

# Injection Stabilization of Failed Highway Embankments

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Restoration of failed soil embankments along the Interstate highway system is a costly and time-consuming maintenance problem for many state highway departments. Unfortunately, few economical or easy solutions are available for repair and improvement of these failed earth embankment sections. In extreme cases highway bridges have been removed and the earth cross-sectional designs changed because attempts at solving existing bridge embankment slope failures were unsuccessful. In related studies to evaluate a new solution for this problem, Alabama, Arkansas, and Missouri have recently installed full-scale highway embankment test sections using the lime and lime/fly ash injection method of in situ soil stabilization. Presented in this paper is a discussion of the lime and lime/fly ash injection technology necessary for stabilization and restoration of typical failed embankment slopes. Also addressed are lime and lime/fly ash laboratory testing, injection materials selection, injection construction technology, and site evaluation. The first two highway embankment injection-stabilization projects were installed in Alabama and Arkansas in 1983. These are presented in a detailed case study format and their relative degree of success is documented after 2 years of service. The Missouri site stabilized in 1984 is also discussed and a preliminary assessment of its success potential is included. Discussed are the injection-stabilization evaluation techniques that have been derived from these demonstration projects, and suggestions for improvement of future projects are offered.

Lime and lime/fly ash (L/FA) injection stabilization for improving the engineering properties of embankment soil mass materials is currently being evaluated by highway maintenance engineers in several states. Pressure-injection stabilization with hydrated lime slurry has been used for more than 20 years to stabilize expansive clay soils, and within the past 8 years the addition of fly ash to the process has created numerous new applications for injection stabilization. Because the injection method uses hydraulically inserted injectors rather than predrilled grout holes, it is considerably faster and less expensive than most conventional grouting methods. The two main reasons for the present favorable economics of the L/FA injection-stabilization method are the ready availability of an inexpensive supply of fly ash and the development of new injection equipment. The anticipated continued use of large quantities of coal promises a steady supply of fly ash for future stabilization projects, and the continued development of new and better equipment for injection should promote future improvements in construction economics and performance.

Injection stabilization using lime and L/FA is now an accepted procedure used throughout the United States by most major railroads to stabilize roadbeds and embankments to

reduce chronic high-maintenance track problems. Stabilization of expansive clays for building foundations and pavement structures using injection stabilization has also grown rapidly during the past decade. Although use of this system is perhaps most prevalent in the southern and middle states, injection-stabilization is being used increasingly in the eastern and western states as more emphasis and construction dollars are shifting to maintenance and rehabilitation of the transportation infrastructure. There are few alternatives for in-place soil treatment, and injection stabilization is suitable for both pretreatment and repair and renovation. In almost every case injection stabilization is the most economical method available.

The availability of fly ash as an inexpensive grout material has encouraged contractor research and development of equipment and procedures for its use in the L/FA-injection method of soil stabilization. A U.S. patent for injection stabilization with lime and fly ash slurry mixtures was issued to the Woodbine Corporation in 1978. Initially, injection stabilization with L/FA slurry was an alternative stabilization method to be used when lime slurry pressure injection (LSPI) was not appropriate. Gradually, however, it has become obvious that there are many uses for L/FA injection that are not merely alternatives to LSPI but an improvement over other alternatives. The stabilization of highway embankments, discussed in the case histories portion of this paper, is one important use of injection stabilization using lime and L/FA that is currently under development. Limited research is in progress to generate geotechnical engineering data and to promote improved performance and economics of the method.

## INJECTION TECHNOLOGY

The most noticeable difference between pressure-injection stabilization and conventional grouting is in the equipment technology. With pressure injection, typically, large volumes of slurry grout, up to 23,000 gal, are bulk mixed and injected into the soil using various types of hydraulic and mechanical injectors capable of penetrating to depths of 40 ft or more. Conventional grouting more often mixes small batches of cement grout that is pumped through stationary grout pipes that have been placed in predrilled holes. Consequently it is a slower and usually more costly technique than injection stabilization.

## Equipment

A truck-mounted injection vehicle with three 40-ft injectors is shown in Figure 1. This self-contained unit has a 2,000-gal slurry tank with a mechanical agitation system and a high-pressure pump capable of pumping more than 3,000 gal/hr at

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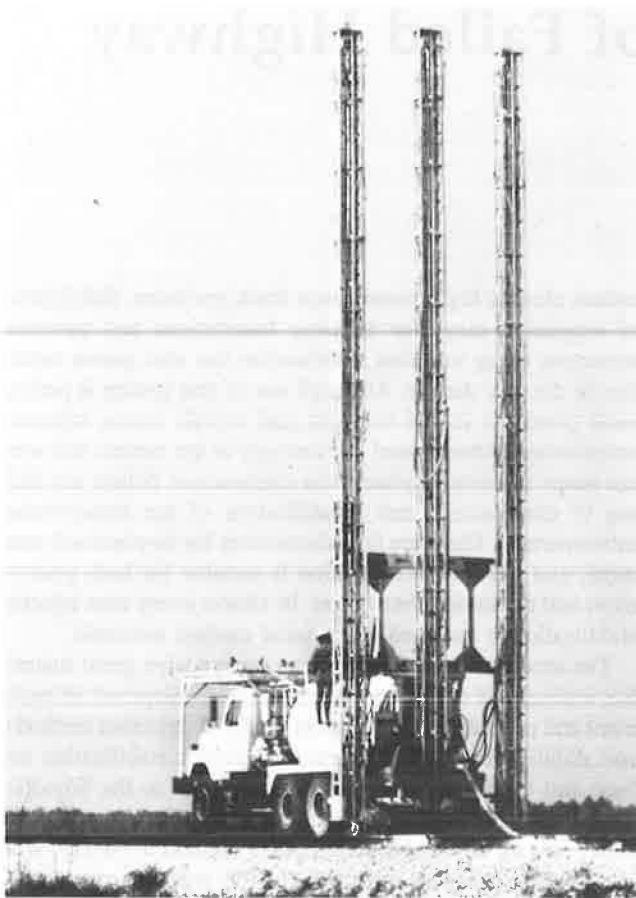


FIGURE 1 Injection truck, 40 ft.

