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Landslide Stabilization Using Wick Drains

Final Report for NCHRP-IDEA Project 57

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MARCH 2001

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APPENDIX A

EXECUTIVE SUMMARY

One of the most effective options to stabilize landslides is to reduce the amount of water they contain by installation of horizontal drains. A new type of horizontal drain material, geosynthetic wick drains, and a new installation method, that of driving drains rather than drilling them, has been evaluated. Horizontal wick drains offer several advantages over conventional horizontal drains: they resist clogging, they are inexpensive (≈$12/m installed), they may be deformed without rupture, and they may be installed by unskilled laborers with a minimal investment in equipment (typical rates exceed 15 m/hr).

Since 1998, more than 100 drains totaling almost 1500m have been installed at eight sites in Missouri, Colorado, and Indiana using bulldozers, backhoes, and standard wick drain driving cranes. Significant drainage has been observed from the wicks, and reductions in the water table have been measured. Drains have been driven 30m through materials with SPT values as high as 28.

As with drilled drains, some drains will be expected to be dry initially, but these drains will often become active during wet periods and serve as an important part of the overall slope stabilization scheme. Drain effectiveness is expected to improve over the first few years as the effects of soil smear during drain installation are removed, peaking at 3-6 years after installation. The effectiveness is then expected to decrease as fine particles start to clog the drain pores. Based on extrapolation of published tests, clogging occurs slowly enough in typical clay soils that the drain service life will be comparable to project lifetime.

The most significant installation problem is pipe flexure when encountering hard materials. It may be controlled by increasing drive pipe diameter and wall thickness, using rigid pipe sleeves, and by bracing from underneath.

Based on our experience and on studies reported in technical literature, the following guidelines are suggested for drain design.

1. Drains should not extend more than 3-5m beyond the slope failure surface.

2. Drains should be installed horizontally or at as low an angle as possible.

3. Drains should be installed in clusters which fan outward, aiming for a typical average drain spacing of 8m in zones that produce water.

4. Wick filter fabric with 70 mesh openings is suitable for soils with a significant sand component. Finer filter mesh (100-200 mesh) should be used for soils that are dominantly silt or clay.

5. The reduction in flow caused by soil smear can be minimized by pushing pipes containing the drains, rather than pounding or vibrating them in place. Cross-sectional area of the pipes should also be kept to a minimum.

6. Finished drains should be protected from root growth by sheathing the drains at the surface with PVC pipes. Drains should be protected from ice in extreme climates by burying the drain outlets. Drain outlets should be manifolded together so that flow can be conveyed to a practical discharge point.

The following limitations are anticipated for horizontal wick drain installation.

1. The ideal material for driving wick drains has SPT values of 20 or less, with maximum values of 30.

2. Maximum drain length is expected to be 30m for hard soils and 45-60m for soft soils.

3. Drains can be driven through some hard or rocky zones, but bedrock, large rocks, or dense sand or gravel will cause refusal.

Landslide Stabilization Using Wick Drains

by

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INTRODUCTION

A method has been developed to use soil wick drains for a novel application of landslide and slope stabilization. Wick drains are flat, fabric-coated plastic channels, which were initially developed to be vertically driven into the ground using a specially adapted crane. The drains are 4mm x 100mm in cross-section, and are shipped in 300m rolls. They accelerate consolidation and settlement by an order of magnitude by significantly shortening the flowpath for water to exit a soil layer (*1*). This study has developed equipment to install wick drains horizontally, so that they might be used to drain landslides. Drains have been installed by this new method in an instrumented test embankment. More than 100 drains have been installed at seven sites in Missouri, Colorado, and Indiana to prove the effectiveness of the procedure.

Horizontal wick drains are intended to address several significant drawbacks experienced by the drilled horizontal drains currently used. Drilled drains, which consist of slotted PVC pipes placed into drilled horizontal holes, tend to clog with fine material and require periodic cleaning, since it is often impractical to place a filter pack over the slots. Since the PVC is inflexible, landslide movement can rupture the drains. Also, drilled drains are expensive, approximately $20-36 per linear meter (*2, 3*). Wick drains are encased in a fine mesh geotextile fabric which reduces clogging, they are economic to install, and they may be deformed by as much as 60-100% before rupture (*4, 5*).

INSTALLATION PROCEDURE

The method of installation is to use a bulldozer or hydraulic excavator to push a small-diameter steel pipe into the hillside. The pipe sections are preloaded with lengths of wick drain, and the first pipe is attached to a disposable drive plate at the front. At the target depth, the pipe is withdrawn, leaving the wick drain in place. The installation procedure consists of the following steps:

1. Wick Preparation – The wick must be rolled and tied to fit inside the push pipe. Wick sections are cut to lengths one foot longer than the push pipe, rolled into tight cylinders, and tied at one foot intervals with five to eight inch long cable ties (Figure 1).

2. Pipe Loading – Pipes are preloaded with lengths of rolled and tied wick. Depending on the inner diameter of the pipe, wick may be pushed through the pipe, or it may need to be pulled through with a piece of rope. The first pipe to be driven should have a drive plate attached to the front end of the wick with cable ties (Figure 2). The front end of the first pipe should not be threaded, as the narrow pipe wall at the threads will cut into the drive plate.

3. Preparation of Drain Location – Because the first pipe has a tendency to slide up the slope during initial driving, a vertical face should be cut into the slope for a driving surface. This face only needs to be a few inches in height.

4. Driving of First Pipe – The drive head is slid over the end of the first pipe and the wick is folded out of the way (Figure 3). The first pipe is then aligned at the desired angle (usually horizontal or less than 5° upward) and pushed one or two feet into the slope. The angle and bearing may be measured again and adjusted slightly at this point, and the pipe is pushed for the remainder of its length.

5. Continued Driving – Additional pipes are driven by first splicing the end of the wick protruding from the pipe in the ground to the end of the wick in the next pipe section (Figure 4). Splicing is accomplished by stapling with a plier stapler. The spliced wick is rolled and tied, the pipes are threaded together, and the new pipe is pushed in the same manner as the first. Pipe sections may be added until the desired drain length is reached or until the driving resistance causes refusal.

6. Pipe Withdrawal – Once the total length is driven, pipes are pulled from the ground by attaching a pulling head and a chain to the end of the protruding pipe and pulling each section smoothly out of the ground (Figure 5). The wick remains in the ground because the drive plate anchors the wick in place and resists withdrawal.

INSTALLATION EQUIPMENT

The equipment required to install horizontal wick drains can be purchased from drill pipe vendors or can be readily constructed in a machine shop (*6*).

Drive Plate

The drive plate (Figure 2) is modeled after the type of plate used in commercial vertical wick drain installation by the Nilex Corporation. The plate is three inches square and is cut from 18 gauge (1.3mm or 0.05-inch thickness) sheet steel. Thicker steel (up to 12 gauge) will also work, but thinner steel may rip or puncture during driving. The steel is intended to fold around the pipe during driving, and then slip off and anchor itself in the soil during pipe withdrawal. A piece of #4 reinforcing bar is welded onto the steel, and a washer is welded to the other end of the re-bar. The re-bar holds the plate in place during driving, and serves as an attachment point for the wick. The washer keeps the wick from sliding off the re-bar during withdrawal.

If it is anticipated that weathered rock, boulders, or other hard material may be encountered during drain driving, thicker steel plate may be used for the drive plate. Alternatively a standard flat 6.4cm (2 ½ inch) steel washer may be slid onto the re-bar to rest between the drive plate and the front of the lead pipe. A 13cm-long (5-inch) carriage bolt and washer may be substituted for the drive plate for very hard or rocky zones (Figure 2).

Drive Pipe

The drive pipe should have a minimum inner diameter of 32mm (1¼ inches) to accommodate the rolled wick. The outer diameter is only limited by the pushing force available by the driving machinery. The work described in this study used 3m (10-foot) lengths of AQ wire-line drill rod, which is flush-threaded both inside and out, with an inner diameter of 35mm (1 3/8 inches) and an outer diameter of 44mm (1 ¾ inches) (wall thickness of 4.8mm or 3/16 inch). This pipe has been used to drive drains 30m in length, and it has been driven through materials with stiffnesses up to 28 blows per foot. Larger diameter drill pipe can withstand higher driving pressures, will allow longer drains in harder geologic materials, and will provide for easier wick loading, but larger pipes are significantly more expensive.

Drive Head

A drive head receives and transmits the pushing load induced by the driving equipment, while protecting the female threads of the drive pipe and reducing the tendency of the pipe to slide off the equipment or to buckle. The drive head shown on Figure 3 consists of a 45cm (18 inch) section of 64mm (2½-inch) diameter pipe, on which is welded a thick flat steel plate. The steel plate has a slot cut into it so that the wick may be fed through and then folded back out of the way. Reinforcing plates and braces were added to make the drive head more robust.

Pulling Head

While a wrapped chain generally has enough friction to pull pipes out of the ground, a pulling head constructed from a short piece of drill pipe with hooks welded onto it makes the attachment process easier. This pipe should have male threads, so that it can be attached to the exposed female end of each section of drill pipe still in the ground (Figure 5).

Drive Equipment

The estimated pushing load required for the drive pipe used is less than 4500-6800 kg (10,000 to 15,000 pounds). We estimate that bulldozers or trackhoe excavators in the 11,000-20,000 kg (25,000 to 45,000 pound) range are best suited for this task. Equipment substantially larger may not provide the fine control needed during driving.

PIPE BUCKLING

The most common problem encountered during drain installation was the tendency of the drive pipe to bend or buckle under the driving pressure. The most serious problem was during initiation of driving a new pipe when its full 3m length was exposed and not confined by the soil of the hillside. The buckling generally subsided once at least a meter of the pipe had been driven into the hill. However, the pipe would also buckle when hard materials were encountered, such as sloping bedrock surfaces or boulder floaters in residual soil.

Larger diameter, thicker walled drill pipe will resist buckling better than the pipe used in this work. We have also used another larger pipe as a sleeve around the drive pipe to prevent buckling (Figure 6). The sleeve may be pushed into the hillside along with the pipe, and then pulled out to be used with the next pipe section. A hook welded onto the sleeve pipe simplifies

the removal of the sleeve each time a pipe section is added (Figure 7). Finally, buckling may also be controlled by supporting the drive pipe from below with timbers, and then forcing the flexure downward by controlling the attack angle on the bulldozer blade or trackhoe bucket (Figure 8).

DRAIN LAYOUT DESIGN

As with drilled drains, the final layout pattern for horizontal wick drains depends on the slope and bedrock geometry and the location of water-bearing zones. The initial design should address drain length, angle, spacing, and filter size, with the recognition that these parameters may need to be altered in the field.

Drain Length

In general, longer drains produce more water because there is a greater inlet length along the drain and because a longer drain is more likely to intersect water producing zones. For drilled drains, Royster (*7*) suggests that drains should not extend more than 3-5m (10-15 feet) beyond the shear zone, as they may convey water into the landslide mass. Lau and Kenney (*8*) also conclude that there is little benefit in extending drains beyond the failure plane intersection with the ground surface at the top of the slope.

We have successfully pushed wick drains 30m (100 feet) through materials as stiff as 20-28 blows/foot. With more robust equipment, such as thicker-walled drive pipe, it is our opinion that drains 45-60m (150-200 feet) in length may be driven through similar soils.

Drain Angle

Drilled drains have typically been installed at a large range of angles above horizontal, from as low as 2 to 3% grade (*9*) to as high as 20% grade (*10, 11*). The angle is often determined by the geometry of the failure surface. It is our experience that wick drains at low angles, and even horizontal, are the most effective. Physically, there is no less gravitational force pushing the water out of the slope than for sloping drains, and low angle drains will lower the water table and pore-water pressures to a greater degree further back in the slope. Higher angle wick drains may be necessitated by a sloping bedrock surface, or by the desire to locate drains along a dipping slide plane or permeable weathered zone.

Drain Spacing

Several research efforts have focused on calculating ideal drain spacing as a function of soil permeability, slope geometry, and drain position (*12, 13, 14, 15*). Royster (*7*) suggests that it is difficult to judge the validity of these studies, since they require soil homogeneity and isotropy and preciseness in drain location which are seldom available in the field. Royster suggests that drain spacing and location in practice are largely matters of "trial and adjustment" and also depend on site accessibility, topography, and the suspected internal drainage of the landslide.

Smith and Stafford (*10*) note that the early experience of the California Department of Highways led them to space drains roughly 8m (25 feet) apart in areas where high quantities of water were produced, and to space drains roughly 30m (100 feet) apart elsewhere, as a method of detecting the producing zones. Federal Highways Administration guidelines (*16*) also suggest that spacing should be based on the location of productive zones, rather than using an even spacing which results in both productive and non-productive drains.

Drain Pattern

There are two general approaches to drain layout: a fan pattern radiating from a single installation point, or a parallel layout from a line of evenly spaced installation points. Based on finite element modeling of drain patterns, Nakamura (*17*) concludes that for a given area of coverage, there is no significant difference in drainage effectiveness between fan and parallel drain layouts. Mekechuk (*18*) notes that based on 32 years of experience, the Canadian National Railways prefers a fan pattern over a parallel arrangement, because installing a number of drains from a single pad is faster, easier, and causes less slope disruption.

Kazarnousky and Silagadze (*19*) propose that rather than draining an entire landslide, many benefits can be achieved by only draining alternate thick slices of the hillside. Each drained slice would contain a concentration of drains, and be flanked by undrained slices. They calculate that, based on side friction and cohesion between the slices, the drained slices will help stabilize the undrained slices, even though the water level in the undrained slices has not been lowered. This analysis has some bearing on a "fan" or clustered drain layout, as opposed to an even parallel arrangement of drains. By concentrating drains where they are most productive, not only is the installation more efficient and inexpensive, but the drained sectors work as friction blocks to improve the stability of the undrained sectors.

Based on these analyses and opinions, as well as our own experience, we prefer installation of horizontal wick drains in fan patterns. Initial drain locations should be based on observed or suspected internal landslide drainage channels. In the absence of such information, the drains should be installed with a broad parallel spacing intended to identify more permeable zones. Drains should be fanned at angles that result in an average spacing of approximately 8m

(measured at approximately one-half the drain length). In our opinion, this method is more efficient and just as effective as installing evenly-spaced parallel drains.

Water Levels Between Drains

Assuming that drains are spaced 8m (25 feet) apart in productive areas, a simplified analysis may be conducted to calculate the effects of the drain on the ground-water table. In general, the water table surface between two drains is an inverted parabola, with low points at the drains and with a high point, h_{max}, midway between the drains (h_{max} is the height of the water table above the level of the drains). For steady-state two-dimensional flow conditions h_{max} can be shown to approximate (*20*):

$$h_{\max} = \sqrt{\frac{2Qx}{Kb}}$$

where Q = drain flow rate

b = length of drain

x = half spacing of drains (L/2, where L = drain spacing)

K = hydraulic conductivity (permeability) of soil

This approximation includes several assumptions:

1. the drain is horizontal and presents no resistance to flow
2. the water table coincides with the drain along its entire length
3. Darcy's law is valid for the situation and the Dupuit assumptions are met

This equation implies that the height of the water table between two drains is a function of the square root of the drain spacing, the reciprocal of the square root of the soil permeability, and the square root of the gradient or water pressure, expressed as Q.

The exact height of h_{max} must be determined from site specific parameters, but a generalized calculation may be used to estimate the magnitude of h_{max}:

Assuming the following parameters:

Drain length (b) = 30 m (100 feet)
Flow rate (Q) = 2 to 20 l/day (0.5 to 50 gallons per day)
Drain spacing (L) = 8m (25 feet)

Then it follows that

If K =	the typical range of h_{max} =
10^{-4} cm/sec	0-0.6m (0-2 feet)
10^{-5} cm/sec	0.3-1.5m (1-5 feet)
10^{-6} cm/sec	1.5-3m (5-10 feet)
10^{-7} cm/sec	3-4.5m (10-15 feet)

Based on a number of plots using the equation above, it appears that the average water table height in the landslide, h_{avg}, $\approx 2/3h_{max}$ when $h_{max} > L/20$. When $h_{max} < L/20$, then $h_{avg} \approx h_{max}$.

This information may be used to approximate the equivalent height of the drained water table, h_{avg}, and to estimate the need for drain spacing closer than 8m. It should be recognized that h_{avg} is a function of the square root of the controlling parameters, and therefore is relatively insensitive to small changes (for instance, reducing h_{avg} by a factor of two requires reducing drain spacing by a factor of four). Furthermore, laboratory tests of permeability will often be conservative, since slope movement, tension cracks, and soil structure fissures often produce high permeability flow channels and a higher level of interconnection between units.

Filter Size and Clogging

Selection of Wick Drain Filter Size

Clogging is generally caused by migration of fine soil particles into the filter fabric, and sometimes through the filter fabric into the wick drain channels. Clogging can be reduced if the

filter fabric is properly matched to the soil type. Typical pore openings in wick drains range from #70 to #200 sieve mesh sizes (0.21 to 0.05mm).

