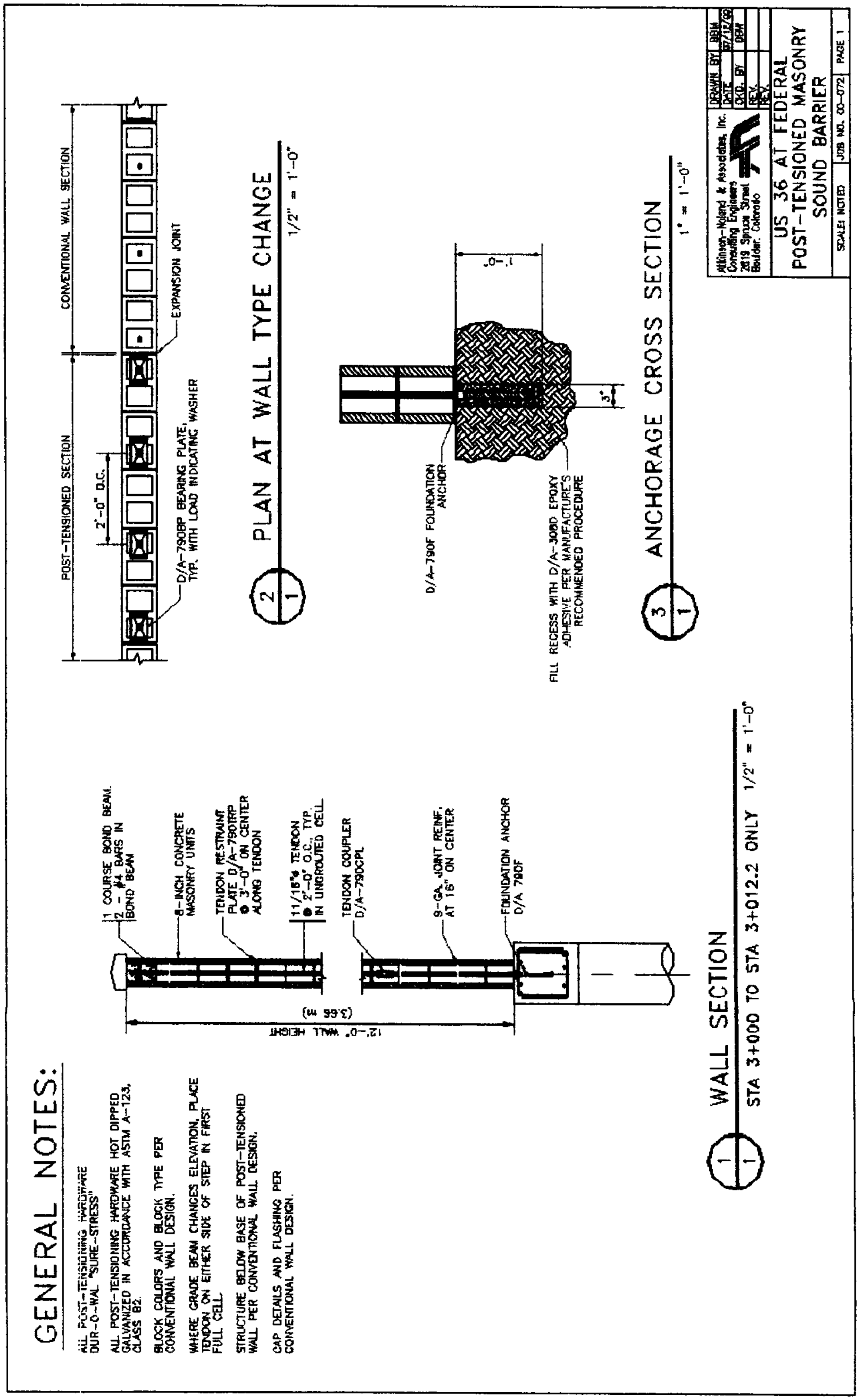


Figure 9. View of the top of the post-tensioned wall showing the sleeve inserted into the bond beam to prevent bonding of the tendon. Mortar beds were placed beneath the bearing plates to form the anchorage at this course. An additional ungrouted course was placed above the anchorage and the wall was topped with a precast concrete cap.


GENERAL NOTES:
ALL POST-TENSIONING HARDWARE DUR-O-WAL "SURE-STRESS"
ALL POST-TENSIONING HARDWARE HOT DIPPED GALVANIZED IN ACCORDANCE WITH ASTM A-123, CLASS B2.
BLOCK COLORS AND BLOCK TYPE PER CONVENTIONAL WALL DESIGN.
WHERE GRADE BEAM CHANGES ELEVATION, PLACE TENDON ON EITHER SIDE OF STEP IN FIRST FULL CELL.
STRUCTURE BELOW BASE OF POST-TENSIONED WALL PER CONVENTIONAL WALL DESIGN.
CAP DETAILS AND FLASHING PER CONVENTIONAL WALL DESIGN.
12'-0" WALL HEIGHT (3.66 m)
1 COURSE BOND BEAM. 2 - #4 BARS IN BOND BEAM
8-INCH CONCRETE MASONRY UNITS
TENDON RESTRAINT PLATE D/A-790TRP @ 3'-0" ON CENTER ALONG TENDON
11/16"φ TENDON @ 2'-0" O.C., TYP. IN UNGROUTED CELL
TENDON COUPLER D/A-790CPL
9-GA. JOINT REINF. AT 16" ON CENTER
FOUNDATION ANCHOR D/A 790F
1 1 WALL SECTION
STA 3+000 TO STA 3+012.2 ONLY 1/2" = 1'-0"
POST-TENSIONED SECTION
CONVENTIONAL WALL SECTION
2'-0" O.C.
D/A-790BP BEARING PLATE, TYP. WITH LOAD INDICATING WASHER
EXPANSION JOINT
2 1 PLAN AT WALL TYPE CHANGE
1/2" = 1'-0"
D/A-790F FOUNDATION ANCHOR
FILL RECESS WITH D/A-308D EPOXY ADHESIVE PER MANUFACTURE'S RECOMMENDED PROCEDURE
1'-0"
3"
3 1 ANCHORAGE CROSS SECTION
1" = 1'-0"
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CDOT RESEARCH

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