50 to 200 psi. It will operate on railroad tracks, paved roads, or compacted surfaces. Other injection vehicles are mounted on rubber-tired or crawler tractor machines (see Figures 2 and 3) for off-road capability such as embankments or construction sites. The bulk slurry mixing tanks are usually 10 ft in diameter by 30 to 40 ft long and are used for mixing either lime or L/FA slurry. These tanks are portable and are easily transported from one site to another with a tractor truck. Some tanks (Figure 4) are equipped with high-pressure pumps so that slurry can be



FIGURE 2 Rubber-tired off-road injection machine operating on an embankment.



FIGURE 3 Trac-powered injection equipment on highway embankment.

pumped directly to the off-road injection machines without going into a secondary holding tank.

The economy and convenience of jobsite lime slaking is now possible with new portable batch slakers, shown in Figure 5. Although these are relatively new to the marketplace, the system has been developed and proven over the past 5 years and is in daily use on stabilization projects. This portable batch slaker is a high-capacity lime slaker that can convert up to 25 tons of quicklime into 30 tons or more of hydrated lime slurry



FIGURE 4 Slurry mixing tank on site in Arkansas.



FIGURE 5 Portable batch high-capacity lime slaker.

in less than 1 hour. It is a totally enclosed, dust-free system that is simple and safe to operate.

In addition to the above mentioned equipment, there are many other ancillary pieces of equipment such as rollers, scarifiers, slurry transport trailers, slurry transfer pumps, conveyors, and vacuum material handlers that are needed to support the logistics of injection-stabilization projects.

### Injection Materials

The basic materials for injection stabilization are lime, fly ash, water, and additives. Quality control and design of slurry mixes are of prime importance. All materials should be purchased according to specifications and tested before use.

#### Lime

In this paper the term lime refers to oxides and hydroxides of calcium. Two types of commercially available lime, calcitic quicklime ( $\text{CaO}$ ) and high-calcium hydrate [ $\text{Ca}(\text{OH})_2$ ], are used on injection jobs. The quicklime must be slaked before mixing, whereas the hydrated lime, which comes in a dry powder form, is ready for immediate mixing. Laboratory testing can be used to indicate effectiveness of any particular commercial source of lime, but it should be emphasized that the quality of the fly ash has a much greater influence on L/FA pozzolanic reaction than does the lime. It can be stated that most commercially available limes meeting ASTM C977 are appropriate for L/FA injection if quality reactive fly ash, which meets the laboratory test series for strength and durability criteria, can be economically obtained.

The portable batching system of lime slaking allows the use of calcium oxide (quicklime) as the raw material that is converted into hydrated lime slurry at the jobsite. According to Boynton (1), there are several advantages to using this system:

Slaking quicklime at the job site with a generous excess of water improves dispersion of the hydrate particles, contributing to finer particle size and slower settling qualities.... In addition...equal importance is attached to reasonably high hydration temperature and rapid agitation in achieving fineness in particle size.... As a consequence, high surface area exerts a profound effect on chemical reactivity, settling rate, putty yield, plasticity, and the generally desired qualities of hydrates for most purposes.... The consensus among authorities is that surface area is the most reliable criterion on reactivity of hydrates; the higher this value, the greater the reactivity.

#### Fly Ash

Fly ash is "the finely divided residue that results from the combustion of ground or powdered coal and is transported from boilers by flue gases" (ASTM Specification C593). Fly ash is collected from the flue gases by either mechanical or electrostatic precipitation devices.

Fly ash is a pozzolan and is defined as "a siliceous or siliceous and aluminous material, which in itself possesses little or no cementitious value, but which will, in finely divided

form and in the presence of moisture, economically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties" (2).

#### Water

Water used in mixing lime and L/FA slurry should be clean and free from injurious amounts of oils, acids, alkalis, salts, organic materials, or other substances that may be deleterious to the soil reactions desired. If nonpotable water is proposed for use, and if there is any doubt concerning compliance with the preceding statement, laboratory tests should be conducted to compare the reactions of similar specimens incorporating potable water.

#### Additives

It is well known that the normal curing of L/FA slurry is dependent on time, temperature, and moisture variables. The chemically accelerated curing of L/FA grout is dependent not only on these three factors, but also on the type and amount of added chemical accelerator. L/FA accelerator can be batch mixed in a slurry tank with 20 to 30 tons of L/FA dry solids and water to increase the early strength of Type C fly ashes. Also, in some instances, an accelerator will increase the pozzolanic reactivity of Type F fly ashes so that they can be used when Type C fly ash is not available. All fly ash should be tested with proposed mix ratios in the laboratory before use. Best results are obtained by mixing the L/FA slurry continuously for 4 hours and withdrawing a sample every hour to evaluate mixing effects. Some fly ash mixtures will require an additive to retard the initial set of the slurry. Some fly ash is so reactive that it will flash set in the mixing tank and some will lose strength with continuous mixing. Proper use of retarders will delay the initial set until the slurry is pumped into the ground.

### EVALUATION OF CANDIDATE SITES

The evaluation of candidate embankment sites for injection stabilization is best accomplished through the joint efforts of highway engineers and the injection contractor. During the past 20 years, several participating research and development engineers have worked to develop soil tests for site evaluation and for predicting success of potential injection-stabilization applications. These tests are modifications of standard soil tests to measure the stabilizing effects of lime and L/FA seams and supernate penetration. As a result of these efforts a test methodology that satisfies current needs for a soil test program has been developed. The new soil tests are relatively inexpensive and straightforward so that numerous tests can be performed. They have been found to give consistent, repetitive results that can be related directly to engineering soil properties. As a rule (a) compression and shear strength tests should be used to evaluate sites with low-strength soils, (b) swell tests should be used to evaluate sites with expansive clays, and (c) consolidation tests should be used to evaluate sites with potential settlement problems. Other standard classification tests that give an

indirect indication of soil properties, such as Atterberg limits, are not recommended.

## Testing

Soil testing for lime injection stabilization is an important part of this technology. The testing program is used to help determine whether lime slurry pressure injection (LSPI) improves the problem sites adequately and it can also be used as a guide in preparing injection specifications. The tests provide data to help quantify the degree of site improvement that might be expected from injection stabilization; however, it is obviously not possible to obtain a one-to-one correlation between laboratory tests and field results.