For a comparison, Mekechuk (*18*) suggests that PVC slots for horizontal drains should be less than or equal to the D_{70} value for the host soil. For a filter soil or geotextile, Hunt (*21*) provides the following criteria:

$4 \text{ to } 5 < D_{15}(\text{filter})/D_{15}(\text{soil}) < 20 \text{ to } 40$ (to provide sufficient permeability)

and

$D_{15}(\text{filter})/D_{85}(\text{soil}) < 4 \text{ to } 5$ (to limit piping of soil)

Similarly Chen and Chen (*22*) propose geotextile size criteria based on permeability tests on several commercial wick drain filters:

$D_{90}(\text{filter})/D_{85}(\text{soil}) < 1.2 \text{ to } 1.8$

$D_{50}(\text{filter})/D_{50}(\text{soil}) < 10 \text{ to } 12$

Atkinson and Eldred (*23*) hypothesize that the wick drain filter fabric allows fine soil particles to pipe, therefore developing a natural graded filter surrounding the wick. They suggest that drains with extremely small pore sizes (10 to 20 μm) are necessary for this process to occur in clayey soils.

Because there are a limited number of options for wick drain filter sizes, it may not always be realistic to meet all of these criteria. The criteria proposed by Chen and Chen (*22*) were developed exclusively for wick drains and appear to be the most appropriate, while the other criteria should be viewed as desirable, but not critical. A cursory examination of these recommendations would indicate that the 70 mesh filter will be effective for silt and clay soils with a significant sand component ($D_{85(soil)} > 0.15$mm and $D_{50(soil)} > 0.02$mm) and the 100 and 200

mesh filters are more effective for almost pure silt and clay soils ($D_{85(soil)}$ >0.05mm and $D_{50(soil)}$ > 0.007mm).

Effects of Soil Smear

Several researchers have investigated soil compaction and smear during vertical wick installation. Pushing or pounding of drains displaces soil and creates a zone of disturbance around the wick, unlike non-displacement methods such as drilling. This disturbed zone typically has reduced horizontal permeability, which has been shown in laboratory studies to be equal to the vertical permeability of the undisturbed soil (*24, 25*) or perhaps one-tenth its original undisturbed value (*23, 26*). The diameter of the disturbed zone has been shown in laboratory experiments to be approximately twice the equivalent diameter of the mandrel used to install the wick (*24, 25, 26*). Atkinson and Eldred (*23*) conclude that this thickness of smear zone is comparable to the thickness of the natural filter created by piping, so for properly sized filter fabric, the effects of the smear zone are eventually removed. Welsh (*27*) suggests that static pushing of the mandrel results in less disturbance than driving or vibrating the mandrel. Therefore, to reduce the effects of soil smear during horizontal wick drain installation, pipes and drive plates should have a small cross-sectional area, and they should be pushed smoothly into the slope.

Effects of Soil Pressure

Clogging can also result from soil pressure compressing the wick filter into the drain channels, thereby constricting water flow along the channels. Chai and Miura (*28*) calculate reduction in cross-sectional area of up to 17% based solely on creep of filter fabric into the drainage channels as a result of a 49 kPa confining pressure, which they interpret as equivalent to

lateral earth pressures under 10 to 15m of natural soil. This reduction in drain area, coupled with migration of soil fines into the filter, resulted in flow rates as low as 4% of maximum within six months. It should be noted that their tests assumed constant drainage, which is not expected for truly effective drains (as discussed below). Moreover, they used a compacted soil with permeability of 10^{-8} cm/sec, which would be at least an order of magnitude lower than expected in the field. They also showed that by reversing the water flow direction for a few seconds, the drains were cleaned and restored to nearly the maximum flow rate. Hansbo and others (*29*) recommend selecting filter permeability and drain discharge capacity higher than expected to counter clogging effects resulting from migration of fine particles or creep of filter fabric.

Long-Term Performance of Drains

The effects of soil smear, fine particle migration, and creep of filter fabric can be combined to gauge the long-term performance of wick drains. Such an assessment is shown on Figure 9, which indicates that for typical clayey soils with permeability on the order of 10^{-7} cm/sec, clogging is not expected to be an issue for many years. Figure 9 assumes drainage during 3 to 10% of the time period after the initial two months.

We are currently monitoring the effects of fine particle clogging in a laboratory test cell containing wick drains encased in clay soil. The test was initiated in August 1999, and we have periodically measured wick drainage rates since that time. The flow dropped to approximately 10% of the original flow rate over a time period of 3 months of continuous flow, although an unknown portion of that drop could be contributed to other factors such as decrease in soil permeability during soil consolidation. Also, wick drains in the field are not expected to have continuous flow, but to flow intermittently following rainfall events. We recently reversed flow

to flush the drains, increasing flow back to the original flow rate. The drop in flow to be measured over the next several months should not be affected by soil consolidation and will provide reliable information on the long term performance of drains.

Effects of Root Growth and Ice

As for drilled PVC drains, horizontal wick drains could also be clogged by root growth or ice. The intrusion of roots into the system may be reduced by sheathing the last 3-5m of wick near the surface in galvanized steel or PVC pipe. The sheath pipe will also work as part of the water collection and conveyance system. Buildup of ice may be reduced by burying collection systems and drain outlet points (*10*). Huculak and Brawner (*30*) report that, even in Canada, "in most instances the drains thaw out before pore pressures increase to a critical value following the spring thaw, in which case the freezing is of no concern."

WATER DRAINAGE FROM WICKS

Because of the heterogeneity of most landslide masses, the flow of ground water through the landslide is difficult to predict, and the flow seems to concentrate in preferential units or zones. Furthermore, infiltration is strongly influenced by tension cracks caused by slide movement and fissures caused by soil development. Rather than a homogeneous, isotropic porous medium flow, Nakamura (*17*) suggests that landslide ground water may concentrate in "water lenses," which are most frequently created as voids caused by dilation of the landslide during slope movement. He reports observing these lenses in drainage tunnels and test pits. In our experience, water lenses may simply be part of a preferred flow network within the soil. For instance, a horizontal wick drain installed in Meeker, Colorado produced water at a rate of up to 20 l/m (5 gpm) for several days before reducing to a trickle. An adjacent drain fanned out from

the same drive pad was dry. Both drains were installed in a homogeneous silty clay fill. We have also experienced substantial flow even in low permeability clay materials (for instance, a drain at the Jasper, Indiana landslide produced over 4 l/m (1 gpm) immediately after installation).

Lau and Kenney (*8*) present contradictory evidence, that drains installed in a varved clay slope (with horizontal hydraulic conductivity of 6 x 10^{-8} cm/sec) had a radius of influence of less than 3m, and that water lenses or fissures did not play a role in ground-water flow. They also suggest that for such tight, homogeneous materials, pore water pressures levels below about 7m depth are stable and insensitive to surface infiltration. Therefore, reductions in piezometric levels by horizontal drains may be considered "permanent."

As with drilled drains, horizontal wick drains will show varying rates of water production, even within the short horizontal distances between adjacent drains. This is especially true during dry periods. A number of case studies have been documented which confirm that a significant number of drilled PVC and steel pipe drains are initially and sometimes permanently dry. Royster (*11*) reports on several projects in Tennessee with the following numbers of dry drains: 6 of 31 (19%), 3 of 52 (6%), 33 of 75 (44%), 4 of 17 (24%), and 22 of 44 (50%). Royster notes that many of these drains became active in the wet seasons. Nakamura (*17*) reports drainage from only 45% of the holes for a site in Japan. Krohn (*31*) reports that 5 of 16 (31%) of the drains installed at a site in Pacific Palisades, California were permanently dry. The data from these reports suggest several principles regarding horizontal wick drains:

1. Many of the drains will be dry upon installation. This has been our experience, and indeed a higher percentage have been dry because most of our drains have been shorter and shallower than those typically installed by drilling.

2. Dry drains will still serve as water outlet points during the wet season (36% of the Jasper, IN drains were wet or dripping following installation, but all produced water after a rainstorm two weeks later).

3. Drains should be installed in areas of suspected water accumulation, such as draws or zones where bedrock is deeper, even if the first drains in the area are dry.

Nakamura (*17*) and Huculak and Brawner (*30*) caution against judging the success of a drainage program based on the volume of water produced. Although large flow volumes are impressive, relatively minor flow tapped from a critical soil unit may be more critical for slope stabilization. Nakamura (*17*) evaluates different flow graphs plotting drain output over time and concludes that the most successful drains for slope stabilization are those that show decreasing flow rates over time (indicating that they have lowered ground-water levels to their inlet level) and those that show drainage only after rainfall events (indicating that they are removing rapidly-infiltrating rainwater). Drains with relatively constant flow rates may be tapping groundwater that is not contributing to landslide movement.

OPTIMAL LANDSLIDE GEOMETRY

Space for equipment maneuvering for horizontal wick drain installation is similar to requirements for drilled drain installation. Push pipes extend from the hillside approximately 5m (15 feet) at most, and a trackhoe bucket or bulldozer must be able to be positioned to drive the pipes at the desired angle. Drains may be driven along the top of the bedrock surface, but residual boulders and bedrock knobs may halt the progress and limit the length of the drains. Therefore, the ideal geometry for pushing horizontal wick drains is to have a deep bedrock

surface, or one that slopes gently upward, with 7-9 m (25-30 feet) of working space in front of the slope.

The elevation of the driving pad should be such that the ground-water table can be lowered substantially, even with drains that slope upward into the hillside. Huculak and Brawner (*30*) suggest that for typical large landslides (greater than several thousand cubic meters in volume), each 0.3m reduction in the water table will increase the factor of safety against sliding by ¾ to 1½ percent. For small landslides, each 0.3m reduction may increase the factor of safety by 3 to 4 percent.

In soft clays, substantial lowering of the ground-water table will cause consolidation settlement of the clay, which is the process vertical wick drains were designed to accelerate. If roadways or structures are located above the slope, this settlement could create the same type of damage as landslide movement. Therefore, in these cases drains should be positioned to maintain the water table at seasonal low levels, to which the soil has presumably already consolidated, and not to lower the water table significantly below these levels.

HORIZONTAL WICK DRAIN SITES

The first installations of horizontal wick drains in Missouri and Colorado focused on proving the feasibility of the wick drain driving method and on refining the installation technique. Wick drains were initially installed at a test embankment, and then drains were emplaced at several locations with varying geology and using various types of driving equipment. Drains were driven through a variety of natural and fill materials with SPT values as high as 28 blows per foot, although 20 blows per foot appears to be the realistic limit for longer drains. Drains were driven through rocky or hard zones over a meter in width, although these

zones sometimes deflected the drain pipe toward the ground surface or completely halted the driving progress.

The latest installation work near Jasper, Indiana, was intended to be a complete landslide remediation project, with drain length and layout sufficient to impact the entire slide mass.

Details of each site installation are given below. English units are used rather than metric because the driving and measuring equipment all used English units. A summary of each site is included in Table 1.

Test Embankment, Rolla, Missouri

Using a bulldozer, drains were initially installed and tested in an instrumented embankment constructed from sandy clay (*32*). The embankment is approximately 60 cubic yards in volume and has a 1:1 front slope face. It is instrumented with six piezometers, 16 nested soil moisture meters and 20 survey markers. One-half of the slope was stabilized with six wick drains, and the other half of the slope was not stabilized, so that it could be used as a control point in the experiments. Figure 10 shows the embankment and wick drain arrangement. A ground-water table was developed in the slope by induced infiltration through a trench at the back of the slope. The slope was then subjected to an increasingly intense simulated rainfall event, using sprinklers to produce a 100-year 24-hour rainfall (0.31 inches/hour, as shown on Figure 11). During this simulation, water levels, wick drainage, and slope movement were measured and recorded.

The results of this initial testing are encouraging, with three lines of evidence supporting the effectiveness of the wick drains. First, the drains removed approximately 40 l/hour apiece (10 gallons of water per hour), lowering ground-water levels by over 1 foot. This is an

equivalent of 0.11 inches of rainfall per hour, over the slope area affected by the wick drains (40% of the total slope area). This drainage rate is well below the estimated capacity of the wick drains, which is 96 gallons per hour (*33*). It is likely that the low permeability of the embankment material controls the drainage rate of the wick drains.

Second, the piezometers show lower ground-water levels in the vicinity of the wick drains (Figure 12). This effect was pronounced at the slope face (lower piezometers) and in the middle of the slope (middle piezometers) throughout the duration of the test. It was not apparent at the rear of the slope (upper piezometers), where piezometers may have been in direct contact with a sand trench installed to enhance infiltration and creation of a water table (*32*).

The third line of evidence supporting the effectiveness of the drains is based on the movement of survey stakes: the stakes show substantially less movement within the drained half of the slope. Total movement was measured and showed that the undrained half of the slope had moved downward or outward from 0.4 to 0.6 feet, and the drained half had moved less than 0.45 feet throughout, and less than 0.2 feet in close proximity to the drains (*32*).

A more detailed description of the construction, testing, and analysis of the test embankment is summarized in a Master's thesis (*32*) written for the project.

Boonville, Missouri

Setting

This site is located on the south side of eastbound Interstate 70, ¼ mile east of exit 101 (which is State Route 5). The slope drops off below and to the south of eastbound I-70, and the asphalt in the shoulder lanes is damaged, where the failure surface emerges at the top of the slope. The failure occurs in a sandy clay and clay fill soil which was placed to fill a valley and

provide a level roadway surface. The fill is approximately 10-18 feet thick and contains an irregular, sloping cobble and boulder layer that is 2-7 feet thick (Figure 13). The cobble and boulder layer represents an early attempt to stabilize the slide by end-dumping cobbles and boulders as a buttress. It appears that the cobbles and boulders were placed in the middle of the slide, rather than at the toe, and that subsequent shallow slope movement, fill dumping, and vegetation growth has covered and obscured the location of the cobbles and boulders. Underlying the fill is interbedded shale and limestone bedrock.

The landslide is steep, sloping approximately 1.5:1. It is heavily vegetated in the spring and summer, with a wet swale along the eastern margin and a creek below the toe of the slope.

It appears that the slope movement is caused by high ground-water levels induced by blockage of the natural canyon drainage by the constructed fill. The wet swale near the slide and thick vegetation on the slide indicate that water is exiting the steep slope face and that drains could intercept much of this water and convey it away from the slope.

Drain Installation

In December 1998, 10 drains varying in length from 18 to 40 feet (249 feet total) were installed in three levels in the slide, as shown on Figure 13. Two of the drains at the upper level began producing small volumes of water overnight (less than 1 gpm). The boulder and cobble zone impeded drain installation in many cases. This zone was not visible at the ground surface and was not anticipated before the drain installation work was initiated. Two inclinometers and two piezometers were installed to track slope movement and ground-water levels.

Over the past two years, the slope inclinometers have shown less than 5 cm of movement. Piezometers were installed at the same time as the wick drains, so the change in water levels due to the drains could not be assessed.

Installation Difficulties and System Modifications

1. A trackhoe appears to provide better accessibility, driving force, and control for wick drain installation than a bulldozer. However, the skill of the operator is the single dominant factor regarding ease and speed of installation.

2. The driving cone should be redesigned to something much simpler and easier to build.

3. The drive rod should be coupled with a heavy pipe sheath to prevent buckling.

4. For an experienced crew, a rate of one 50-foot wick per hour is reasonable. A crew would consist of a trackhoe operator and two laborers.

5. An ideal wick drain design for this use would be circular in cross-section, with a diameter less than one inch, prepared in easily attachable 10-foot lengths. This would eliminate the need to roll and tie wicks before pipe loading.

6. An ideal driving rig would couple hydraulic rams for pushing with a pneumatic hammer to pound the drive pipe through stiff layers. The rig would also have a convenient rack for adding pipe sections.

St. Joseph, Missouri

Setting

This site is located on the south side of eastbound Interstate 229, ½ mile east of exit 4 (which is East Lake Boulevard). The slope is above I-229, and slope movement has repeatedly

uplifted the shoulder of the roadway. MoDOT maintenance crews have periodically shaved down the shoulder to grade and repaved. The failure occurs in a natural clayey silt loess slope consisting of up to 40 feet of loess overlying 10-30 feet of residual clay overlying weathered limestone and shale (Figure 14). The headscarp at the top of the landslide is approximately 16 feet high, and the landslide shows considerable deflation, erosion, and loss of material within the slide mass. A ditch at the toe of the landslide adjacent to the roadway shoulder contains ponded water and significant growth of hydrophilic vegetation. The cut-wall of the ditch shows some evidence of water drainage in the form of dark spots.

Because of the evidence of long-term water drainage, it appears that high water levels in the slope have contributed to instability.

Drain Installation

In May of 1999, seven drains varying in length from 40 to 67 feet (327 feet total) were installed into the cut-wall of the ditch, parallel and spaced approximately 15 feet apart. One of the drains immediately produced a small volume of water (less than one gpm).

Installation Difficulties and System Modifications

1. The drive cone was replaced with a simpler and cheaper drive plate, modeled after the drive plate used by Nilex Corporation for vertical wick drain installation.

2. A drive pipe sheath of heavy gauge, larger diameter pipe was used to prevent buckling of the pipe during pushing.

3. Rather than pre-loading a long section of wick, 10 and 20 foot sections were used and stapled together when necessary. This is the method of splicing used by Nilex, and the result was a faster installation process with much less labor required to move pipe.

4. A short drive head and face plate was constructed and used to protect the threads on the drive pipe and to prevent damage to the wick.

Rio Blanco, Colorado

Setting

The site is located at mile 15.7 on State Highway 13 just south of the town of Rio Blanco, Colorado. At this location, SH 13 is on a fill embankment constructed over a valley, and the slope has moved on both sides of the road, damaging driving lanes on both sides (Figure 15). The fill consists of 25 to 30 feet of clay and clayey silt, which overlies weathered shale and siltstone bedrock. A geologist from the Colorado Geological Survey suspects that the fill not only disrupts natural ground-water flow down the valley, but that it also blocked a natural spring to the southeast (*34*). Slope movement occurs primarily in the Spring, when snowmelt raises the regional ground-water level.

