Soil Nailing: The MoDOT Experience

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Proceedings: Fourth International Conference on Case Histories in Geotechnical Engineering, St. Louis, Missouri, March 9–12, 1998.

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Paper No. 5.10

ABSTRACT

Soil nailing is a construction technique that is used to strengthen existing ground by installing grouted steel bars into the ground at closely spaced intervals. This increases the shear strength of the in-situ soil so that successive excavation lifts from top down can be made. The Missouri Department of Transportation (MoDOT) has overseen the construction of two temporary soil nail walls in the St. Louis metro area and one permanent wall in the Kansas City metro area. All three projects involved roadway widening under existing overpasses, which required the removal of the soil berm and construction of a soil nail wall next to the existing abutment. The ground conditions, construction methods and soil testing procedures for the projects varied widely from one another. These projects provided experience and valuable lessons in the design and construction of soil nail walls not only to MoDOT personnel, but also to the wall constructors and design firms involved in the projects.

KEYWORDS

Creep
FHWA
Grout
Production Test
Shotcrete
Test Excavation
Ultimate Bond Stress

INTRODUCTION

Soil nailing is a ground modification technique used to reinforce and strengthen existing ground. Reinforcement is accomplished by installing grouted steel bars into the ground at closely spaced intervals which increases the shear strength of the in-situ soil so that successive excavation lifts from the top down can be made. The process steps to constructing a soil nail wall stated in FHWA "Soil Nailing Field Inspectors Manual" are as follows:

1. Excavate cut (3 to 6 feet in height).
2. Drill holes for nails.
3. Install and grout nails.
4. Place drainage strips, initial shotcrete layers and install bearing plates and nuts.
5. Repeat process to final grade.
6. Place final facing (on permanent walls).

The Missouri Department of Transportation, as of January, 1997, has overseen the construction of three soil nail walls. Two temporary walls along Interstate 70 in the St. Louis metro area and one permanent wall under U.S. 71 in the Kansas City metro area. The ground conditions in St. Louis were entirely different than those encountered in Kansas City as were the construction methods and the soil nailing procedures used.

ST. LOUIS

The first two soil nail wall applications for MoDOT occurred on Interstate 70 at Lindbergh Boulevard and Fee Fee Road, just west of Lambert International Airport. A collector-distributor ramp was to be built along westbound I-70 under Lindbergh Boulevard and Fee Fee Road overpasses between the existing abutment and pier. This plan involved constructing cantilever walls next to the existing abutments with the removal of the north spillslope of Lindbergh Boulevard and

Fee Fee Road overpasses. Temporary shoring had to be devised by the contractor to stabilize and hold the bridges during the construction of the retaining walls. Subsurface Constructors, Inc. of St. Louis originated the idea of soil nailing for temporary shoring for the construction of retaining walls designated as A5316 (Lindbergh Boulevard) and A5318 (Fee Fee Road). Reitz and Jens, Inc., Consulting Engineers, were then contracted to design the temporary shoring systems.

The plans, construction special provisions, and design calculations were then submitted to MoDOT in July, 1994.
The Federal Highway Administration (FHWA) assisted the department in reviewing plans and special provisions. The plans and special provisions were accepted with some additions and changes to the soil nail test specifications.

The planned temporary shoring wall A5316 consisted of 150 nails with a minimum embedment length of eighteen feet installed at a 15 degree angle to the horizontal. The nail locations were spaced at maximum of four feet horizontally and vertically. This covered an excavation of approximately 20 feet in height and 150 feet in width. The nails were 1 1/4 inches in diameter with a planned minimum grouted hole diameter of 6 inches.