Engineers have made a significant contribution to LSPI testing by developing and refining evaluation tests. These test procedures, which simulate the LSPI field condition, involve treating soil samples with lime slurry to form a glaze or seam, then curing and testing. The test results of the lime glaze and seam-stabilized test samples are then compared with test results from nontreated control samples. The amount of dry lime solids used in LSPI evaluation testing is usually 1 percent of the soil dry weight. This has been determined to be the maximum amount of dry lime injected during a single-stage LSPI injection spaced on 5-ft centers. The laboratory tests can also be used to evaluate the benefits of a second injection pass or even a third injection. The test results can then be used as input for preparing appropriate job specifications. Lime glaze and seam-stabilized samples can be used in swell, consolidation, and compression testing. This method of sample testing was developed jointly by researchers at Woodbine Corporation and the University of Arkansas. The lime-glazed and seam-stabilized method can be used with either undisturbed or remolded soil samples. As the lime-treated samples are to be compared with the untreated control samples, both will serve the purpose of evaluating lime/soil reactivity and predicting strength, swell, and stiffness improvements.

## Lime/Fly Ash Soil Testing

The purpose of the L/FA soil-testing program is to determine the potential improvement L/FA-slurry injection will produce in the candidate site and to guide in preparing appropriate specifications. These test procedures, which attempt to simulate L/FA-injection results, involve treating soil samples with the L/FA slurry to form seams, then curing and testing. Test results from the L/FA-treated samples are compared with control samples to evaluate the potential benefits of L/FA injection stabilization and with LSPI results when appropriate, to aid in selecting the most appropriate injection material.

## Investigation Plan

The investigation plan for each site should include a preliminary surface investigation followed by development of a plan for detailed subsurface investigation and laboratory tests. The subsurface investigation should be scheduled to allow ample

time for sample preparation, curing, and testing. The actual injection project should not proceed until all necessary laboratory tests of soil and materials are satisfactorily completed. As presented later in this paper under case histories, failure to test the actual materials to be used can result in unsatisfactory material performance. Time and money saved by omitting necessary engineering, testing, and planning steps is soon forgotten if a material failure occurs.

## EVALUATION TEST

The laboratory testing program for injection stabilization currently uses several test procedures. These tests are described in the sections that follow.

### Glaze-Stabilized Compression Test

The glaze-stabilized compression specimen is shown in Figure 6. The purpose of the glaze-stabilized compression test is to determine the increase in sample compression strength provided by the reinforcement from the glaze-stabilized coating. The lime-glaze compression test was first reported by Blacklock (3). Test samples can be prepared from either undisturbed or remolded soil. Control test samples are prepared and cured identically to the treated samples.

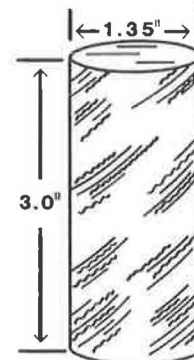


FIGURE 6 Glaze-stabilized compression specimen.

Detailed instructions for lime-glaze stabilized compression tests are given by Boynton and Blacklock (4). The instructions for L/FA glaze are identical except for the substitution of L/FA slurry for lime slurry.

### Seam-Stabilized Compression Test

The seam-stabilized compression specimens are of two types, straight seam (Figure 7) and angle seam (Figure 8). The straight-seam sample is designed for evaluation of the compression strength-reinforcement component of the stabilized seam, and the angle-seam sample is designed for evaluation of the shear-reinforcement component of the stabilized seam. Typically, the contribution of both compression and shear will be used in repairing cracks in embankment failures. These



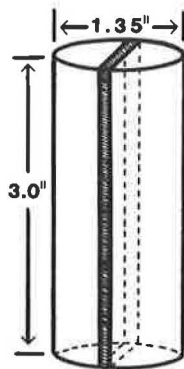


FIGURE 7 Straight split-seam-stabilized compression specimen.

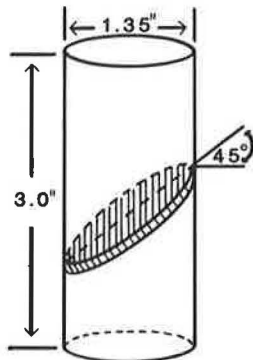


FIGURE 8 Angle split-seam-stabilized compression specimen, shear reinforcement.

samples can be prepared from undisturbed soil samples but experience indicates a preference for remolded samples. These can also be glaze-coated to allow evaluation of combinations of shear, tension, and compression strength reinforcement. Seam-stabilized compression test instructions are given by Boynton and Blacklock (4).

#### Glaze-Stabilized Consolidation Test

The glaze-stabilized consolidation specimen shown in Figure 9 is for the purpose of evaluating the settlement improvement provided by lime-injection stabilization of natural embankment soils. This sample is prepared by cutting undisturbed samples and then applying a glaze-stabilization coating of lime or L/FA slurry to both the top and bottom surfaces of the samples.

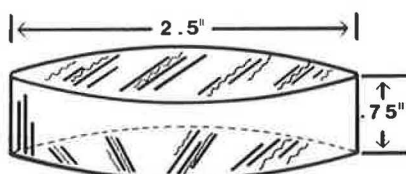


FIGURE 9 Glaze-stabilized consolidation specimen, settlement reinforcement.

#### Seam-Stabilized Swell Test

The seam-stabilized swell specimen shown in Figure 10 is for the purpose of evaluating the swell-reduction function of lime or L/FA seams. This sample is prepared by remolding soil and placing a lime slurry seam in the center. Seam-stabilized swell test instructions are given by Boynton and Blacklock (4).

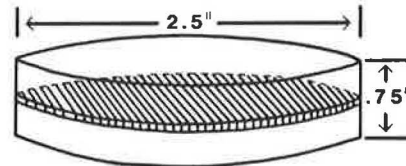


FIGURE 10 Seam-stabilized swell specimen, expansion neutralization.