Based on the apparent influence of ground water on the slope instability of the embankment, we assumed that drains installed in the uphill face of the embankment aimed at the former spring to the south would effectively maintain low ground-water levels in the slope.

Drain Installation

In June of 1999, six drains varying in length from 40 to 50 feet (255 feet total) were installed at two levels on the uphill face of the embankment. Unfortunately, in order to allow equipment access to the uphill embankment face, an access road was constructed that resulted in an elevated working pad approximately 15 feet off the bottom of the valley floor. The pad was

elevated to raise the working area above the muddy valley floor, but it also required the wick drains to be installed above the ground-water table. None of the drains produced water.

Installation Difficulties and System Modifications

1. The problem of rolling and tying wicks before pipe loading has essentially been eliminated because this task is done in advance, during short work breaks, and at other odd times by members of the crew. The goal is to always have all spare drive pipe loaded with rolled and tied wick, and to have ten or fifteen spare sections of rolled and tied wick ready to be inserted into pipe.

Meeker (North), Colorado

Setting

This site is located at mile 47.7 on State Highway 13, north of Meeker, Colorado. The slope drops off below and to the east of northbound SH 13, and the asphalt in the roadway is damaged, where the failure surface emerges at the top of the slope (Figure 16). The failure occurs in a clay and silty clay fill soil which was placed to fill a valley and provide a level roadway surface. The fill is approximately 20 to 50 feet thick. Underlying the fill is siltstone and claystone bedrock.

Slope movement occurs primarily in the Spring, when snowmelt raises the regional ground-water level.

Drain Installation

In June of 1999, six drains varying in length from 48 to 70 feet (365 feet total) were installed in a fan pattern from the base of the slope below the roadway. Several of the drains

immediately produced water, and one produced a volume as high as 5 gpm for several days, before reducing to a steady trickle.

Installation Difficulties and System Modifications

1. The threaded driving head was replaced with a larger-diameter sleeve with a stout face plate, which proved faster and more robust.

2. A technique was developed to minimize the tendency of the drive pipe to buckle, consisting of orienting the bulldozer blade to encourage the pipe to bend downwards, and then resting the pipe on wood timbers to counteract the buckle.

Meeker (South), Colorado

Setting

This site is located at mile 47.5 on State Highway 13, just south of the Meeker North Landslide. As for the Meeker North slide, the slope drops off below and to the east of northbound SH 13, and the asphalt in the roadway is cracked, where the failure surface emerges at the top of the slope (Figure 17). The geology is also similar to the Meeker North slide, except that the fill is approximately 50 to 60 feet thick over siltstone and claystone bedrock.

Slope movement here also occurs primarily in the Spring, when snowmelt raises the regional ground-water level.

Drain Installation

In June of 1999, six drains varying in length from 70 to 80 feet (430 feet total) were installed in a line along the base of the slope below the roadway. Several of the drains immediately produced small volumes of water (less than 1 gpm).

Rye, Colorado

Setting

This site is located on the north side of State Highway 165, approximately one mile northwest of the town of Rye, Colorado. The slope drops off below and to the north of westbound SH 165, and the asphalt in the roadway is damaged, where the failure surface emerges at the top of the slope (Figure 18). The failure occurs in a clay soil which was placed to fill a valley and provide a level roadway surface. The fill is approximately 30 to 35 feet thick. Underlying the fill is claystone bedrock.

Slope movement occurs primarily in the Spring, when snowmelt raises the regional ground-water level. A ditch behind the slope (to the south) ponds water, and a subdrain system installed several years before has been disrupted by slope movement and no longer functions.

These factors indicate that high ground-water levels are a predominant factor controlling slope movement, and control of ground water is necessary for slope stabilization.

Drain Installation

In June of 1999, 21 drains varying in length from 18 to 40 feet (559 feet total) were installed in two lines at different elevations within the slope below the roadway. Drains were installed using a standard wick drain driving crane provided by the Nilex Corporation, but with the boom aligned horizontally instead of vertically (Figure 19). Because the boom on this crane was 55 feet in length and the set-up required driving drains back between the trackhoe treads, the maximum length drains could be driven was 40 feet. However, the goal of this work was to show the viability of installing horizontal wick drains with this equipment, which was

accomplished. The largest cranes Nilex has available could potentially install horizontal drains 100 feet in length.

Several of the drains were moist the following day, although no drains showed substantial water flow. Installation of an uphill cut-off trench the following winter lowered the ground-water table below wick levels and appeared to have reduced slope movement substantially.

Installation Difficulties and System Modifications

1. A number of future modifications to the driving crane were identified, including attachment of a high pressure waterjet system to reduce side friction (already available on some of Nilex's larger equipment). In addition, an ANFO loader could be used to blow a sand drain around the wick as the mandrel is withdrawn. These loaders are currently used in the mining industry to blow Ammonium Nitrate – Fuel Oil pellets (prill) into horizontal drilled holes in the mine working face.

Jasper, Indiana

Setting

This site is located on the east side of State Highway 545 3 miles south of Dubois, Indiana, which is close to the larger town of Jasper. The slope is above SH 545, and slope movement has repeatedly uplifted the shoulder of the roadway (Figure 20). A small retaining wall was installed in the late 1980's, and the north end of the wall has overturned due to insufficient embedment of the supporting piers (Figure 21).

The failure occurs in a natural slope consisting of up to 25 feet of residual silty clay and clay overlying weathered limestone, shale, and sandstone. The ditch at the toe of the landslide

adjacent to the roadway shoulder contains ponded water and significant growth of hydrophilic vegetation.

The slide mass has multiple scarps and tension cracks, and the top of the slide has a graben feature, which we interpret was caused by extension of the slide mass away from the hillside. A sewer line runs through this graben, and according to a geologist from the Indiana Department of Tranportation (*35*), the sewer line has been broken and replaced at least twice. The interpretation of whether sewer leakage initiated the landslide or landslide movement caused sewer leakage is an ongoing issue of concern for InDOT.

Because of the evidence of long-term water drainage and numerous fissures through which surface water may enter the landslide, it appears that high water levels in the slope have contributed to instability.

Drain Installation

Previous horizontal wick drain installation efforts focused on proving the feasibility of the drain driving method and on refining the installation technique. The work at the Jasper slide was intended to be a complete landslide remediation project, with drain length and layout sufficient to impact the entire slide mass. Consequently, in June of 2000, 44 drains varying in length from 20 to 100 feet (2613 feet total) were installed at the site over a period of nine working days (drain locations are shown on Figure 20). The length of some of the drains was limited because of their proximity to the sewer line. Sixteen of the drains produced water immediately following installation, and as close as we can tell, 19 produced water after rainfall, and nine were permanently dry (individual drains could not be monitored after installation,

because the drains were bundled into irrigation pipes, which were partially buried, as shown on Figure 22).

Landslide Analysis

To assist in analysis of the landslide, two slope inclinometers and eight piezometers were installed in the slide mass. Soil samples from the borings were tested in INDOT's laboratory for triaxial compressive strength, grain size distribution, Atterberg limits, unit weight, and water content. Borings logs and laboratory data is included in Appendix A. A summary of the residual clay soil properties is as follows:

- the material is a CL consisting of approximately 40% clay, 30% silt, and 30% sand,
- the material has an effective peak friction angle of 27° and an effective peak cohesion of 180 psf, and
- the material has a unit weight (at natural moisture content) of 121 pcf.

Inclinometers and piezometers have been monitored periodically following their installation in June and July, and the results are shown in Appendix A. In summary, the inclinometers have shown less than 4mm total movement near the top of the slope (3-SI on Figure 20) and less than 2mm movement near the middle of the slope (2-SI on Figure 20).

The only piezometers installed before the wick drains, which could theoretically record a drop in water level due to the drains, are TP-2, TP-3, and TP-5 (Figure 23). A drop in water level in excess of 3 feet was measured in TP-2, which is located within 5 feet of two wick drains. Piezometer TP-3 was dry upon installation, and has showed only a trace of water since July 19, so the effect of the wick drains could not be tracked. Piezometer TP-5 showed a steady increase

in water level (over 10 feet), following installation. Because this piezometer is located more than 15 feet from a wick drain, we expect the influence of the drain to be minimal.

Other piezometers installed at the site (1-P, 2-P, 3-P, 4-P, and 5-P) were installed several weeks after the drains were emplaced, because the drilling contractor could not begin the work when planned in early June. These piezometers have not shown substantial changes in water levels since late June, although 1-P, 2-P, and 5-P are close to wick drains and the water level in those areas are likely to be lower than they were in early June.

For computer stability analysis of the landslide, three conditions were evaluated: current stability, stability with high ground water (assumed to represent conditions which have caused periodic movement of the slope), and stability with drains installed.

The model was calibrated to the second set of conditions, that of high ground water, since the factor of safety could be assumed to equal one. High ground-water levels were estimated assuming inflow from the graben at the top of the slope and outflow at the ditch line, with a smooth water table surface following topography between these two end points (Figure 24). Because the slide has already moved, the soil along the slide plane should be modeled with residual strength values. The laboratory strength values represent peak strengths, so to scale them down to residual values, the effective cohesion was decreased to a nominally low value near zero (20 psf), and the effective friction angle was adjusted to produce a factor of safety of one. The back-calculated friction angle was 22°, which is approximately ¾ of the peak friction angle.

Current stability was evaluated using ground-water levels measured during the dry summer months, without the influence of wick drains (Figure 25). Strength values were those determined by back-calculation. The resulting minimum factor of safety was 1.28.

Stability with wick drains installed was evaluated by adjusting the ground-water table to equal:

1. the levels measured in piezometers located close to the analyzed cross-section (2-SI and 3-SI on Figure 26),

2. the elevation of the two wicks intercepting the cross-section (shown on Figure 26), and

3. the elevation calculated between the wicks, using equations presented earlier in this report.

The resulting minimum factor of safety was 1.46, a 14% increase over current conditions, and a 46% increase over critical high ground-water conditions. This analysis assumes that the wick drains fix ground-water levels, even during wet periods, because they provide a constant outlet point for water in the slope.

Installation Difficulties and System Modifications

1. We found that the drive plate would sometimes shear off when pushed through hard or rocky zones. Two methods of reducing shear were to place a washer between the drive plate and the drive pipe (for moderately hard zones) or to use a carriage bolt and washer instead of the drive plate (for very hard or rocky zones).

2. We developed the threaded pulling head with hooks for chain attachment (Figure 5) to replace the simple wrapped-chain method used previously. This greatly accelerated the pipe pulling process, and also made it more convenient to pull 20 feet of pipe at a time.

LONG TERM DRAIN PERFORMANCE

Drains installed in 1998 and 1999 have showed no evidence of clogging by dirt or algae, except where the drains lay directly on the ground surface and had been trampled (Figure 27). At locations where a short PVC pipe was used to encase the drain and was inserted a few feet into the soil, the drains were in excellent condition (Figure 28) (*6*).

Drains at the Boonville, St. Joseph, and Meeker North and South sites show evidence of continued water drainage a year after installation (Figure 29).

While not measured directly for this study, the long-term deformability of wick drains is an important factor influencing the ability of the drains to continue to function in actively moving landslides. Published technical data shows that wick drains are capable of elongation deformation of up to 60 to 100% before rupture (*4, 5*).

Continued monitoring of the drains over the next few years will include periodic observations of drain conditions, water levels, and slope conditions for the Missouri and Colorado sites (installed in 1998 and 1999). The Indiana site (installed in 2000) will be more closely monitored through eight piezometers and two inclinometers.

PIPE GRIPPING MECHANISM

While not outlined in the original scope of the project, an opportunity developed for three senior mechanical engineering students to design and construct a pipe gripping and pushing mechanism for the project. The purpose of this mechanism is to accelerate the driving process and reduce pipe buckling by having a pair of clamps that would grip the drive pipe, and the whole mechanism and pipe would then be smoothly pushed into the soil using hydraulic pressure from the driving equipment.

The mechanism designed and built by the students is shown on Figures 30, 31, and 32. The project included a three-dimensional finite element analysis to establish proper design parameters. One half of the mechanism was actually constructed, but no field tests have been run.

DRAIN INSTALLATION RATES AND COSTS

Drain installation rates and costs are a function of the experience of the installation crew and the site geology and layout. On the whole, per foot costs will decrease and installation rates will increase for longer drains, installed from a few fan pads rather than from individual pads. The best estimates of actual footage rates and costs per foot from this project are made from the Jasper, Indiana work, where the crew gained substantial experience over the course of the project and rapidly increased their rates, as shown in the table below:

Day	Hours Worked	Feet of Drain Installed	Rate (ft/hr)
1	3.5	25	7.1
2	6	220	36.7
3	5.5	235	42.7
4	6.5	325	50.0
5	4.5	130	28.9
6	7	385	55.0
7	6.5	345	53.1
8	7.5	460	61.3
9	7.5	488	65.1
Total	54.5	2613	47.9

These results show that after the first day, when the crew was learning the installation procedure and when four of the five drains attempted either hit rock or experienced some other installation problem, the rate of installation was on the order of 50 feet/hour (or 0.02hrs/foot).

The costs for installation depend on the availability of in-house equipment and personnel. An estimate of costs may be made assuming that a subcontractor is hired to do the work:

Trackhoe and operator	= \$95/hour
Three laborers	= 3 x \$20/hour
Wick drain	= \$0.50/foot (varies by volume ordered)
Drive plates	= \$2/drain (if each drain = 50 feet, then cost = \$0.04/ft)

Therefore, an estimated cost per foot is:

\$95 x 0.02 hrs/foot + \$60 x 0.02 + 0.5 + 0.04 = \$3.64/foot

If per diem fees are added to this value (approximately \$400 per day) this would add approximately \$1 per foot to the cost, assuming production of 400 feet per day.

The costs to purchase and develop horizontal wick installation equipment are as follows:

Purchase of 150 feet of AQ drill rod:	= \$10/foot = \$1500
Construction of drive and pulling heads:	= \$200 (estimate)
Construction of 100 drive plates	= \$100 (estimate)
Total	= \$1800

PUBLICATIONS AND PRESENTATIONS

The following publications and presentations were completed in association with this research project:

Santi, P.M., Elifrits, C.D., and Liljegren, J.A., accepted for publication, "Horizontal Wick Drains for Landslide Stabilization," Civil Engineering (to be published in the June 2001 issue).

Santi, P.M., Elifrits, C.D., and Liljegren, J.A., in press, "Design and Installation of Horizontal Wick Drains for Landslide Stabilization," Transportation Research Record (to be published in 2001).

Santi, P.M., Elifrits, C.D., and Liljegren, J.A., 2001, "Design and Installation of Horizontal Wick Drains for Landslide Stabilization," Transportation Research Board Catalog of Practical Papers (http://www4.nationalacademies.org/trb/onlinepubs.nsf/web/practical_papers).

Santi, P.M., Elifrits, C.D., and Liljegren, J.A., 2001, "Design and Installation of Horizontal Wick Drains for Landslide Stabilization," Presentation at Transportation Research Board Annual Meeting.

Santi, P.M. and Liljegren, J.A., 2000, "Design Aspects of Horizontal Wick Drains for Landslide Stabilization," Association of Engineering Geologists 43rd Annual Meeting Program with Abstracts, San Jose, CA.

Santi, P.M. and Elifrits, C.D., 2000, "Highway Landslide Stabilization Using Wick Drains," Proceedings of the 51st Annual Highway Geology Symposium, Seattle, WA, pp. 99-106.

Santi, P.M., Executive Producer, and Shipley, T., producer, 2000, "Landslide Stabilization Using Wick Drains," Technical Video: Video Communications Center, University of Missouri-Rolla, 10 minutes.

Liljegren, J.A., 2000, "Horizontal Wick Drains: A Testing and Design Study," Unpublished M.S. Thesis, University of Missouri-Rolla, Rolla, MO 65409 93 p.

Santi, P.M., 1999, "Horizontal Wick Drains as a Cost-Effective Method to Stabilize Landslides:" Geotechnical News, Vol. 17, No.2, pp. 44-46.

Liljegren, J.A. and Santi, P.M., 1999, "Introduction of Horzwick Technology for Landslide Remediation," Association of Engineering Geologists 42nd Annual Meeting Program with Abstracts, Salt Lake City, UT.

PARTNERSHIPS ESTABLISHED

A number of partnerships were established with agencies and wick drain manufacturers to complete this project. An estimate of the value of each one is given below:

Organization	Matching Provided
University of Missouri Research Board	$35,519
Appleyard Fund, UMR School of Mines and Metallurgy	$4,000
Indiana Department of Transportation	$7,500 (piezometer and inclinometer installation subcontract) $6,500* (trackhoe rental for drain installation) $7,500* (personnel to assist in traffic control and drain installation)
Colorado Department of Transportation	$3,000* (use of CDOT bulldozer for drain installation) $7,500* (personnel to assist in traffic control and drain installation)
Missouri Department of Transportation	$5,000* (personnel to assist in traffic control and drain installation)
Colorado Geological Survey	$1,000* (personnel to assist in identification of appropriate sites)
Nilex Corporation	$5,000* (mobilization and use of their vertical wick installation rig)

American Wick Drain Corporation	$1,000 (their estimate for 1000 feet of donated wick drain)
	TOTAL = $83,519

*my estimate based on personnel time and equipment used on our project

SUMMARY

Since 1998, more than 100 drains totaling almost 1500m have been installed at eight sites. Significant drainage has been observed from the wicks, and reductions in the water table have been measured. Equipment to install the drains is inexpensive and easily procured. Drain installation is quick (≈15 m/hr), inexpensive (≈$12/m), and easily learned by untrained crews.