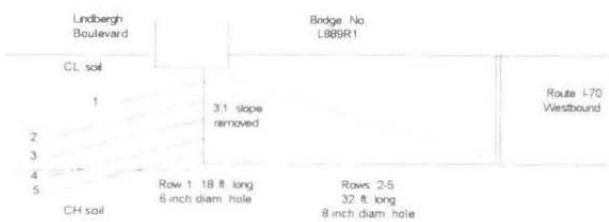

Fig. 1 Profile of Temporary Wall at Lindbergh Boulevard

The in-situ soil at the sites consisted of lean clay with liquid limits ranging from 30-39 and plastic indexes varying from 9 to 20. The soil parameters used by Reitz and Jens for design are as follows:

Internal angle of friction	$\theta = 29°$
Cohesion	$C = 300$ psf
Unit weight	$\gamma = 120$ pcf
Ultimate bond stress between grout and drilled hole	$\mu = 7.5$ psi

The ultimate bond stress between grout and drilled hole used in design was in line with calculated typical anchor capacities in soil. Reitz and Jens used Caltrans "Snail" computer program in design. Since soil nailing was new and untested, a factor of safety of 1.5 was required for temporary shoring. Before construction of the shoring could begin verification tests had to be performed. The purpose of this test is to verify that the design adhesion capacity can be attained by the chosen installation methods. During verification tests sacrificial test nails were tested to 200 percent of the design adhesion capacity.

The verification tests contained two parts; the creep test and pullout failure and followed FHWA test acceptance criteria: 1) The total movement at the maximum test load must have exceeded 80 percent of the theoretical elastic movement of the unbonded length, 2) Creep movement between 6 and 60 minute readings at the specified 150 percent of the design load must be less than 0.08 inch, 3) Pullout failure must not occur before or at the maximum test load with pullout failure defined as the inability of the test nail to maintain a constant test load without excessive movements.

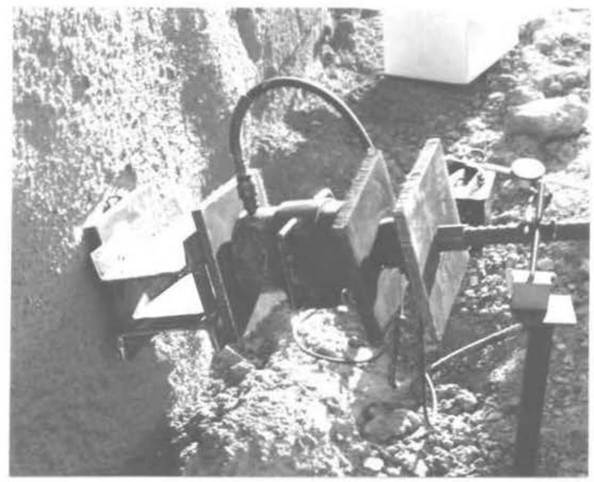

Fig. 2 Verification Test Setup at Lindbergh Boulevard

Two verification nails were installed just outside the shoring limits using a Klemm drill rig with a continuous flight auger. They were designated as VT-1 and VT-2. The twenty foot long nails with an 18 foot embedment depth had a 12 foot bonded length. The design load calculated for the test nail with 12 foot bond length, 6 inch diameter hole and ultimate bond stress of 7.5 psi was 10.2 kips.

The two verification tests were run on September 19, 1994. Both nails failed in creep and pullout. The first test nail (VT-2) failed in creep at 140 percent of the design load. Pullout failure occurred at 165 percent of the design load. From this pullout load, the ultimate bond stress was calculated to be 6.2 psi. The second nail (VT-2) failed in creep at 100 percent of the 10.2 kip design load. Pullout failure occurred at 114 downward movement had occurred. Monitoring later in the day showed that outward and downward movement had ceased.

It was recommended that on the remaining easterly half of the bottom excavation, a stabilizing berm be left in front of the face, the nail holes be augered, nails placed and the holes grouted before removal of the berm to the final face. It was also advised not to leave an excavation face open overnight, and that a face should only be excavated to the point where nail, drainage strip, and wire mesh installation along with shotcrete closure can be done in one shift.