#### Material Test

In addition to the soil-stabilization tests discussed earlier, testing of all source materials is necessary. It is well known that there is considerable variation in fly ash reactivity and performance. The seam and glaze tests will help evaluate these performance properties; however, it is always best to evaluate the materials separately by performing a series of cube tests or compression cylinder tests. These tests should evaluate time, temperature, and strength variables for different mixing times, mix ratios, and material suppliers.

#### EMBANKMENT FAILURE MECHANISMS

Embankment failures can be divided into two general groups, those occurring in embankments built on foundations of soft clay and silt, and those built on stiff soil foundations (5). Embankments built on foundations of soft clay and silt are typified by cracks originating in the vicinity of the bottom of the interface between the fill and the top of the foundation, as shown in Figure 11; whereas, those built on hard or stiff foundations are typified by surface failures originating with surface cracks, as shown in Figure 12. A study of the origination, location, and growth pattern of embankment cracks is paramount to understanding the need for different renovation techniques because the inherent soil strength may not contribute to the stability of the embankment slope if the embankment fill is substantially cracked. Therefore, crack mending can be critical to embankment renovation.

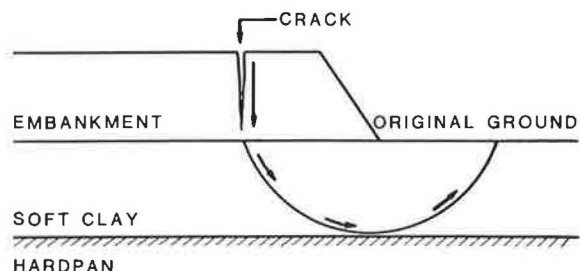


FIGURE 11 Failure surface passing through crack in embankment.

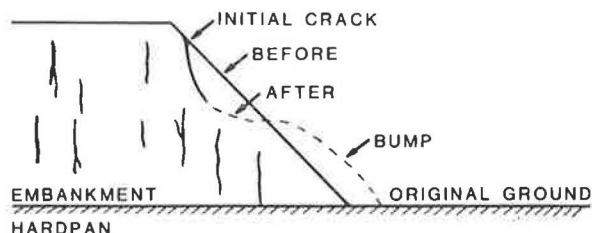


FIGURE 12 Failure surface passing through crack.

There are certain characteristics of lime and L/FA seams that should be recognized. Figures 13–16 illustrate the concepts of how crack repair is made by LSPI and L/FA seams, respectively. These seam-stabilization concepts were given important consideration in the design of the seam- and glaze-stabilized laboratory evaluation tests previously discussed.

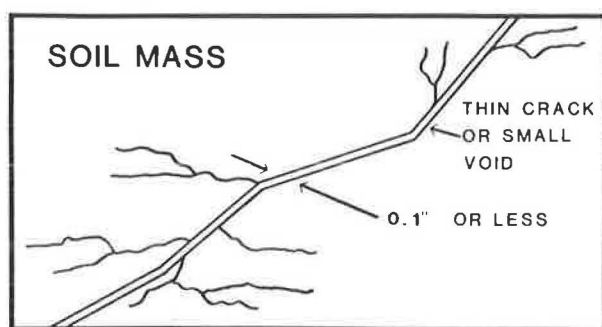


FIGURE 13 Soil crack before stabilization with lime slurry pressure injection.

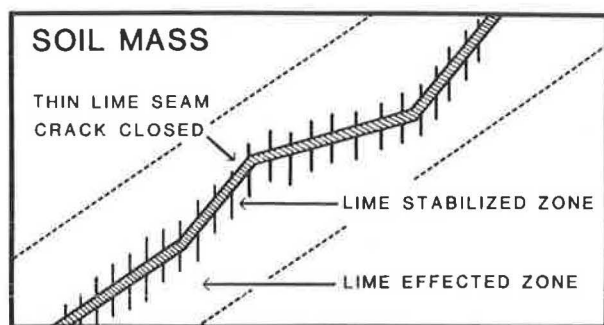


FIGURE 14 Soil crack after stabilization with lime slurry pressure injection.

Injection stabilization increases the strength of embankments by adding reinforcing strength and mending existing cracks, allowing peak strength of the embankment fill and the foundation subsoil to be mobilized simultaneously, thus reducing progressive failure effects. Cracks may develop in embankments because of excessive tensile stresses in the underlying fill due to differential settlements or because of shrinkage stresses due to drying. Many tension cracks frequently begin at the bottom of the fill, progress upward, and may not be detected until the embankment is seriously failing. The injection-stabilization method has been developed to treat cracks and planes of weakness in situ, even those cracks that are not visible from the surface (Figure 17). In general, cut and replace does not mend

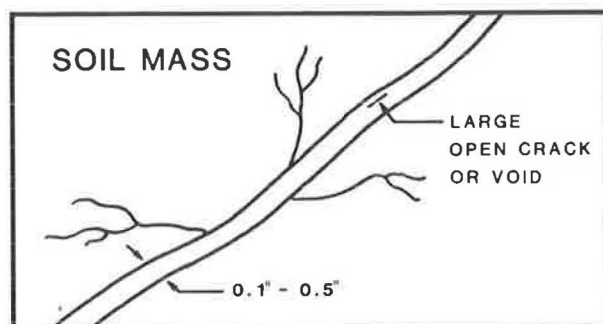


FIGURE 15 Large soil crack before stabilization with lime/fly ash injection.

existing tension cracks in the undisturbed mass below the cut and those cracks can continue to grow, propagating into the newly placed material. Because of the impact of embankment cracking on the stability of fills, the laboratory-testing program must evaluate the effectiveness of injection grouts for seam reinforcement, crack filling, and prevention of crack growth. Split-glazed lime or L/FA compression tests can be used to evaluate the benefits of slurry to repair cracks and increase embankment strength by adding tensile, compression, and shear reinforcing strength. Seam tests can be used to evaluate the benefits of hardened seams to stop crack growth, mend existing cracks, and prevent formation of new cracks.