The most significant installation problem is pipe flexure when encountering hard materials. It may be controlled by increasing drive pipe diameter and wall thickness, using rigid pipe sleeves, and by bracing from underneath.

Based on our experience and on studies reported in technical literature, the following guidelines are suggested for drain design.

1. Drains should not extend more than 3-5m beyond the existing or potential failure surface.

2. Drains should be installed horizontally or at as low an angle above horizontal as possible.

3. Drains should be installed in clusters which fan outward, aiming for a typical average drain spacing of 8m in zones that produce water.

4. Wick filter fabric with 70 mesh openings is suitable for soils with a significant sand component. Finer filter mesh (100-200 mesh) should be used for soils that are dominantly silt or clay.

5. The reduction in flow caused by soil smear can be minimized by pushing pipes containing the drains, rather than pounding or vibrating them in place. Cross-sectional area of the pipes should also be kept to a minimum.

6. Finished drains should be protected from root growth by sheathing the drains at the surface with PVC pipes. Drains should be protected from ice in extreme climates by burying the drain outlets. Drain outlets should be manifolded together so that flow can be conveyed to a practical discharge point.

The following limitations are anticipated for horizontal wick drain installation.

1. The ideal material for driving wick drains has SPT values of 20 or less, with maximum values of 30.

2. Maximum drain length is expected to be 30m for harder soils and 45-60m for soft soils.

3. Drains can be driven through some hard or rocky zones, but bedrock, large rocks, or dense sand or gravel will cause refusal.

4. A significant number of dry drains can be expected on a project (just as for drilled drains), and these drains often become active during wet periods.

FURTHER WORK

The work completed in this project has developed equipment and installation procedures for horizontal wick drains so that full-scale landslide stabilization can be readily completed by work crews with no prior experience, and at a low cost and equipment investment to DOTs. The Missouri and Colorado installations proved the feasibility of the method and the Jasper, Indiana work was a complete landslide remediation project. Our future goals are to complete and test the

pipe gripping mechanism, and to complete full landslide stabilizations at two additional sites. The laboratory test evaluating long-term clogging will be continued, and the usefulness and methodology of installing sand filters around the drains should be explored.

ACKNOWLEDGEMENTS

Funding for this work was provided by the NCHRP-IDEA Program of the Transportation Research Board, Grant NCHRP-57, the University of Missouri Research Board, and the Appleyard Fund of the UMR School of Mines and Metallurgy. Test sites were stabilized in partnership with the Nilex Corporation, the American Wick Drain Corporation, the Indiana, Missouri, and Colorado Departments of Transportation, and the Colorado Geological Survey.

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Table 1. Summary of Wick Drain Installation Projects (*6*)

Site	Location	Date	Geology	Driving Equipment	# of Drains	Length (feet)
Rolla, MO (test embankment)	Fraternity Circle, N. of I-44 exit 185	8/98	Sandy clay fill over limestone	International Harvester (unknown model, approx. 6800kg or 15,000 lbs. operating weight)	6	20 (36m or 120' total)
Boonville, MO	S. side of Eastbound I-70, ¼ mile E. of exit 101 (S.R. 5)	12/98	Sandy clay and clay fill with 2'-7' thick cobble layer over shale and limestone	Case 550E bulldozer Case 9030B trackhoe	10	18-40 (76m or 249' total)
St. Joseph, MO	S. side of Eastbound I-229, ½ mile E. of exit 4 (E. Lake Blvd.)	5/99	Clayey silt loess overlying residual clay and weathered limestone and shale	Viatallis FX 130 trackhoe	7	40-67 (100m or 327' total)
Rio Blanco, CO	S.H 13, mile 15.7	6/99	Clay and clayey silt fill over weathered shale and siltstone	Caterpillar M318 wheeled excavator	6	40-50 (78m or 255' total)
Meeker S., CO	S.H. 13, mile 47.5	6/99	Clay and silty clay fill over claystone	Caterpillar D4C XL bulldozer	6	70-80 (131m or 430' total)
Meeker N., CO	S.H. 13, mile 47.7	6/99	Clay and silty clay fill over claystone	Caterpillar D4C XL bulldozer	5	48-70 (93m or 305' total)
Rye, CO	N. side of S.H. 165 1 mile N. of Rye	6/99	Clay fill	Caterpillar 215B LC trackhoe with vertical wick driving boom	21	18-40 (170m or 559' total)
Jasper, IN	E. Side of S.H. 545 3 miles S. of Dubois	6/00	Up to 21' silty clay and clay over weathered shale, limestone, and sandstone	Komatsu PC200LC trackhoe	44	20-100 (796m or 2613' total)

Figure 1. Rolled wick being loaded into drive pipes.

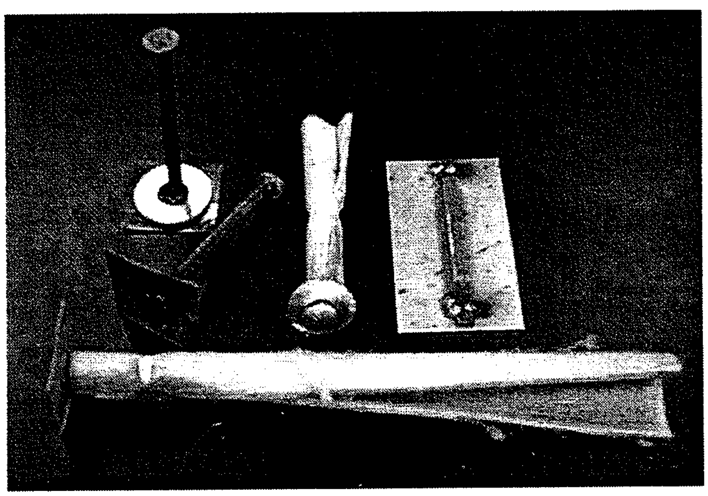


Figure 2. Drive plates with supporting washer (upper left), carriage bolt used for driving (center), drive plate attached to rolled wick (bottom), and standard drive plate for vertical wick drain installation (upper right).

Figure 3. Drive head in place on drive pipe.

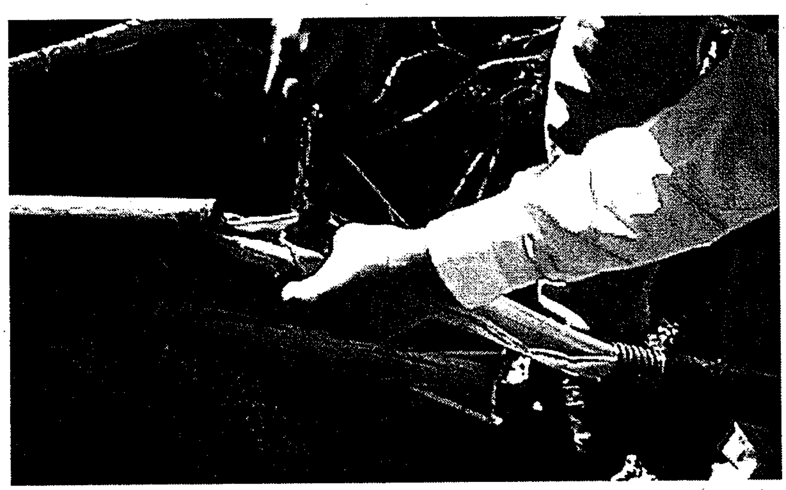


Figure 4. Splicing a new wick section before attaching the next pipe.

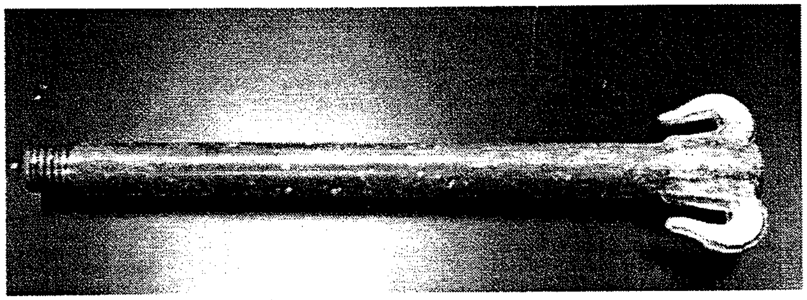


Figure 5. Pulling head which threads onto drive pipe. Hooks are used to chain head to trackhoe bucket.

Figure 6. Sleeve pipe used to prevent buckling of drive pipe when pushed into slope.

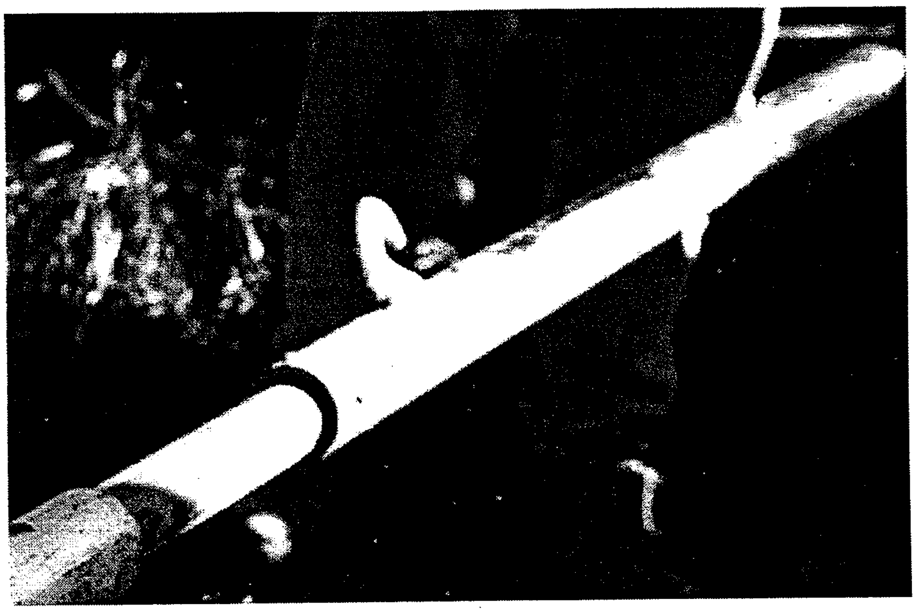
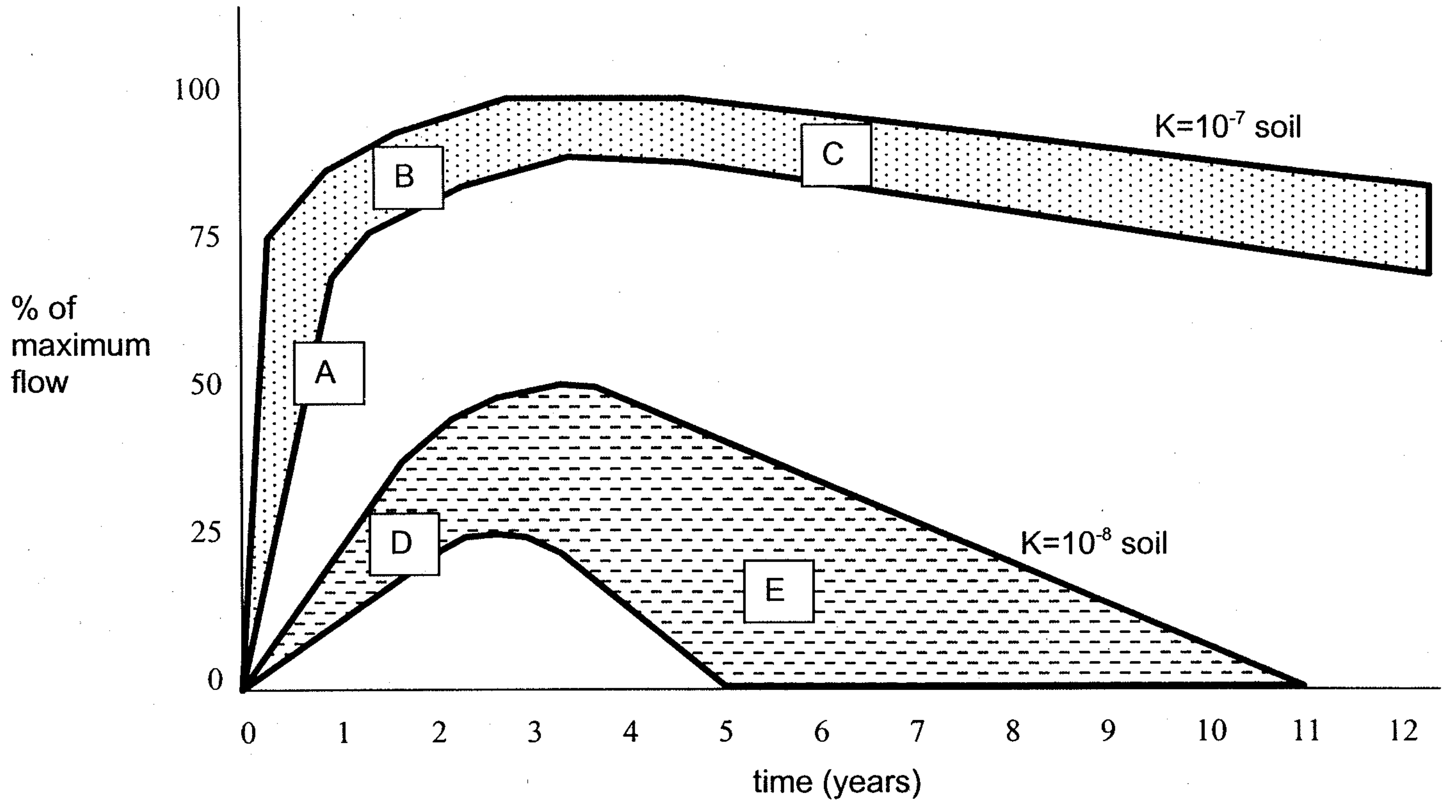


Figure 7. Close-up of sleeve pipe hook. Hook is attached to chain to assist in removing sleeve pipe after it is driven into the slope with the drive pipe.

Figure 8. Control of pipe buckling by supporting from underneath with timbers.



Notes:

A. Slope based on Lau and Kenney's (*8*) modeling results: for a $K=10^{-8}$ cm/sec permeability clay, drain influence is not fully realized for 5 years. Nakamura (*17*) showed that drain discharge is directly proportional to K, so if $K=10^{-7}$ cm/sec, then drain influence should be fully realized in 0.5 years.

B. Work by Hansbo and others (*29*) showed that because of smear effects, drain capacity is 70% of maximum after 6 months and 88% of maximum after 4 years (for $K=10^{-7}$ cm/sec).

C. Based on Chai and Miura's (*28*) lab work that showed clogging by $K=10^{-8}$ cm/sec clay to 4% of maximum flow after 6 months of constant flow. We assumed that only two months of constant flow occurred, followed by 1 (upper boundary) to 3 (lower boundary) days of flow per month. We also assumed that clogging rate is directly proportional to K (since Nakamura (*17*) showed that discharge was directly proportional to K. Therefore, clogging would be expected at 1/10 the rate as far a $K=10^{-8}$ cm/sec clay.

D. Slope based on Lau and Kenney's (*8*) modeling results: for a $K=10^{-8}$ cm/sec permeability clay, drain influence is not fully realized for 5 years.

E. Based on Chai and Miura's (*28*) lab work that showed clogging by $k=10^{-8}$ cm/sec clay to 4% of maximum flow after 6 months of constant flow. We assumed that only two months of constant flow occurred, followed by 1 (upper boundary) to 3 (lower boundary) days of flow per month.

Figure 9. Estimate of long-term clogging effects on driven wick drains.

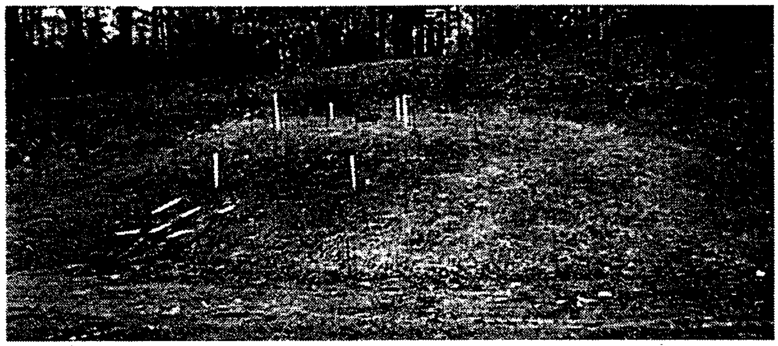


Figure 10. Test embankment layout. The left side was stabilized with six wick horizontal wick drains (exiting the slope encased in the white PVC pipes attached to black hoses). The right side was not stabilized. Vertical white pipes are shallow piezometers.