The temporary wall at Lindbergh was completed in November, 1994. The cast in place L wall A5316 was completed in February, 1994.

Fig. 4 Completion of Wall A5316 at Lindbergh Boulevard

The construction of the temporary soil nail wall at Fee Fee Road went quicker with less problems due to applying what was learned from the soil nail wall at Lindbergh Boulevard.

The initial design of temporary shoring was similar to that of the Lindbergh Boulevard with corresponding nail spacing and inclination, dywidag bar diameter and grade. The planned soil grout bond stress was 6 psi, but the verification test nails at Lindbergh Boulevard had exhibited lower adhesion values, so a testing program was set up to accelerate verification testing for possible wall redesign.

A set of six verification nails were tested with different lengths, diameter and assigned soil grout bond stress values, that would correspond to acceptable factors of safety. The six nails were tested on February 9, 1995. The last test nail VT-6 (A5318) with an embedment depth of 32 feet, bonded length of 26 feet, 8 inch diameter and tested for an ultimate bond grout stress of 2.5 pounds per square inch successfully passed the creep and pullout portions of the verification test. The production nails for the Fee Fee Road temporary shoring were 32 feet long with 8 inch diameters.

The temporary shoring was completed in March, 1995, and the cast in place wall A5318 was completed in May, 1995.

KANSAS CITY

The site for the first permanent soil nail wall built for highway work occurred in Grandview, Missouri, just south of Kansas City on U.S. Route 71 and Truman Drive. The project that included the planned soil nail wall was for the City of Grandview, Missouri. The soil nail wall was for the widening of Truman Drive located under existing MoDOT bridges A3644 (northbound) and A3645 (southbound lane). The widening required the removal of the north spill fill slope of the Route 71 overpasses.

The permanent soil nail wall was approximately 232 feet long. The wall was divided into 3 sections, one main section running perpendicular to Route 71 136± feet long with two wing sections 48± feet long. The planned median wall height was 19± feet.

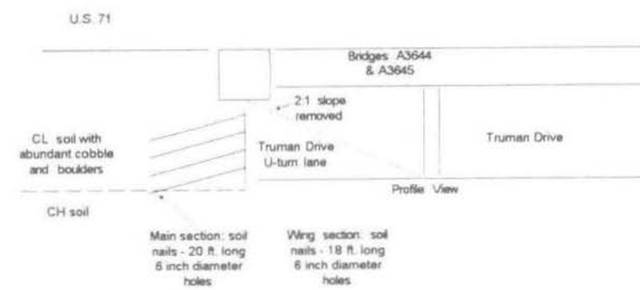

Fig. 5 Profile of Permanent Wall at Truman Drive

The wall design had conservative nail spacing. Typical nail spacing was 3.5 feet vertical and 3.5 to 4.0 feet horizontally. The plans called for 20 feet embedment of nails at the main section with 18 feet embedment in the winged sections. The nails were one inch epoxy coated 60 ksi steel bars installed into 6 inch diameter holes drilled at 15 degrees down slope from the horizontal. The wall consisted of 4 inches of shotcrete and 10 inches minimum of concrete. Three inclinometers were installed just behind the wall. One located in the median of U.S. 71, one on the shoulder of the northbound lane, and one on the shoulder of the southbound lane. The inclinometers were installed to a depth of 10 feet below the excavation. The inclinometers were to be read before excavation and before beginning each stage of excavation. Readings

TABLE I

TEST NAIL	DATE TESTED	SOIL-GROUT BOND ADHESION TESTED (psi)	DIAMETER	BONDED LENGTH	UNBONDED LENGTH	FAILURE MODE	SOIL-GROUT ADHESION ATTAINED (psi)
VT-4	10/17/94	3.2	8"	12'	8'	Creep/Pullout	2.67
VT-5	10/17/94	3.2	8"	17'	8'	Pullout	2.3
VT-6	10/20/94	3.2	8"	12'	8'	Creep	--
VT-7	10/21/94	2.0	8"	20'	11'	Creep	--
VT-8	10/21/94	2.0	8"	26'	10'	(Failed in pullout at 325% of design load)	5.3

percent of the design load. From this load failure, the ultimate bond stress was calculated to be 4.3 psi.