Safety factors can be shown to increase rapidly with increase of fill strength. Computerized structural analysis methods can be used to analyze the strength effects of stabilized lime-soil or L/FA-soil seams, given the properties of the soil mass. Slope-

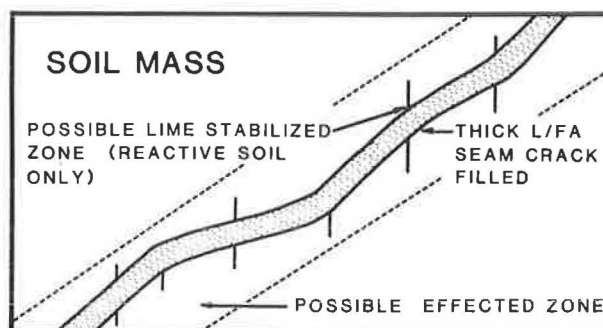


FIGURE 16 Large crack after stabilization with lime/fly ash injection.

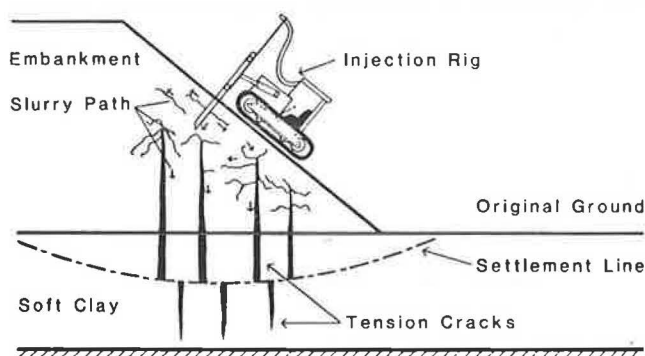


FIGURE 17 Tension cracks filling with lime/fly ash slurry.

stability analysis can be used to calculate safety factors for both cracked and uncracked embankment fills.

## EMBANKMENT STABILIZATION PROCEDURES

The procedures for injection stabilization of highway embankments have evolved over the past several years with changes and improvements being made during the recent highway case studies programs. The procedures currently recommended for highway embankment stabilization using injection stabilization methods are as follows:

1. The failed embankment, as shown in Figure 18, is bladed and compacted into shape and drainage is corrected.
2. The surface is proof rolled and compacted at prescribed limits of moisture and density, perpendicular to the face of the slope.



FIGURE 18 Slope failure on highway embankment.

3. The injection pattern is graphically planned to allow for injection variables of depth, single injection, double injection, lime or L/FA, or a combination of both. The injection sketches should then be prepared, as shown in Figures 19 and 20.

4. Each site is injected in a prescribed sequence usually beginning with the longitudinal rows at the toe of the slope and then progressing to transverse rows along the face of the slope, as shown in Figure 21. Double-injected areas require a short stage wait before injecting the diagonal off-set hole pattern.

5. Following the injection, the lime and fly ash mixture on the surface of the site is scarified, or disked, into the top 6 in. and then compacted to seal the surface.

6. Grass should be planted when the proper growing season arrives. The mixing and compaction, described in item 5 above, should prevent any excessive surface erosion from occurring until the new vegetation is established.

## CASE HISTORIES

The following three highway embankment case histories of injection-stabilization projects are presented to illustrate the adaptability and versatility of the method. Injection stabilization has many other geotechnical applications. It has been used successfully on: (a) railroads, (b) dikes and levees, (c) runways, (d) streets and parking lots, (e) pre-treatment, of building foundations, (f) construction dewatering, and (g) renovation of building foundations. Several of these projects have already been presented in case studies (4, 6, 7, 8).

### Case 1: Evaluation of Lime/Fly Ash Pressure-Injection of an Alabama Roadway Embankment

#### Preliminary Investigation

The site is located in Lowndes County, Alabama, along I-65 about 30 mi south of Montgomery (9). The area is located at the approximate contact of the Ripley Formation and the cretaceous prairie Bluff Chalk. Both of these formations are in the Black Belt or Black Prairie physiographic district and contain a large amount of calcium carbonate and a high percentage of smectite in the clay fraction. The slide was located in a side-hill section and was approximately 385 ft long as measured along the toe of the slope. The distressed embankment section traverses the outlet end of a roadway culvert. Once the stream discharges from the culvert the water runs parallel to the toe of the slope for approximately 300 ft; however, the significance of this orientation was not recognized until the area was cleared of undergrowth during the construction phase. This section of Alabama experiences approximately 50 in. of rainfall per year so the toe of the slope is usually wet.

#### Design Criteria and Procedure

Woodbine Corporation investigated the site and proposed using L/FA injection stabilization with Type C fly ash produced in Texas for the project. However, it was subsequently pointed out by Alabama Highway Department engineers that the transportation cost of shipping Type C fly ash would offset any eco-

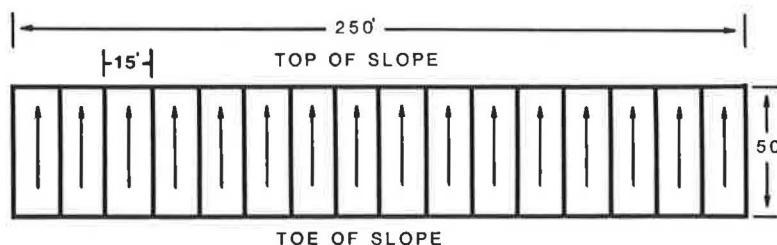


FIGURE 19 Injection equipment progress chart.

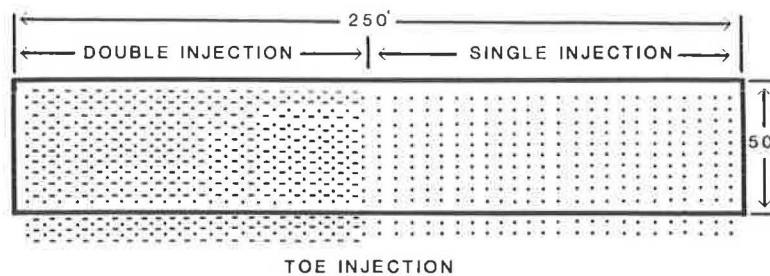


FIGURE 20 Embankment injection patterns.