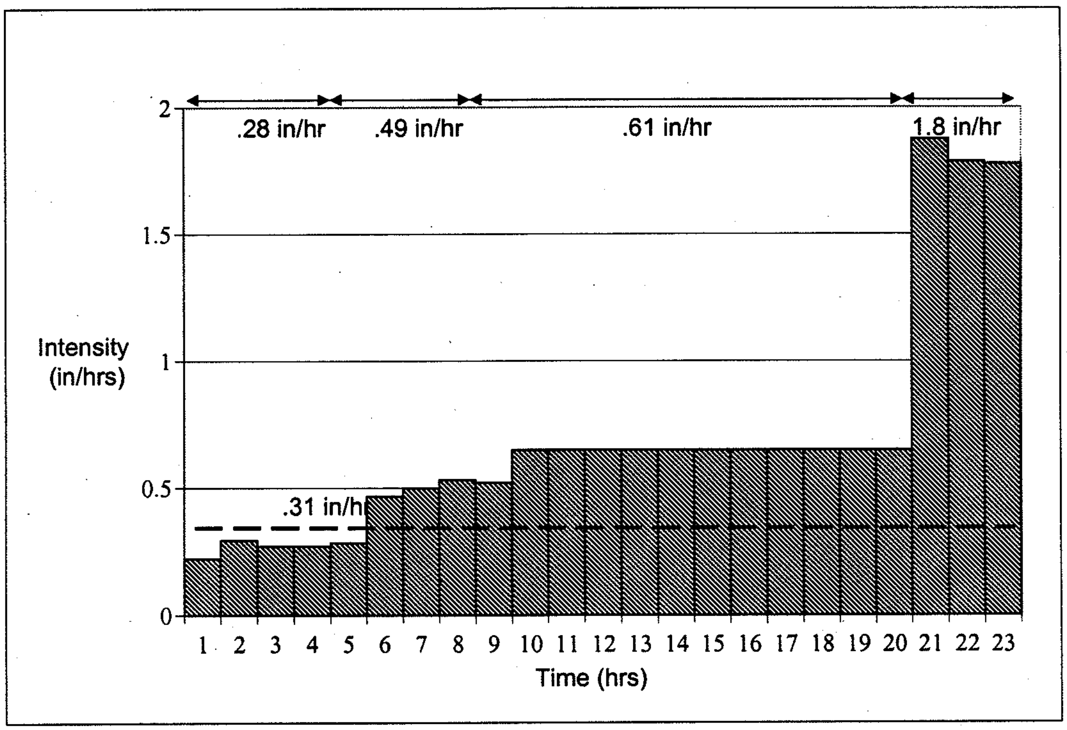


Figure 11. Intensity rates for applied water during simulated rainfall experiment (from Liljegren, 2000 (*32*)). The 100-year 24-hour rainfall is 0.31 inches/hour.

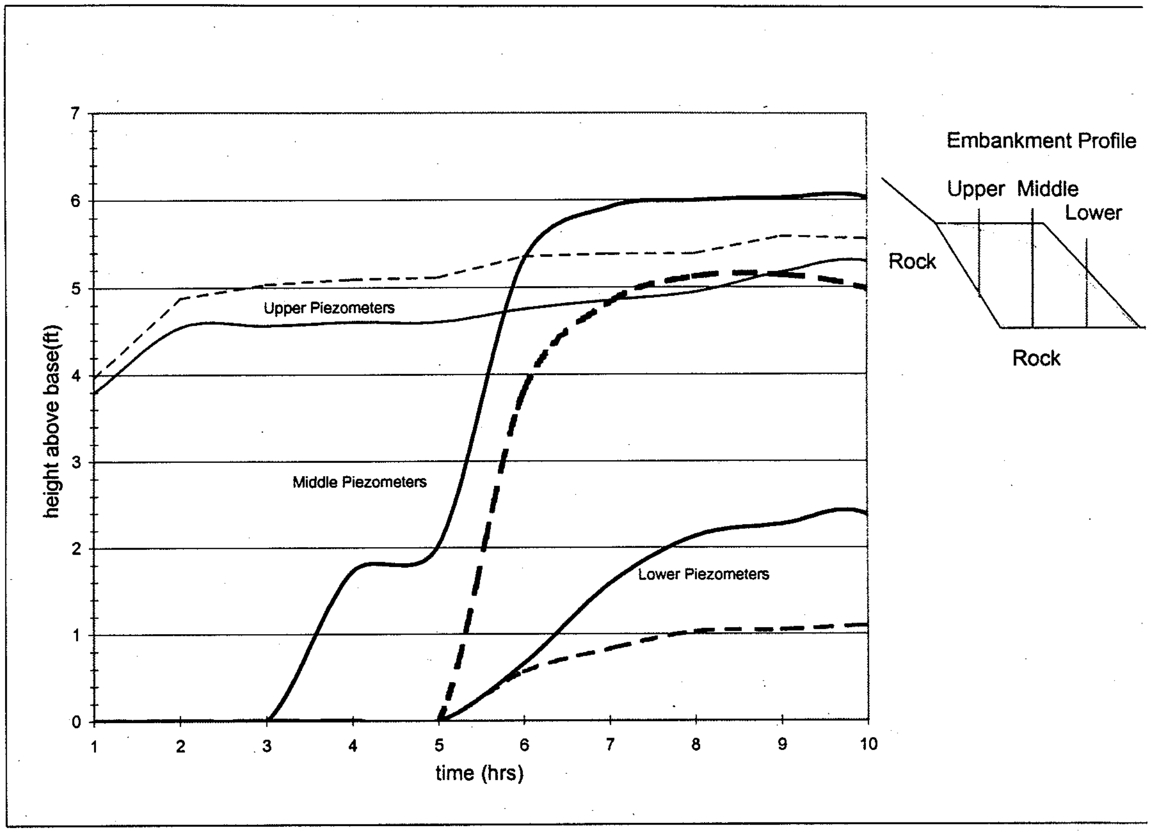


Figure 12. Water levels during the simulated rainfall experiment (from Liljegren, 2000). Dashed lines are piezometer readings from the stabilized side of the embankment and solid lines are readings from the unstabilized side.