After installation of the two original verification test nails, Subsurface Constructors elected to install approximately 2/3 of the top row of 6 inch diameter nails with 18 feet embedment before the verification tests were run. They ran the risk of having to take out the nails and/or install additional nails at their own expense. After the failure of VT-1 and VT-2, Reitz and Jens, Inc. recommended finishing the installation of the first row of nails as designed with the remaining nails having 8 inch diameter holes. This would allow the designed 4' x 4' spacing and 18' embedment depth to remain in place and still have the needed factor of safety.

MoDOT agreed that the installation of the first row of nails with 6 inch diameter should be completed. The department recommended that a 10 inch diameter verification test nail be installed in addition to the eight inch diameter test nail in the case that the eight inch diameter nail failed the verification test criteria, there would have been no delay installing the ten inch diameter test nail and waiting for the grout to gain strength. Subsurface Constructors pointed out the fact that they did not have any 10 inch augers and that the cost would be prohibitive.

The third verification nail VT-3 was installed on September 27, 1996, and tested on September 30, 1996. The test nail had a bond length of 13 feet with an embedment depth of 18 feet from the pullout load, the ultimate stress was calculated to be 3.25 psi. The nail failed in both creep and pullout. Pullout occurred at 150 percent of the design load of 8.5 kips. This was based on an ultimate bond stress between grout and drilled hole of 4.3 psi.

Five more verification tests were run on increasingly longer nails (see Table I). With the passing of verification test nail VT-8, the final design for the bottom row of nails was 32 feet of embedment with an ultimate soil grout adhesion of 2.0 psi. This allowed for a final factor of safety of 1.5 in the snail runs. Construction then proceeded with the increased length of 32 feet and 8 inch diameters.

Fig. 3 Construction of Temporary Wall at Lindbergh Boulevard

Construction continued without problem until the installation of the bottom row of nails. The westerly half of the last lift was excavated on November 16, 1994. This last lift consisted of a fissured clayey loess. During the excavation, sloughing and back breaks occurred. The contractor drilled and grouted the nails in the excavation lift but did not shotcrete the face and attach the bearing plates and nuts. The face was left open overnight.

Early the next day a large tension crack was noticed on the west side of the wall running vertically behind the bridge abutment. Sloughing and overbreaks had increased and grew larger overnight. Discussion between FHWA, MoDOT, Subsurface Constructors, Kozeny Wagner, and Reitz and Jens personnel was immediately held and, upon the FHWA's recommendations, an excavator was used to unload approximately 4 feet of soil surcharge from behind the top of the wall. The placement of drain strip and welded wire mesh and application of shotcrete was done at the fastest possible pace. Survey monitoring was established to determine direction and amount of movement. The surveying program initiated in the morning of 11/17/94 revealed from presurveyed points that the wall had outward movement of 0.10 feet. Survey readings in the early afternoon revealed 0.02 feet of were planned for one week, two weeks, and four weeks after completion of the wall.

Potential problems with the planned wall came to light when the consultant design firm of Burns and McDonnell contacted the FHWA seeking advice and mentioned that the embankment material behind the wall contained cobbles and boulders. This statement prompted the FHWA to contact MoDOT due to problems encountered with soil nail installation in ground with obstructions such as cobbles and boulders which can cause instability at the cut face of soil nail excavations.

The geotechnical unit of MoDOT responded by requesting drilling logs and wall plans from Burns and McDonnell, checking the original boring logs for structures A3644 and A3645, and performing confirmation auger borings in the proximity of the planned wall.