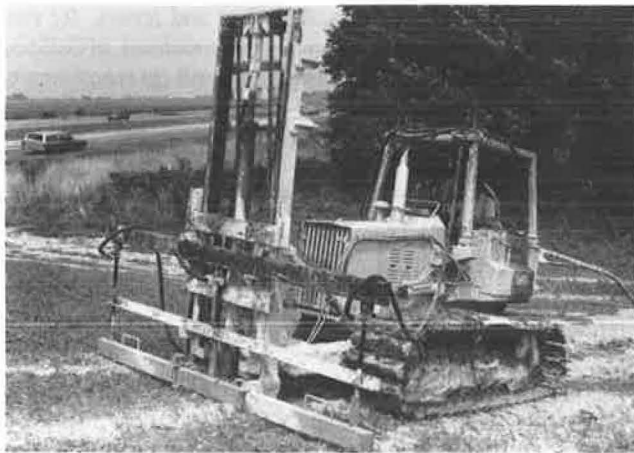


FIGURE 21 Injection rig advancing on injection pattern.

nomic advantage of this type of treatment. Therefore, the decision was made to use locally produced Type F fly ash, and to add 1 percent Type I portland cement to enhance the strength gain. The lime used in this project was high calcium hydrate.

#### Construction Criteria and Procedure

State personnel prepared the site by removing vegetation and smoothing and dressing the face of the slope. This included obliterating the slide scrap and backfilling the small stream course along the toe of the slope. The culvert's headwall and wingwall were also removed (one wingwall had previously been removed by the force of a slide) to better accommodate the injection equipment. The slide area was approximately 385 ft long and the face of the slope was 105 ft long.

After the site was prepared, the contractor moved an 18,000-gal slurry mixing tank to the site. Water, purchased from the city of Greenville, was hauled to the site and pumped into the tank. Lime and fly ash were then transported in bulk to the site and pneumatically unloaded into the slurry tank. The lime was pumped into the mixing tank first to help suspend the heavier fly ash. After the slurry was sufficiently mixed it was pumped to a smaller holding tank mounted on an injection rig capable of injecting to a depth of 40 ft. The cement was added to the slurry in this holding tank. Injections were made at the edge of the pavement to depths up to 40 ft and on the face and toe of the slope to a depth of 10 ft using a crawler-tractor injection machine.

The injection pattern on the first injection was 5 ft on center

and 10 ft deep on the face and toe of the slope. The injection was performed by pushing the injector rods and pumping the slurry to refusal at 18- to 24-in. intervals. Refusal was defined as that point at which slurry began to run freely at the surface from previous injection holes or from areas where the surface soils were fractured. At times the slurry would erupt from the ground more than 50 ft from the injection point. A total of 122 tons of fly ash and 45 tons of hydrated lime were initially injected. Based on the previous evaluation of the soils at the site by the contractor and the results of the laboratory tests, the decision was made to use hydrated lime slurry for the second injection. The same injection pattern was used as on the first injection, and placed diagonally between the first injection points. A total of 76 tons of hydrated lime were injected during the second injection. This work was completed in June 1983.

Throughout the injection process continued movement of the slope occurred, evidenced by the appearance of numerous surface cracks over the face of the slope, some as wide as 3 in. at the surface. Because of the continued earth movement during injection and the apparent unstable condition of the slope, Alabama Highway Department personnel elected to add a rock buttress at the toe of the slope along the stream course soon after injection, thereby disqualifying it as a viable injection-stabilization demonstration project. After the buttress was constructed, the embankment slope was benched. During this benching operation, the presence of lime seams was evident in the face of the benches. Seams were also evident in the extruded Shelby tube samples.

#### Conclusions and Recommendations

It is the opinion of the authors that a lack of appropriate engineering material testing and site evaluation contributed to the lack of success of this project. The following points and recommendations are made:

1. The decision to change from Type C to Type F fly ash was based on economics rather than engineering principles.
2. This was not a proper site for an injection-stabilization demonstration because of the presence of the discharge culvert at the toe of the slope. This was not detected during site selection because of the heavy vegetation present.
3. It is recommended that in future research projects of this type a site be chosen that is entirely made up of embankment with no complicating structures in the immediate area.
4. The duration of the research should be for a period long



enough to allow monitoring of curing and measurement of performance over several years.

### Case 2: Arkansas Highway Earth Embankment Lime/Fly Ash Stabilization

Highway embankment surface slides are a recurring maintenance problem throughout the state of Arkansas. Approximately 65 slides occur each year in District 1 in eastern Arkansas. In this region the soil type is a clay or silty-clay alluvial river deposit of high montmorillonite content. The slope failures are usually shallow, surface-type slides 10 ft deep or less with a classical configuration. They generally do not destroy the pavement surface, but if left untreated, they can eventually lead to a complete roadway failure. Highway maintenance economics have dictated that very few of these slides can be treated to achieve correction because economical permanent methods have not been available. Thus, a majority have been temporarily repaired by simply pushing the failed material back in place. In many instances, this has resulted in repeated failures at a single site within a given construction season.

#### *Demonstration Specifics*

In 1982 a failed site was selected at the Bolling Road bridge overpassing I-40 near West Memphis, Arkansas, to be used in a federally sponsored L/FA pressure-injection demonstration project. The soil used to construct this embankment originally was a grey, highly plastic, partially organic clay, classified A-7. The slope had failed repeatedly over the past few years, including two failures that occurred in the months before injection. The principal area of failure was near the bridge abutment, where a large slide had occurred that was 8- to 10-ft deep with a ripple effect that went down to the toe of the slope (Figure 18). The length of the slope selected for the demonstration was approximately 500 ft. The entire face, toe, and cone of the slope containing a surface area of 28,778 ft<sup>2</sup> was treated with a double injection of L/FA slurry on a 1½-ft diagonal offset blanket-grid pattern. The injected mixture contained 248,700 lb of Type C fly ash and 85,600 lb of hydrated lime mixed with water and surfactant to form 101,320 gal of L/FA slurry. The total cost for injection was \$14,000, which is \$4.66/yd<sup>2</sup> (10).