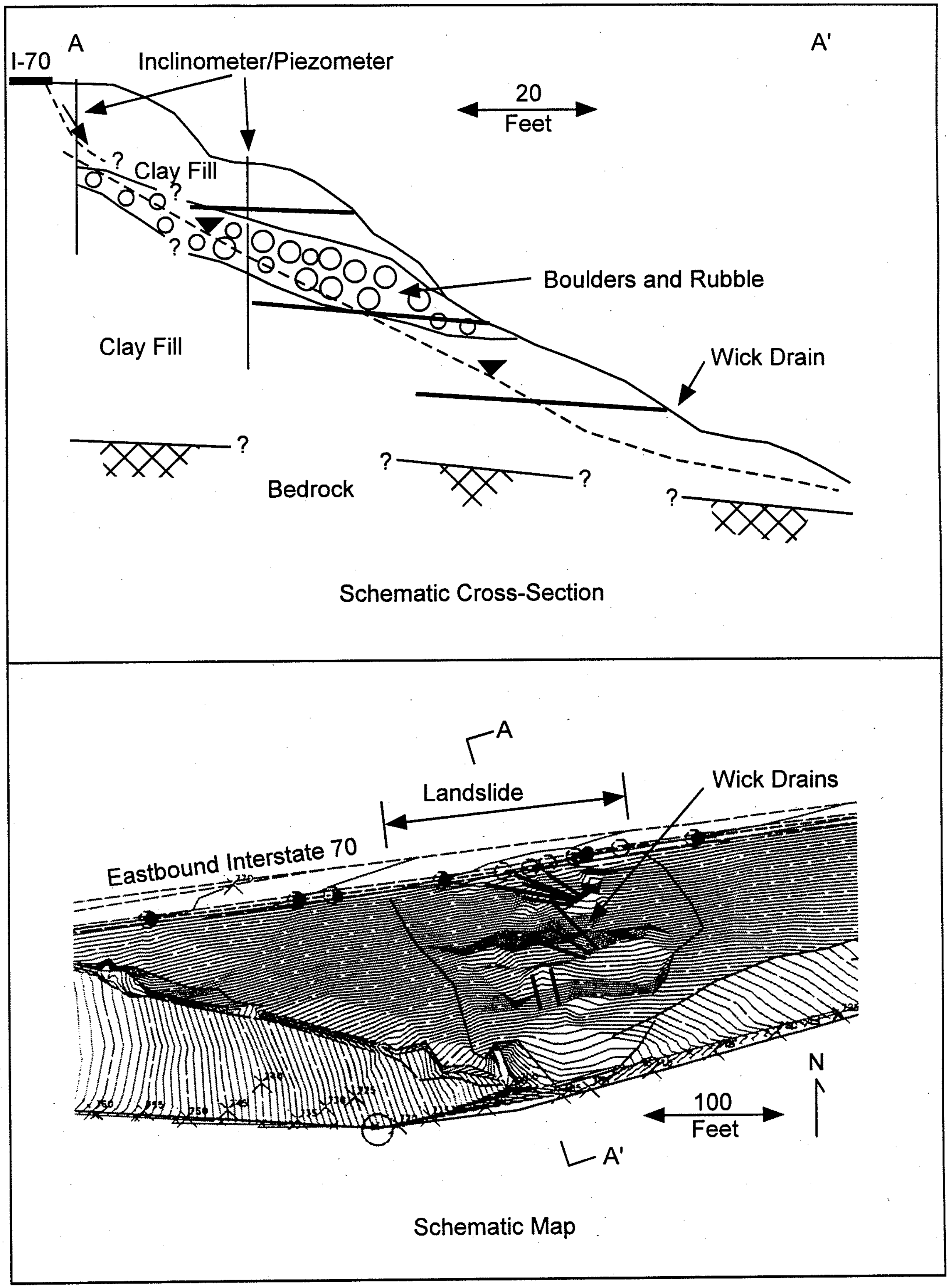


Figure 13 - Schematic Drawings of the Boonville, MO Landslide

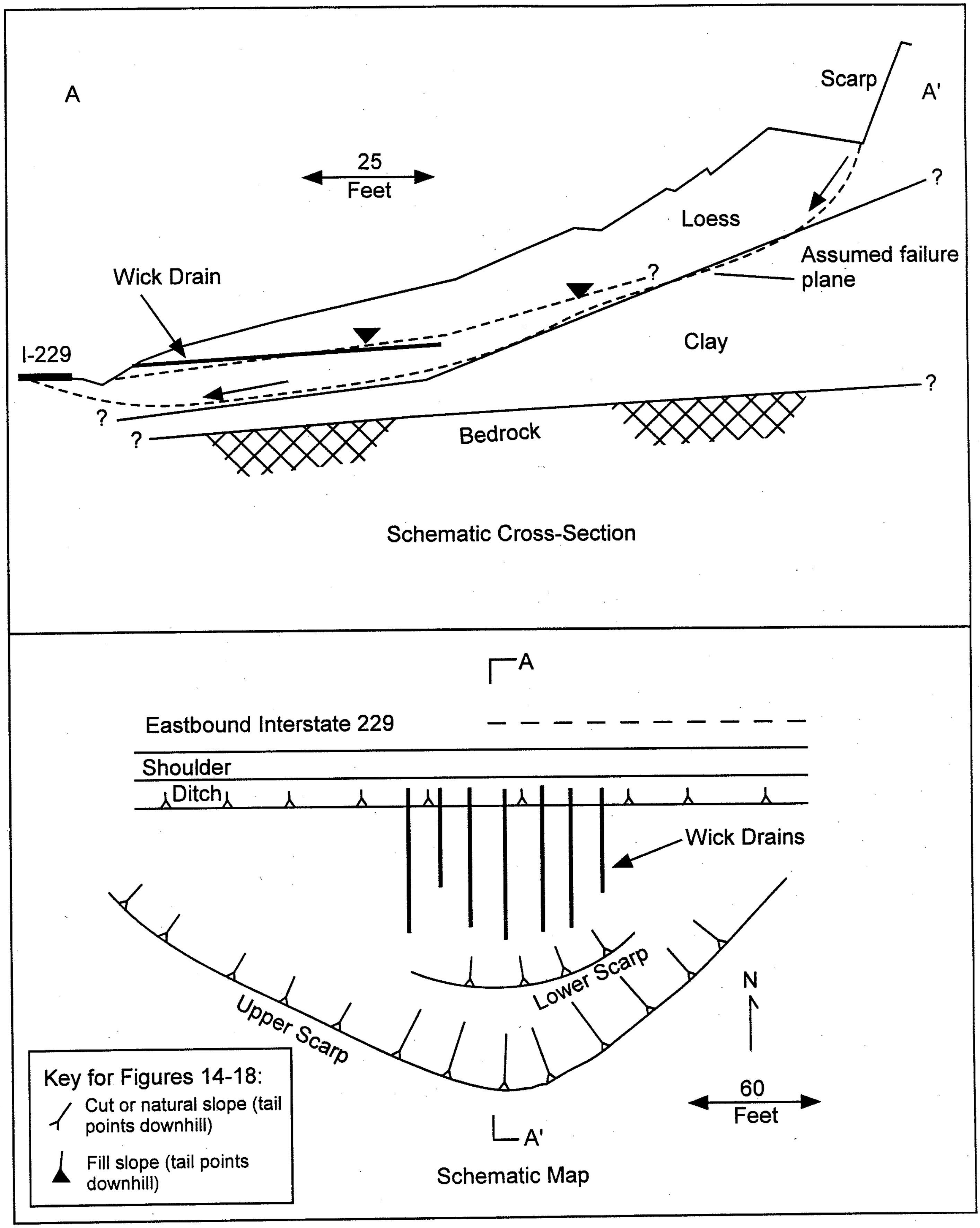


Figure 14 - Schematic Drawings of the St. Joseph, MO Landslide

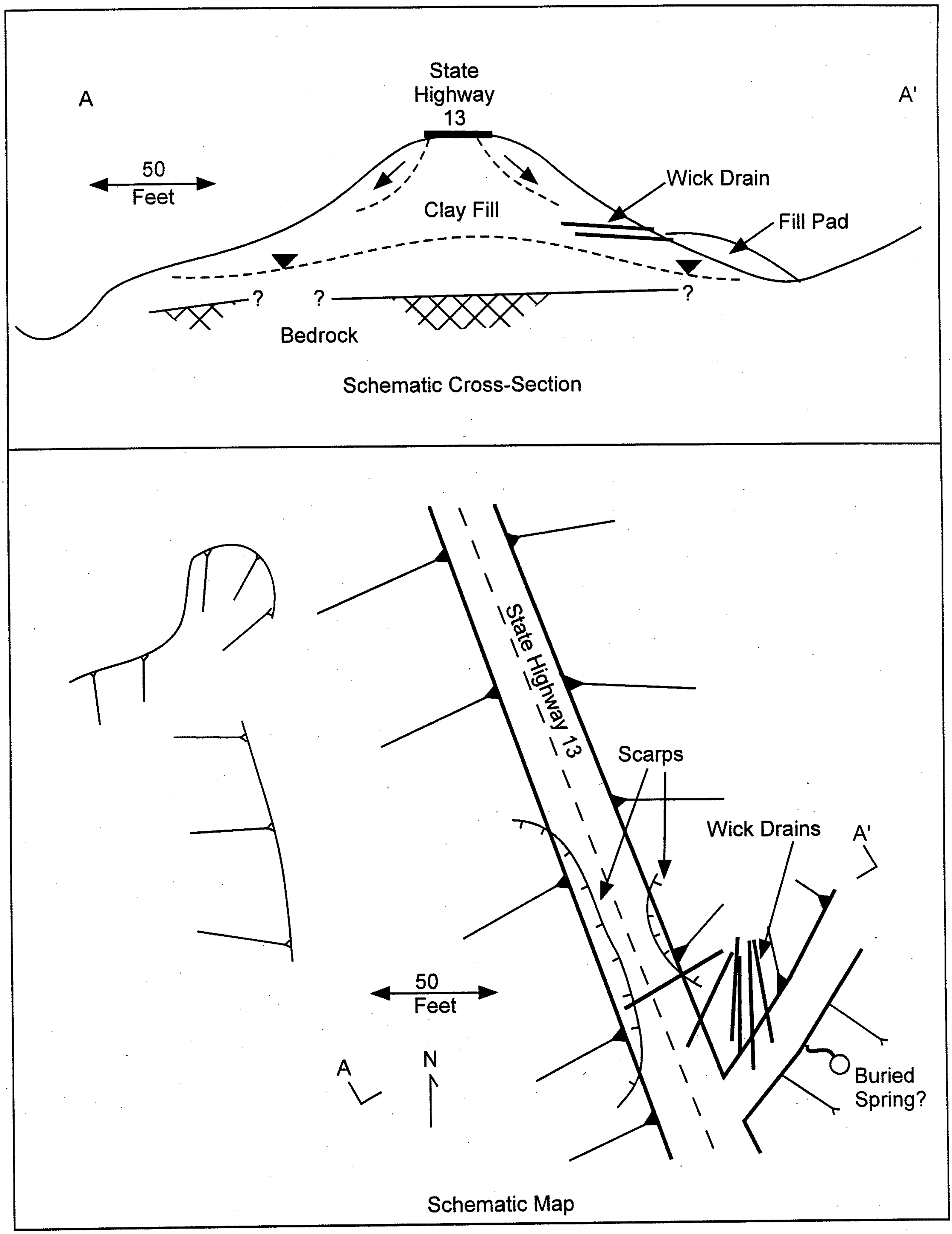


Figure 15 - Schematic Drawings of the Rio Blanco, CO Landslide

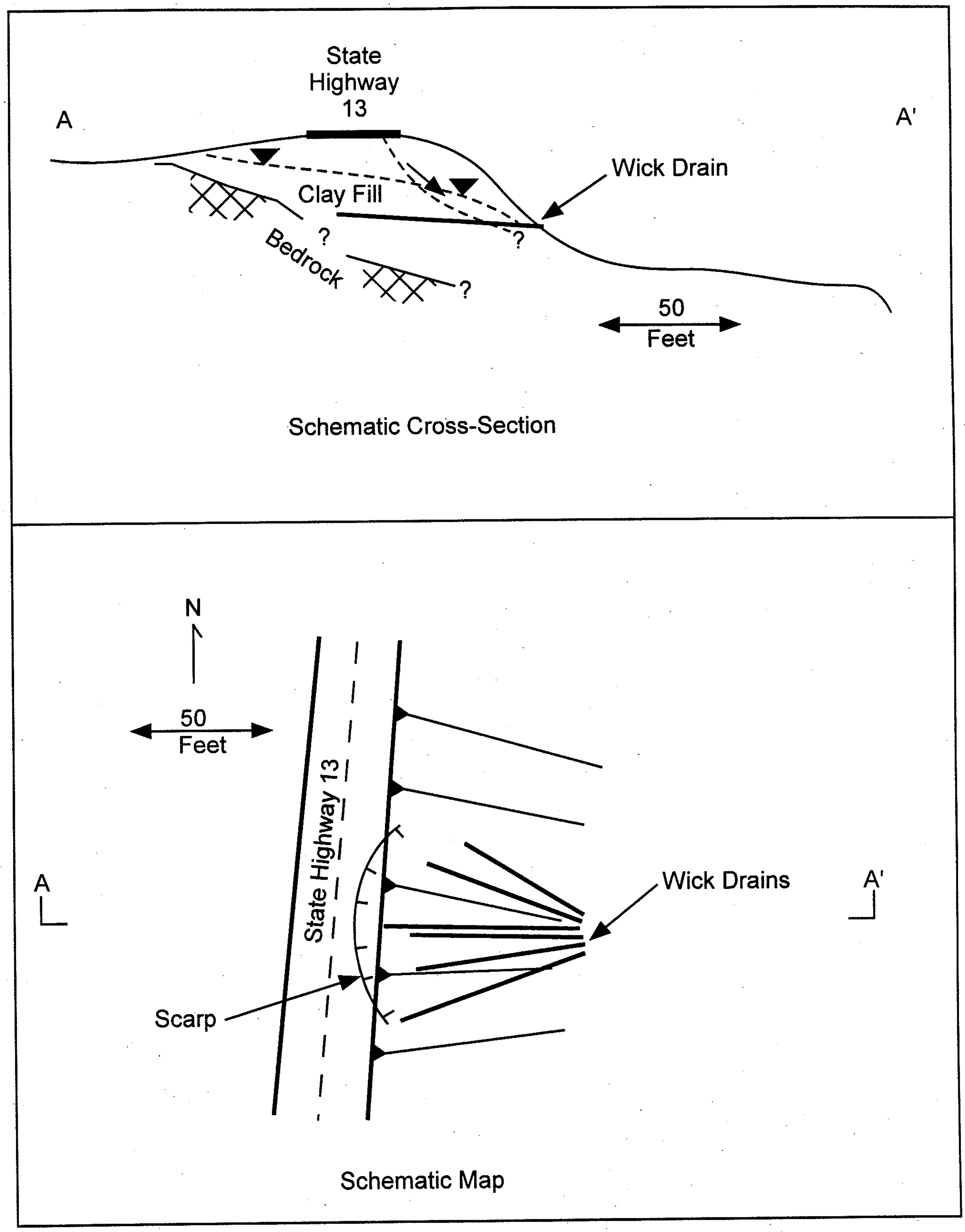


Figure 16 - Schematic Drawings of the Meeker (North), CO Landslide

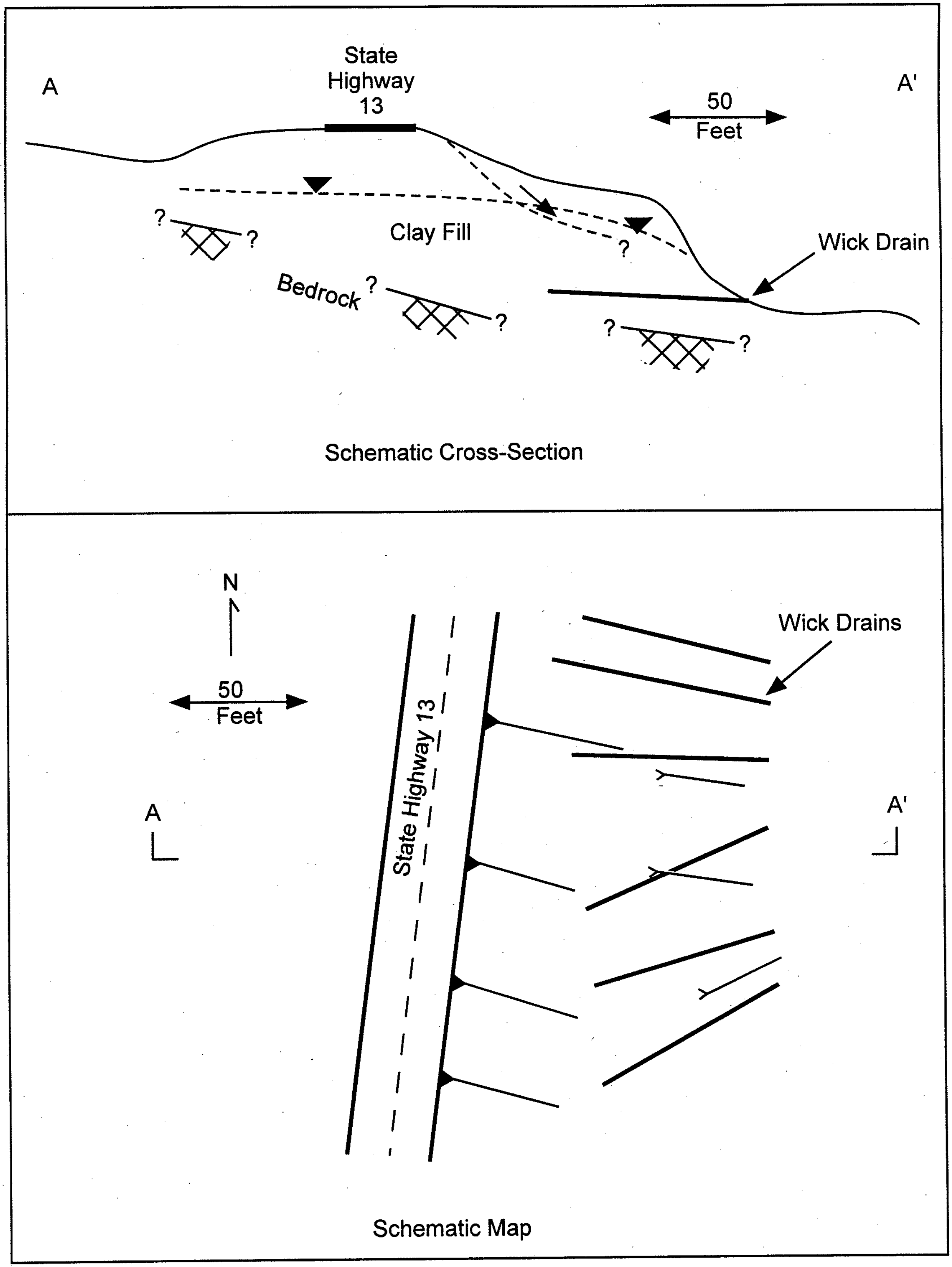


Figure 17 - Schematic Drawings of the Meeker (South), CO Landslide

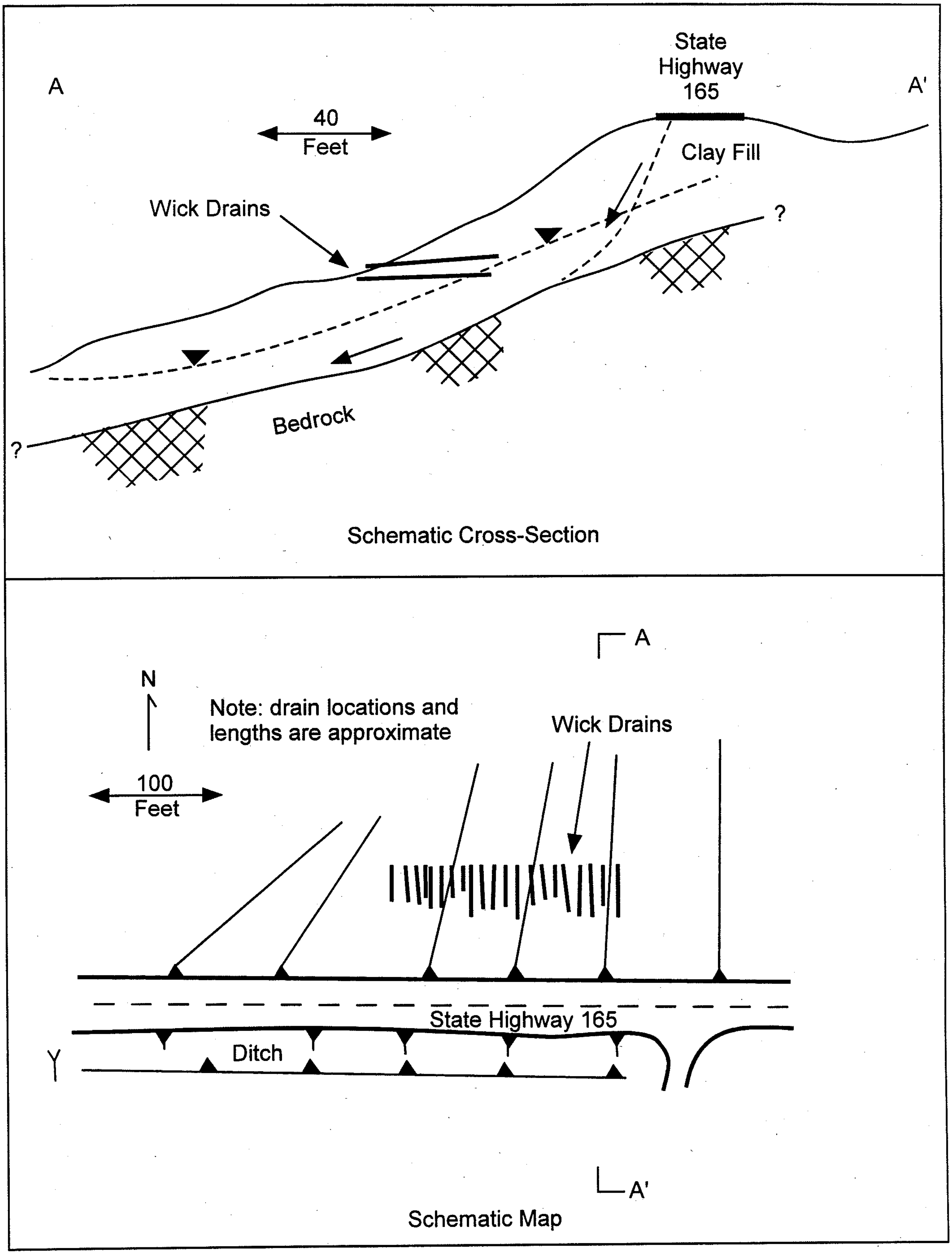


Figure 18 - Schematic Drawings of the Rye, CO Landslide

Figure 19. Installation of drains at the Rye, Colorado site using a standard wick drain driving rig provided by Nilex Corporation. Note that the rig boom is lowered to push drains horizontally back through the tracks underneath the equipment.

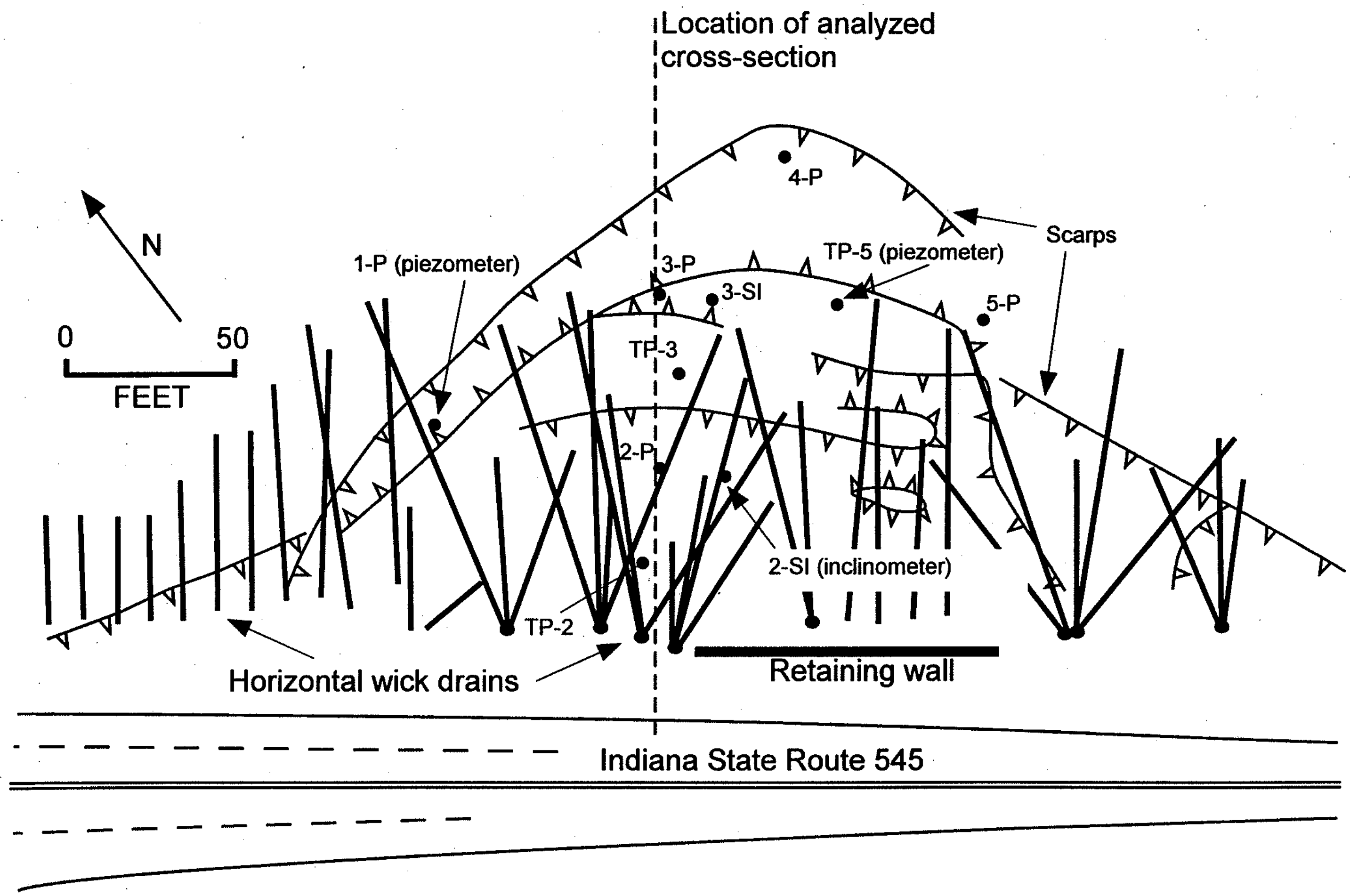


Figure 20. Features of the SR 545 landslide near Jasper, Indiana

Figure 21. Failed retaining wall at Jasper, Indiana landslide. Note overturning at left end of wall.

Figure 22. Wick drains bundled into irrigation pipe. After burial, only irrigation pipe outlet at bottom of picture will be exposed.