The logs of borings, plans and provisions, and subsequent auger borings for the wall were reviewed by the geotechnical section and several recommendations were made for insertion into the plans and provisions. The most important recommendation being a vertical test excavation on the side slopes of the north bridge ends. The test excavation was to be observed at initial excavation, 24 hours later and, if possible, 48 hours later. A detailed description was to be made of the performance of excavation over time. The percentage of boulders and cobbles in the cut were to be noted for location and extent. The test excavation should have had the ability to stand vertical for at least one day. The test excavation would also have indicated drilling methods that would be needed to install the soil nails.

The main contractor was Ellis Construction Company, the subcontractor, Hydro Group, was chosen to construct the soil nail wall. Before construction could begin, verification nails had to be installed. The test nails were installed using a Krupp drill. The drill advanced the rotary cutting bit along with 6 inch casing. An uncased hole was attempted but the hole collapsed while extracting the drill stem. After removal of the cutting bit and drill stem, grout was pumped through the casing as it was slowly removed. The test nails had 20 feet of embedment with a bonded length of 15 feet and an unbonded length of 5 feet. The nails were tested for an ultimate soil grout bond stress of 1000 psf (6.9 psi).

Three test nails were installed on the side slope of the southbound lane outside the limits of the wall. The nails were tested to 200 percent of the design load of 15.7 kips. The requirements for a passing verification test were the same as the test nails on the St. Louis walls except for the creep test portion, a more stringent requirement of movement less than 0.04 inches between the 1 minute and 10 minute increment after loading. Creep was monitored between the 100 percent and 200 percent loading increment. A backing plate was installed between the reaction frame and excavated face.

Test nail 1 had 0.162 inches of movement between the 1 minute and 10 minute increment loading at 200 percent of the design load. The backing plate at this loading began to torque forward causing excessive movements to be measured by the dial gauge.

The other two remaining test nails exhibited creep movement of 0.03 inches or less between 100 and 200 percent of the design load.

The test nails were accepted and construction began with the excavation of the first lift. Shotcrete was applied to stabilize the face before drilling. The top row of nails were lowered 8 inches below planned elevation and drilled at a 12 degree slope instead of the planned 15 degrees. This was done to allow the drill rig under the bridge beams.

Due to the amount of cobbles and boulders in the excavation, obtaining a neat face was impossible. In some places, up to three feet of material sloughed off. These overbreaks resulted in an overrun of concrete when casting the final face.

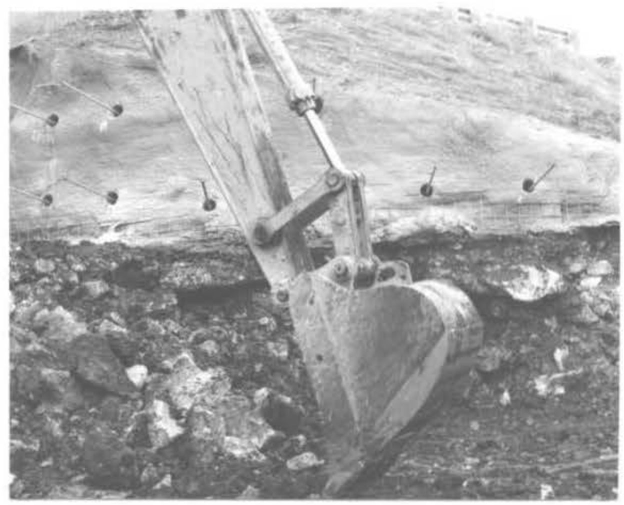

Fig. 6 Excavating Boulder Filled Slope at Truman Drive

All the holes for the nails were cased to keep them open. Grouting was done through the casing. The grout was a water/cement mix. This flowable grout found the voids in the embankment. Initial calculations called for 479 sacks of cement for the drilled holes, but in reality 2400 sacks were used.