#### *Construction Procedure*

The L/FA injection procedure was conducted in stages, preceded by the highway department's maintenance forces pushing the slope back into place in order for the contractor to have a smooth workable surface. As the project began, the contractor double-injected the toe of the slope to a depth of 7 ft. The first pass was spaced on 5-ft centers and the second was spaced on the diagonals between the first injections. Next, the contractor double-injected the face of the slope to a depth of 10 ft in the same way as on the toe of the slope.

After the injection operation was completed, the L/FA slurry left on the surface of the slope was scheduled to be mixed with the soil, and recompacted by others. Later inspection visits to

the site revealed that final proof rolling was never completed; therefore, no compaction was accomplished. This was required to ensure that there were no soft spots in the near-surface materials and that the surface was properly sealed. The omission of this last important step was determined to be the cause of the shallow surface slough that occurred 18 months later.

#### *Monitoring Equipment Installation*

The monitoring equipment installed by the Arkansas Highway Department after injection consisted of two slope inclinometer tubes and 10 temperature and moisture sensors for both the L/FA-injected slope and the control slope situated across the road. The moisture sensors were placed at three separate locations at various depths on both the injected and control slopes. Each sensor was to give the temperature and electrical resistance from which the soil moisture content could be determined. These sensors did not function properly and were later abandoned. The slope inclinometer tubes were installed at two locations to a depth of 40 ft on both slopes. The slope inclinometers were to measure subsurface movement that could not be detected by visual surface measurements. It is not known if any data were obtained from these installations.

#### *Evaluation Period*

The embankment performance-monitoring plan called for inspection four times a year for 5 years, including evaluations during both dry and wet periods. Inclinometer and moisture gauge readings were planned, and visual indications of surface and subsurface failures were to be noted on both the control and injected embankments. Soil samples were to be taken once a year for 5 years to note any changes from initial conditions. Conclusions and recommendations were to be based on data obtained during the yearly evaluations.

#### *Performance to Date*

The L/FA injection stabilization was performed in July 1983. On the first day the injection work was performed, a regional demonstration was held in West Memphis, Arkansas, and attended by personnel from state and federal agencies throughout the region. During the demonstration one of the maintenance engineers from Arkansas, who was familiar with the history of this slope, stated that if the slope was still standing after the next spring he would consider the job a success. The slope to be treated had failed twice in the spring before injection. Shortly after completion of the injection one of the slopes on the opposite side of the Interstate failed. This slope had been repaired at the same time the test slope and adjacent control were repaired. Early in December 1984, the control section failed. This was 18 months after injection of the test section. In January 1985, inspection of the test slope revealed that a shallow surface slough had occurred approximately 185 ft from the bridge end. The slough is 12 to 18 in. deep and extends for about 60 to 70 ft. Photographs of the treated slope showing the original area of failure before injec-



FIGURE 22 Bolling Road embankment: primary slide zone, 18 months after lime/fly ash stabilization.

tion and the shallow surface slough are shown in Figures 22 and 23.

In February 1985, Arkansas issued a Research Informer declaring that the injected slope had failed and concluding that the method of treatment performed at this location was not successful. However, as of this date, 2½ years after treatment, the primary failure area of the slope shows no signs of movement and is performing satisfactorily.

In the authors' opinion the shallow surface slough does not constitute a failure of this demonstration and the research project should not have been terminated. No funds were recovered because of early termination of the demonstration.

### Conclusions and Recommendations

The following conclusions and recommendations are presented:

1. When a failed slope is pushed back into place before injection the entire face must be proof rolled or compacted to ensure that there are no soft spots or areas of loosely compacted material.

2. Immediately after injection the lime or L/FA slurry on the surface should be mixed into the top 6 in. and properly recompact. This was not done on this job.



FIGURE 23 Bolling Road embankment: observed shallow surface slough, March 1985.

3. All proof rolling and compaction work should be done perpendicular to the face of the slope and never parallel to it. A long, shallow surface slough such as the one that occurred here can actually be caused by loosening the material on the downhill side by a heavy track machine running parallel to the face. This could have been done by the machine that redressed the slope just before injection.

4. Inspection of the surface slough in June 1985 revealed that the failed material contained grass and rocks and was dry and uncompacted, and the surface was still showing L/FA that had never been mixed and recompact.

5. Deep-seated embankment slope failures can be repaired by multiple injections of L/FA slurry.

6. The evaluation of any demonstration should be continued for the full period to learn as much as possible about the process and its results. Premature abandonment does not provide necessary long-term information about the process under evaluation.

7. When any failure does occur a complete evaluation should be made so that useful new technological information can be generated to aid in future design and implementation. In the authors' opinion the purpose of any demonstration or research project should be to learn as much as possible from both successes and failures, so that future projects can benefit from the accumulated knowledge and experience.

8. All L/FA-injection projects should include the 4-hr mixing test already mentioned to evaluate quick-setting injection materials. The fly ash used on this embankment was later found to suffer excessive strength loss during the 4-hr mixing strength test. This material problem did not surface during the standard tests then used to evaluate the L/FA soil reactions.

### Case 3: Missouri Highway Earth Embankment Lime/Fly Ash Stabilization

This slide-repair project is located on Route 77, Cape Girardeau County, Missouri. The embankment had a history of previous failures and in the past several construction procedures had been tried with little success to stabilize the recurring slides. All evaluation tests on the project were conducted by the Missouri Highway Department using both standard soil tests and lime-glaze and L/FA-seam tests.

### Soil Tests

The slide zone is composed of two soils. The fill was originally constructed of Sharkey clay, which is alluvial in origin. The Sharkey clay is a highly plastic, grey, waxy clay and was the cause, in conjunction with the steep slopes, of the slides. The demonstration section was approximately a 3 to 1 slope; however, slopes as flat as 6 to 1 have suffered slide failures in this area.

Test results on soils obtained from the fill show liquid limits exceeding 50, with the maximum value determined at 67. The Sharkey clay soils are usually lime reactive. The second soil type found within the slide zone is the Memphis soil which is a loess material. The Memphis soil was imported by maintenance personnel for slide repair. Memphis soils are also lime

reactive, but the improvements are less dramatic than in the more plastic clays.