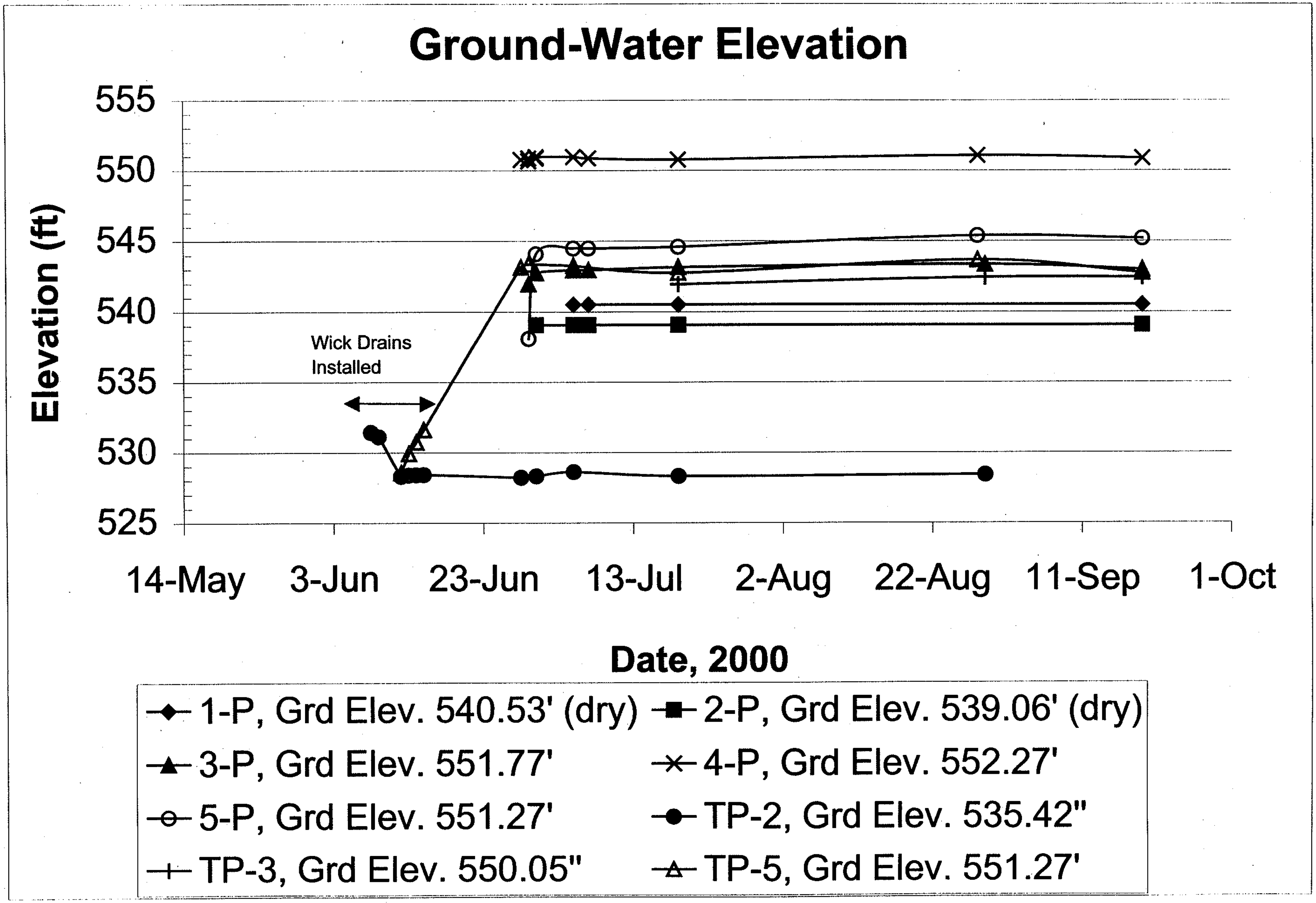


Figure 23. Jasper Ground-Water Levels

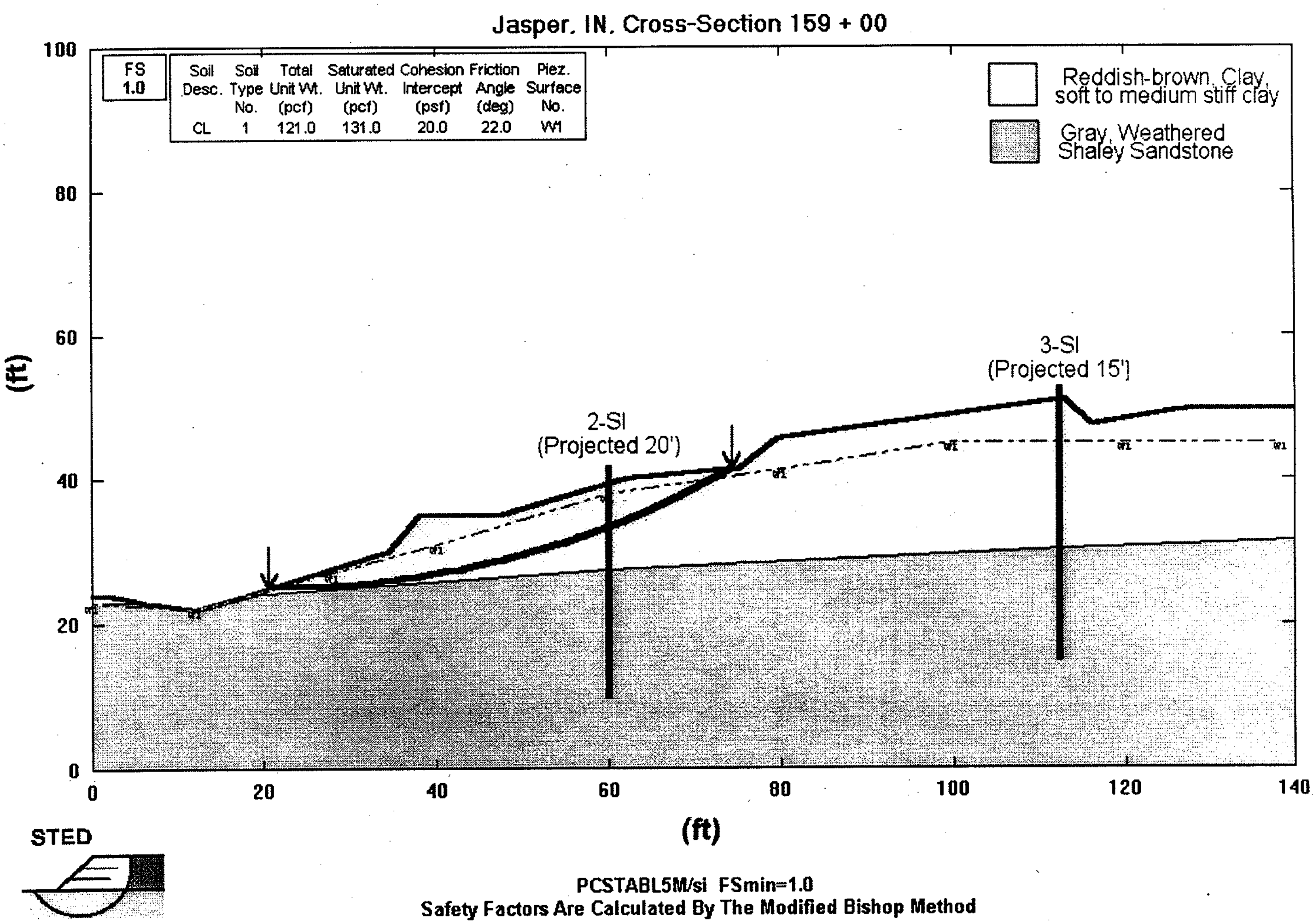


Figure 24. Stability at Jasper, IN with high ground water

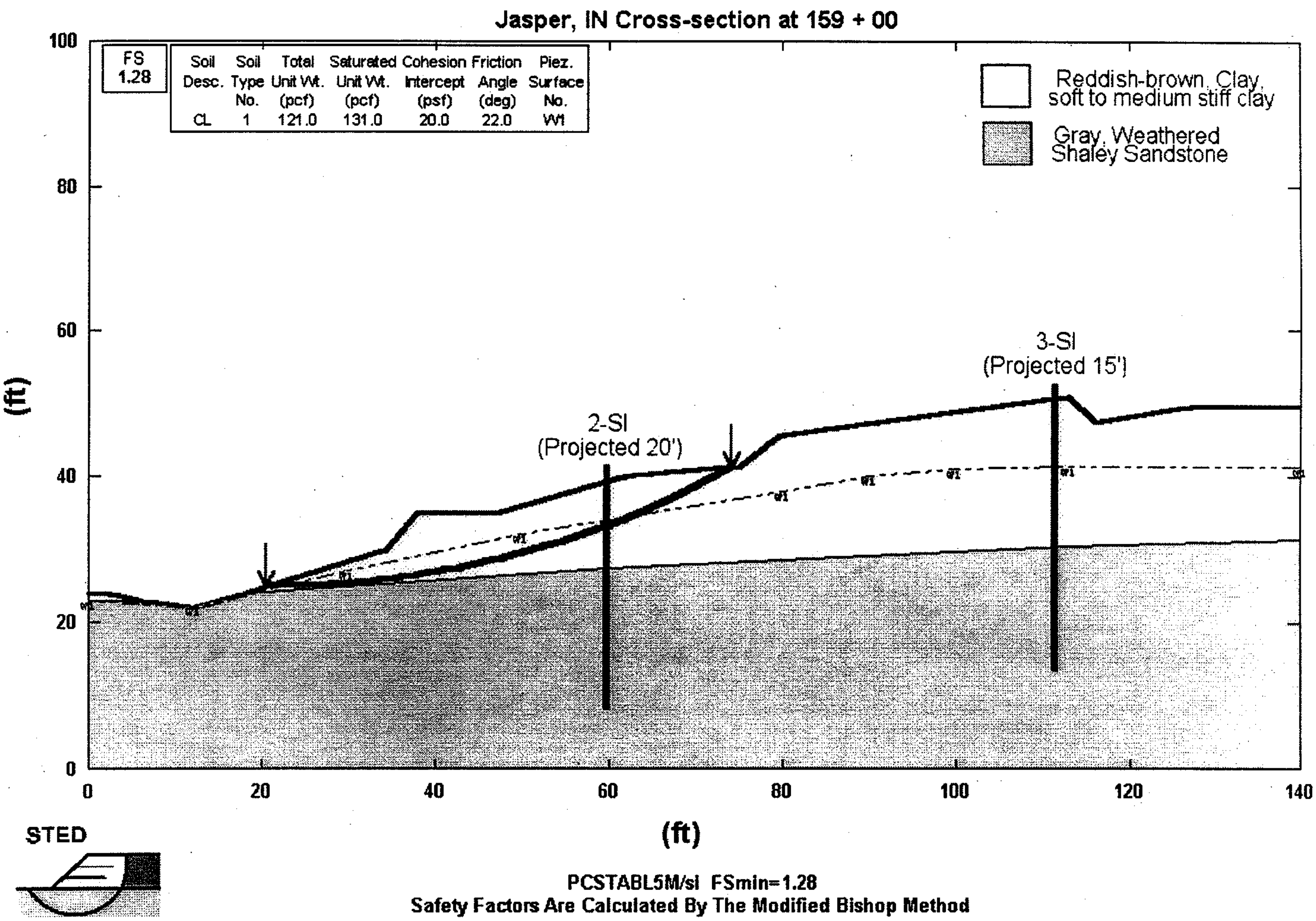


Figure 25. Stability at Jasper, IN under current conditions

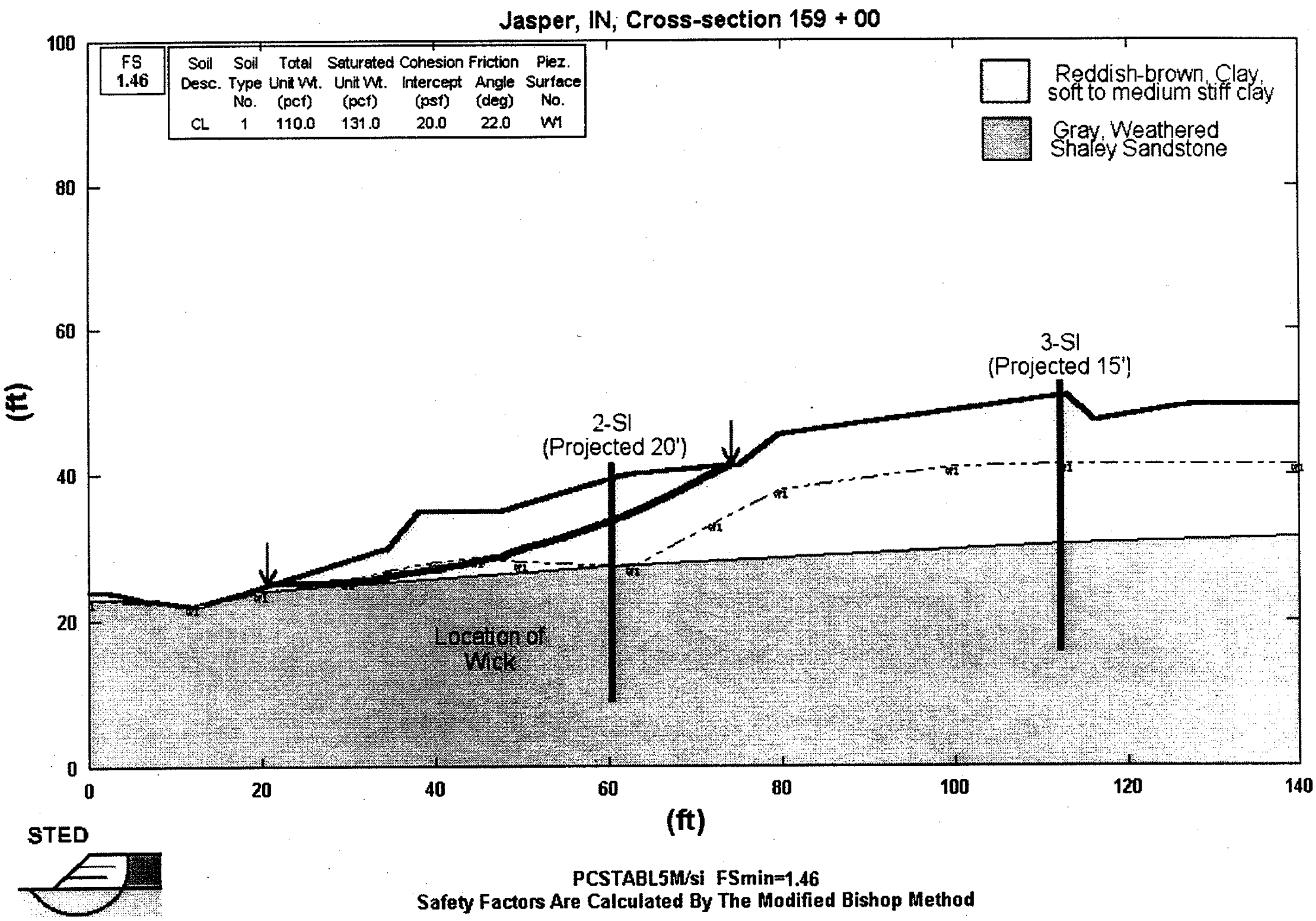


Figure 26. Stability at Jasper, IN with wick drains installed

Figure 27. Wick drain at Meeker (South), Colorado Landslide one year after installation. Drain has been exposed and run over by equipment. Note dark staining of ground saturated by recent water discharge from drain. Light staining of ground is salt accumulation from evaporation of water discharged from drain.

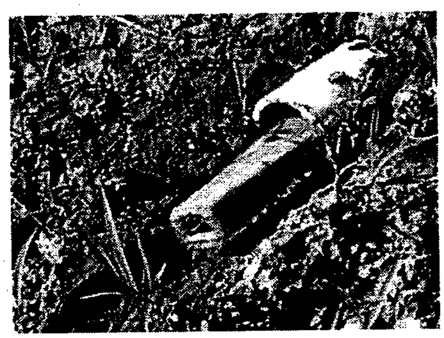


Figure 28. Wick drain at St. Joseph, Missouri Landslide one year after installation. Drain has been protected by PVC sleeve pipe and appears to be in excellent condition.

Figure 29. Drainage from the Meeker (North), Colorado Landslide one year after installation. At this location, six drains were bundled into a single irrigation hose and buried. Algae is growing at the pipe outlet and the grass is noticeably more healthy than surrounding areas.