On December 6, 1995, construction was observed by both MoDOT geotechnical personnel and Burns and McDonnell personnel. It was observed that the installed and grouted nails of the first two rows were not grouted out to the previously shotcreted face, leaving the shotcrete face hanging on the exposed face with no bond between the shotcrete facing and the nails. Only the production test nails should have had an unbonded zone between the shotcrete face and the nail. After discussion with MoDOT district construction personnel, the production test nails were designated and the rest of the nail holes were grouted as much as possible and the rest of the hole filled with shotcrete to the face. The plates were installed over the shotcrete and torqued down to complete the soil nail system.

Horizontal movements up to 1.5 H/1000 can be anticipated for a typical soil nail wall. For a 19 foot high wall, 0.028 feet (0.34 inches) of horizontal movement is to be expected. The inclinometer I-01 (at southbound lane shoulder) showed a maximum outward movement of 0.6± inches while inclinometer I-03 (at northbound lane shoulder) exhibited a maximum movement of 1.0± inches. This movement can be attributed to two factors: 1) There was a significant lag in time between nail installation and installing the bearing plates for the first two rows. The bearing plates secure the nail to the shotcrete face and completes the soil nail assembly. Without this connection there is no restraining element to prevent the outward movement of the wall. 2) Inclinometers also indicated movement when there was drilling in close proximity to the inclinometer. The boulders or cobbles located in the spill fill probably moved against the inclinometers during drilling.

The last of the major problems encountered was Hydro Group's decision to test the designated test nails after installation of all rows of nails. The job special provisions drafted by Burns and McDonnell did not address production nail installation and testing schedules. The common practice is to install a row of nails and then test the designated production test nails in that row before proceeding to install the next row of nails. Hydro Group ran the risk of having one or more production test nails fail and having to replace it and some or all of the installed nails between the failed proof test nail and the adjacent passing proof test nail. This would have been very difficult especially if the failed test nails were located on the top row of nails. A temporary berm would have to have been constructed to enable the drill to reach the height of the failed nails and replace them.

To test the upper rows of nails, welded supports were added to a tripod to allow support for the dial gauge for heights ranging from 4 feet to 14.5 feet. The pump and testing crew and inspectors stood in a cat shovel raised to the nail level. Ten percent of the nails in each of the four rows were designated as test nails. Of the approximately 200 nails, 19 were tested. All test nails passed exhibiting little or no movement.

The installation of shotcrete, drainage strips, nails and testing of designated production nails was completed in early January, 1996, with the cast in place portion being completed in February, 1996.

Fig. 7 Completed Retaining Wall at Truman Drive

Both soil nailing sites had very different soil and construction conditions and nail installation techniques, but had the common attribute of being great learning experiences. The lessons learned were: 1) Before design of the soil nail wall, if at all possible a test nail should be installed outside the limits of the wall and tested to pullout failure and the ultimate soil-grout bond stress can be calculated. This can be used in design rather than a value from a table. This would eliminate most failed verification tests and construction down time.
2) Excavation faces should not be left open overnight. A lift should only be excavated to the point where nail, drainage strip, and wire mesh installation along with shotcrete closure can be done in one shift. 3) Monitoring points or inclinometers should be installed or established to detect movements that send warning of a potential problem or possible failure in the making. 4) If the stability of the face is in question, a test excavation should be made to determine if the excavation has the ability to stand vertical for at least one day. 5) A row of installed nails, except for test proof nails, should be grouted full to the excavation face as much as possible and the remainder of the hole filled with low slump grout or shotcrete. The bearing plates should be installed over the shotcrete along with the nuts as quickly as possible to complete the soil nail assembly. This will help prevent straining and movement of the ground. 6) The test proof nails in each row should be tested and passed before excavating the lift below them. 7) Adopting the FHWA soil nail specifications will help eliminate many of the above noted problems. The FHWA specifications were built on experience with other soil nail projects and have been written to address potential problems before they become problems. 8) The most important thing when going into a soil nail wall project, either temporary or permanent, is to have a good working relationship, not an adversarial one, with the wall designer and contractor.

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