### *Injection Procedure*

Lime was mixed into a slurry at the rate of 2½ to 3 lb/gal of water while the lime and fly ash were mixed at a 1 to 3 ratio by weight and slurried at a rate of 4 lb L/FA/gal of water. Injection pressures ranged from 50 to 200 psi. A total of 139 tons of lime and 301 tons of fly ash were injected into the 9,322 yd<sup>2</sup> embankment slope area. During the site selection and evaluation phase the decision was made to single-inject a portion of the slide on 5-ft centers and to double-inject the balance of the slide. L/FA was used for the single-injected area, and lime slurry followed by L/FA was used for the double-injected area. Because a single-injection pattern is more economical than a double one, the purpose was to evaluate the performance of both patterns to determine the most effective and economical method to use for future work.

The injection work was accomplished during the period September to October 1984. A 100-ft section was double injected and the balance of 700 ft was single injected. All injections were made to a depth of 10 ft, except for one area that was injected 12 ft deep.

### *Performance to Date*

The injection stabilization was completed in October 1984, and through December 1985, 14 months later, no movement was observed in the slope. The slope was visually inspected in November 1985 by Missouri Highway Department personnel who reported the slope to be in good shape. The guardrail was straight and no movement or tension cracks were observed.

A row of iron fence posts was set 3 ft into the ground and 4 ft above the ground, approximately ⅓ of the distance up from the bottom of the slope. No movement of these posts has been noted since installation. Site monitoring will be continued for 5 years. The three noninjected control slopes at this location failed within the first 6 months of this demonstration. Plans call for injection of these slopes in 1986.

### *Conclusions and Recommendations*

1. Both the single L/FA injection and the double combination lime and L/FA injection have prevented any recurring slides for approximately 15 months after installation.
2. Additional installations should be made to optimize the most economical, effective method to stabilize embankment slopes in this area.

### **RESEARCH NEEDS**

The rate of future progress in injection stabilization will be substantially increased if additional funding is allocated for technology research and development for construction renovation of highway soils. Although currently funded demonstra-

tion projects are of considerable value, they do not address basic injection-technology needs of admixture development, material characterization, full-scale strength testing, design methodology, and nondestructive site evaluation.

### **SUMMARY**

Injection stabilization is an emerging technology with increasing application opportunities. To date, the largest markets for injection stabilization have been stabilization of existing railroads to reduce maintenance, increase line speeds, and improve safety; and stabilization of building sites and pavement structures in expansive clays. This same injection technology developed over the past 20 years can now be applied to existing highway pavement and embankment stabilization, as well as civil construction projects, as emphasis shifts from new construction to maintenance and rehabilitation of the infrastructure.

The three completed injection projects discussed in the case histories section of this paper show specific examples of how lime and fly ash can be used to stabilize highway earth embankments. Of the three projects discussed, the Alabama project was considered unacceptable because of poor material design, improper site selection, and additional work that was performed on the slope. The Arkansas site remained standing after 2 years, with the exception of one shallow surface slough, which occurred because of a lack of adequate pre-injection compaction and post-injection mixing and compaction. The primary area of deep failure, which had failed repeatedly before injection, has resisted any further movement for 2½ years. The Missouri project is performing 100 percent successfully, with no observed movement to date.

A fourth site in northern Louisiana is scheduled for injection in 1986. This site will include injecting all four quadrants of a failed Interstate crossing. Two quadrants will be injected with lime slurry and two with L/FA slurry. The planning at this site has included recommended injection improvements and necessary construction changes supported by the generation of data from Alabama, Arkansas, and Missouri.

In addition to the three reported case histories, numerous other slides have been successfully injected for private industry and other agencies, including the Corps of Engineers, over the past 10 years.

Much progress has been made to date on the use of injection stabilization of embankments; however, improvements are needed in engineering, material testing, mix design, and soil-density control. Stabilization of surface slope failures requires good moisture and compaction control before injection coupled with post-injection mixing and compaction. It is recommended that additional demonstrations be conducted to further develop injection stabilization as a viable, economically feasible method for correcting highway embankment failures.

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# Underpinning Considerations for Design Unit A-140, Metro Rail Transit Project

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The proposed rail transit system, Section A-140 of the Southern California Rapid Transit District, consists of two cut-and-cover stations and approximately 1.5 mi of twin bore tunnel. Along the proposed alignment are numerous structures many of whose foundations rest above the invert of the proposed tunnels or adjacent to the proposed station excavations. Consideration is given to protection of structures along the proposed route. The influence zones for tunnel mining and station excavation, based on design criteria, available literature, and past experience, are established. Next, settlements of the buildings within the influence zone are predicted and compared with the estimated allowable settlements. Those buildings whose predicted settlements exceed allowable settlements are thereby identified. Technically sound and economically feasible underpinning methods are considered for protection of those structures whose predicted settlement exceeds the allowable settlement, and the most effective underpinning scheme is proposed for each structure. Finally, the current project status is briefly outlined.

The Southern California Rapid Transit District (SCRTD) is in the process of building a rail transit system to serve the people of metropolitan Los Angeles. The initial line (see Figure 1) will begin at Union Station, travel west, pass the Civic Center and the Jewelry Mart and then travel north, approximately parallel

to Wilshire Boulevard, to the San Fernando Valley, a distance of approximately 18.5 mi.

Section A-140, of the proposed rail transit system, the subject of this paper, consists of two cut-and-cover stations and almost 1.5 mi of twin bore tunnel. It begins at approximately Station AR 112+30 in the Union Station parking area and extends to approximately Station AR 199+47 in the vicinity of the intersection of 7th and Hope Streets. The approximate locations of each major type of construction are given in Table 1.

Along the proposed alignment are numerous structures many of whose foundations rest above the invert of the proposed tunnels or within the zone of influence of the proposed station excavations. Therefore, consideration has to be given to protection of structures along the route. The purpose of this paper is to discuss the options considered for protecting these structures.

## SUBSURFACE CONDITIONS

In general terms, the subsurface conditions along Design Unit A-140 consist of alluvium over weak claystones and siltstones (1, 2). The general subsurface conditions are shown in Figure 2. The alluvium largely consists of clean sands and gravels, but may also contain some silt, clay, and boulders. The thickness of