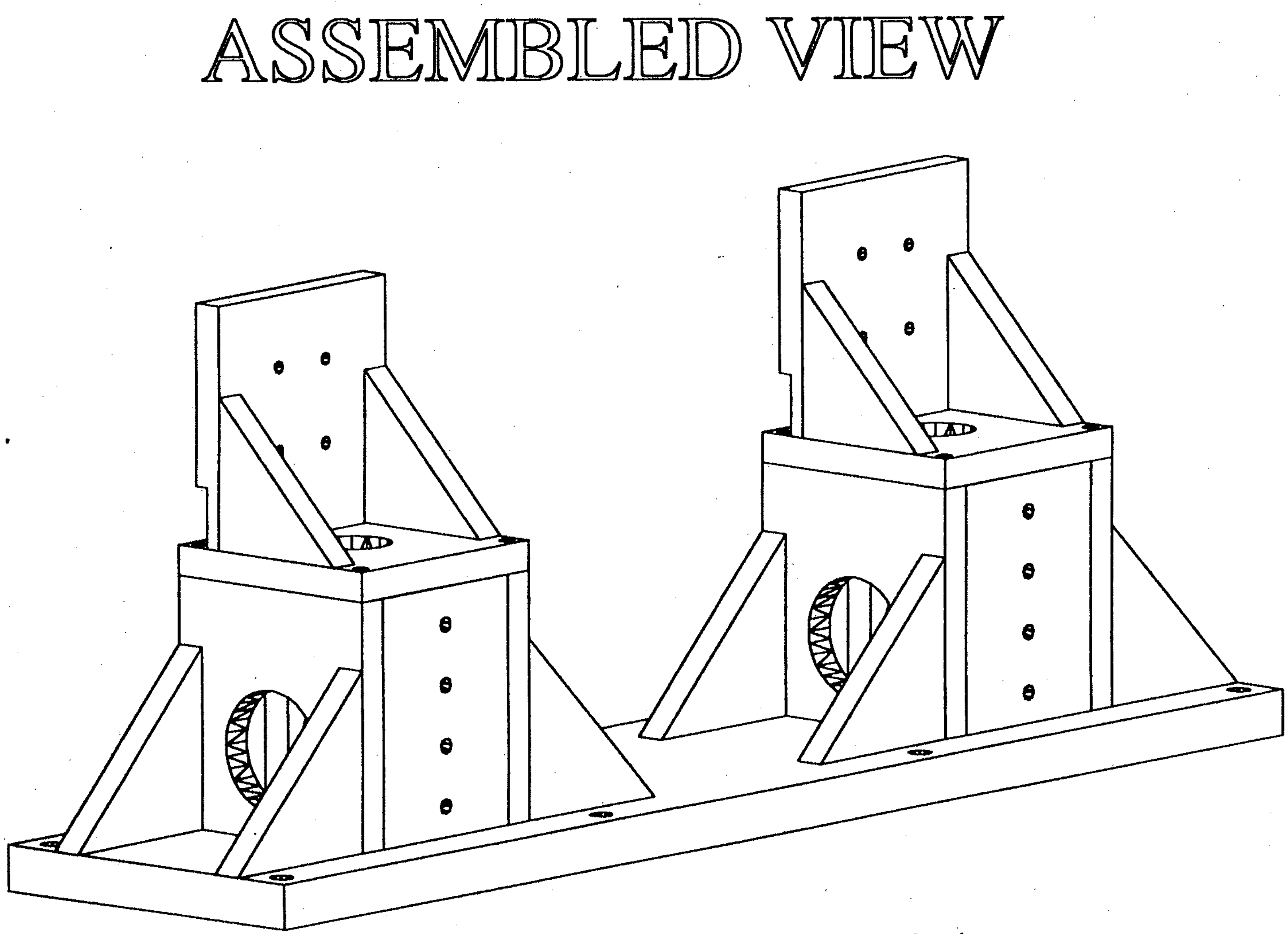


Figure 30. Drawing of Pipe Gripping Mechanism

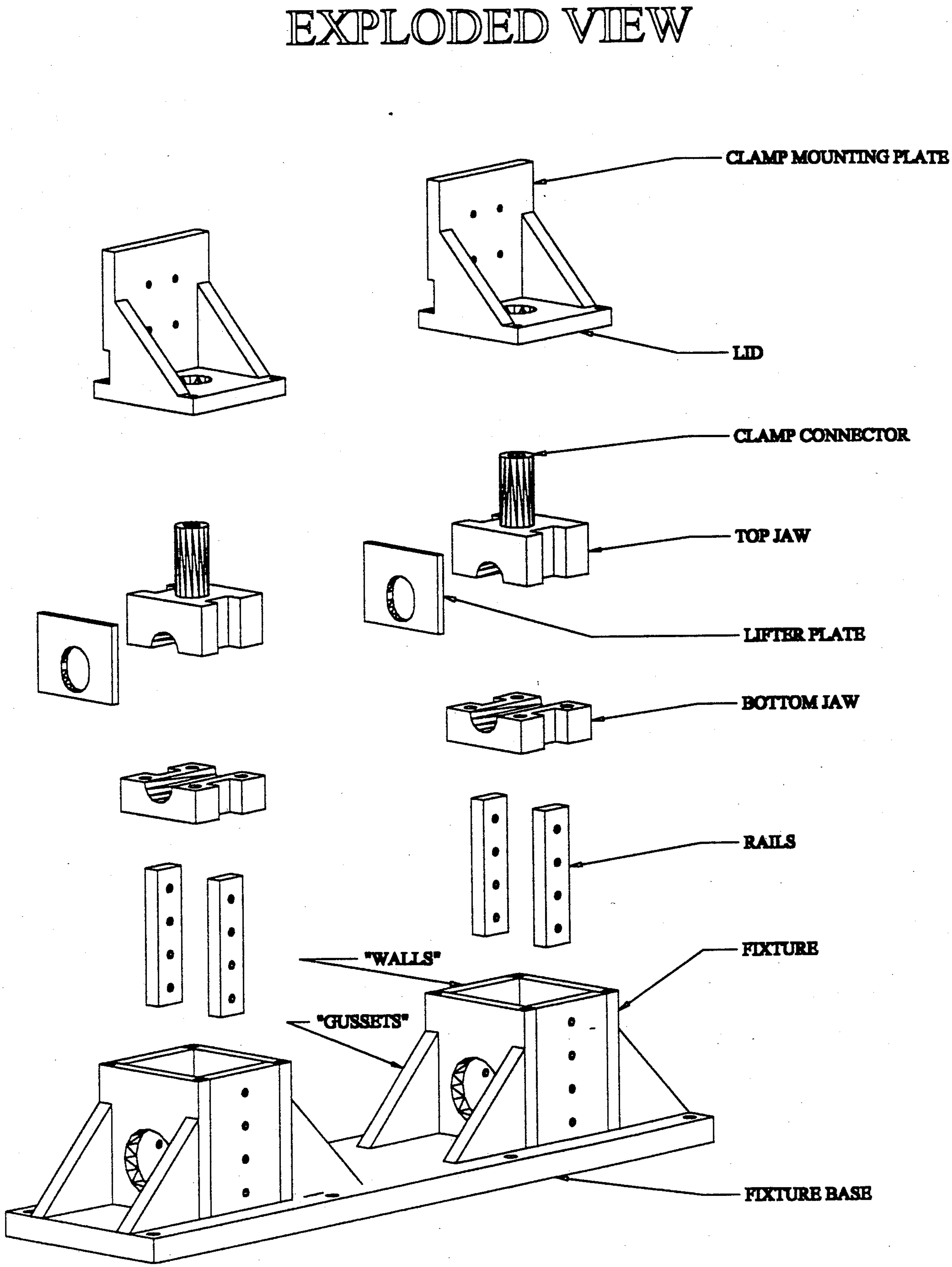


Figure 31. Details of Pipe Gripping Mechanism

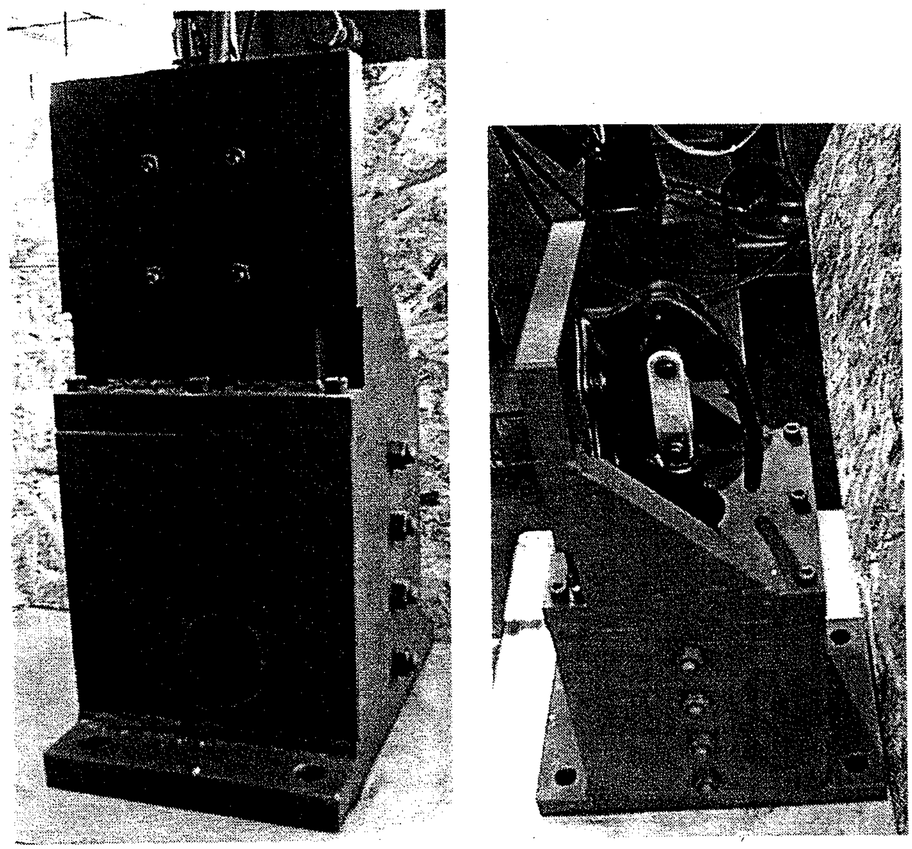
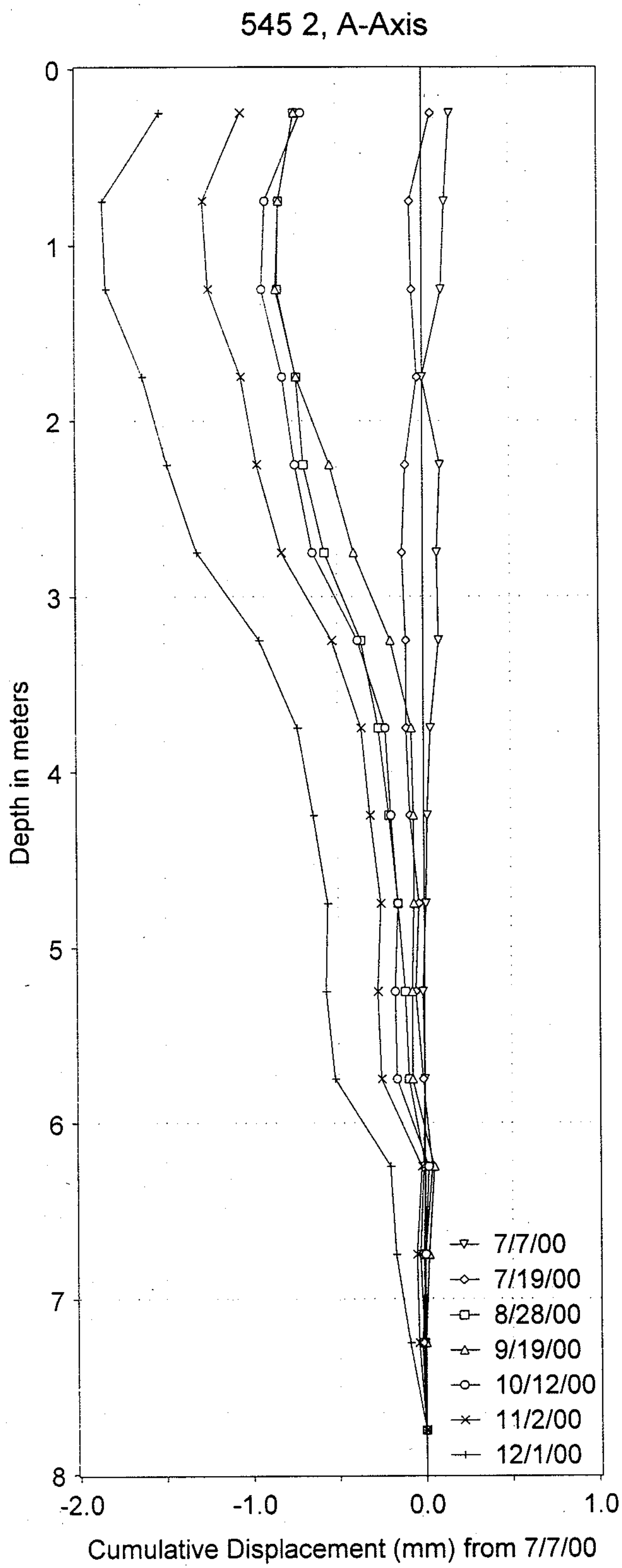
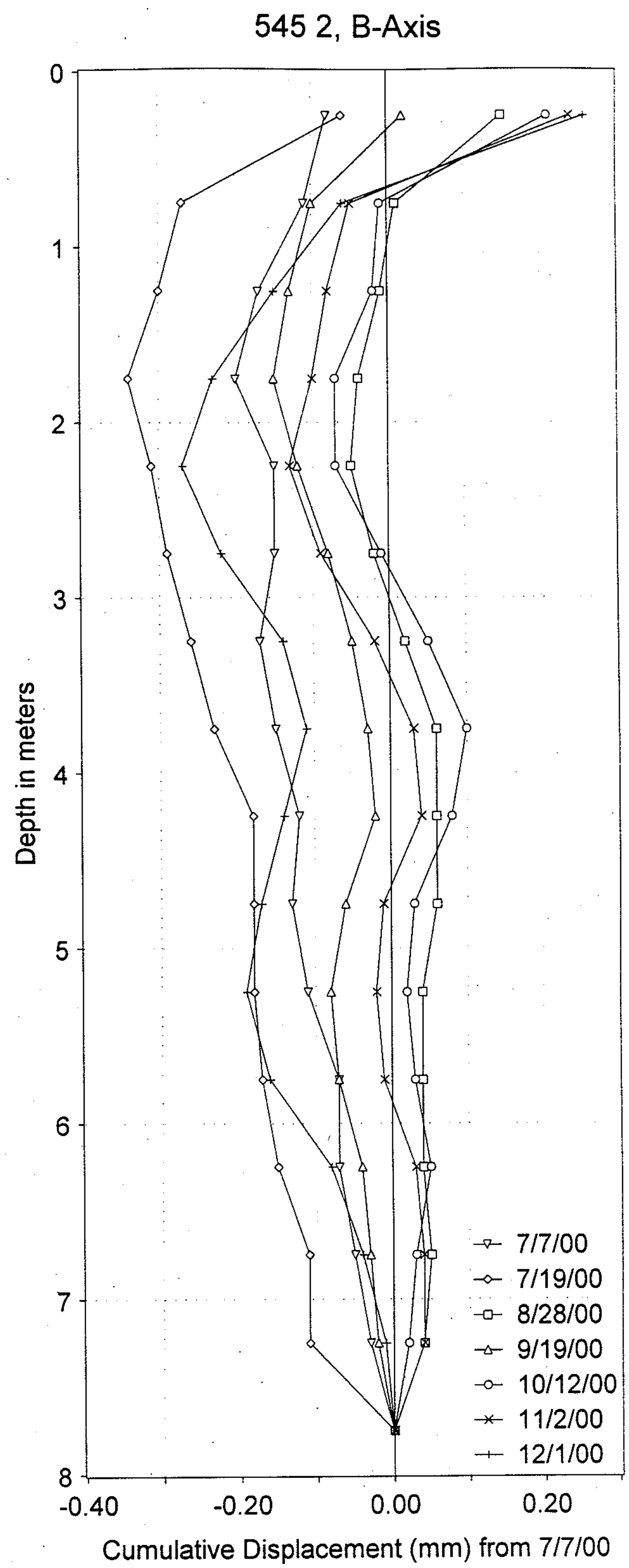


Figure 32. Photographs of the prototype pipe gripping mechanism.

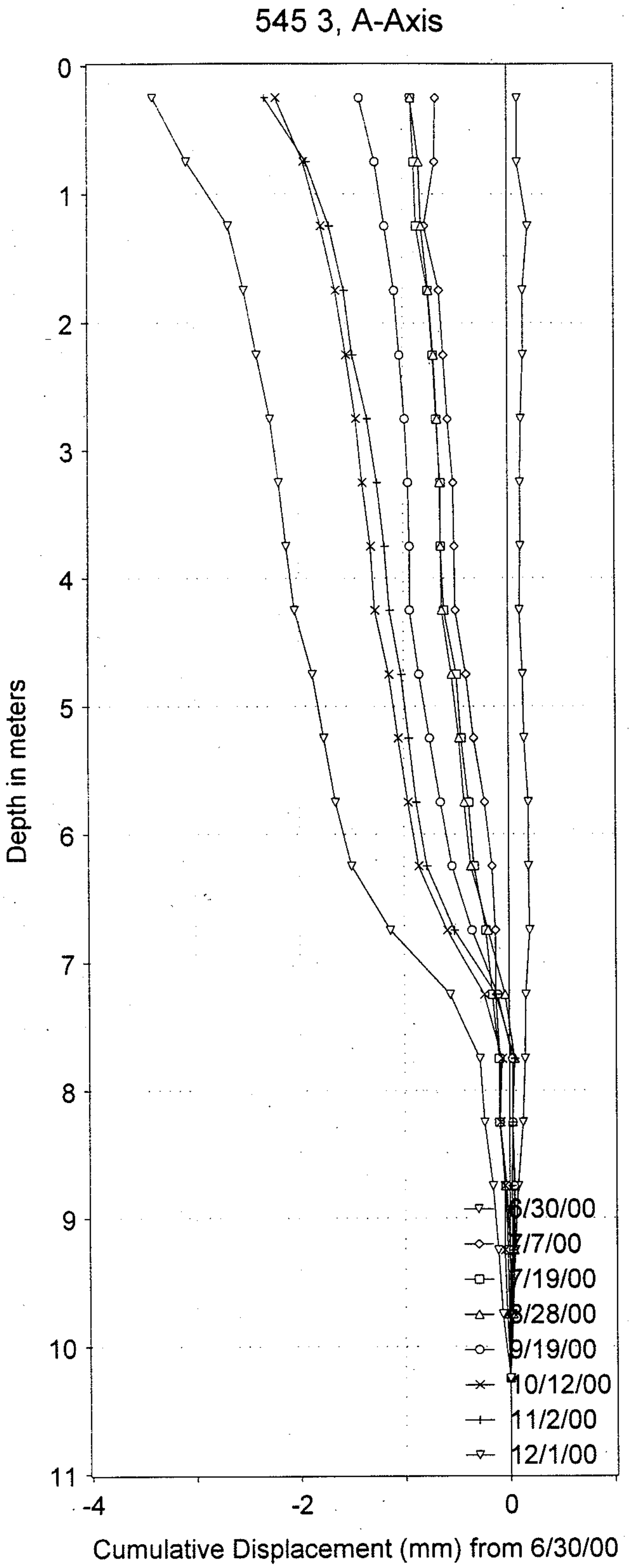
Appendix A

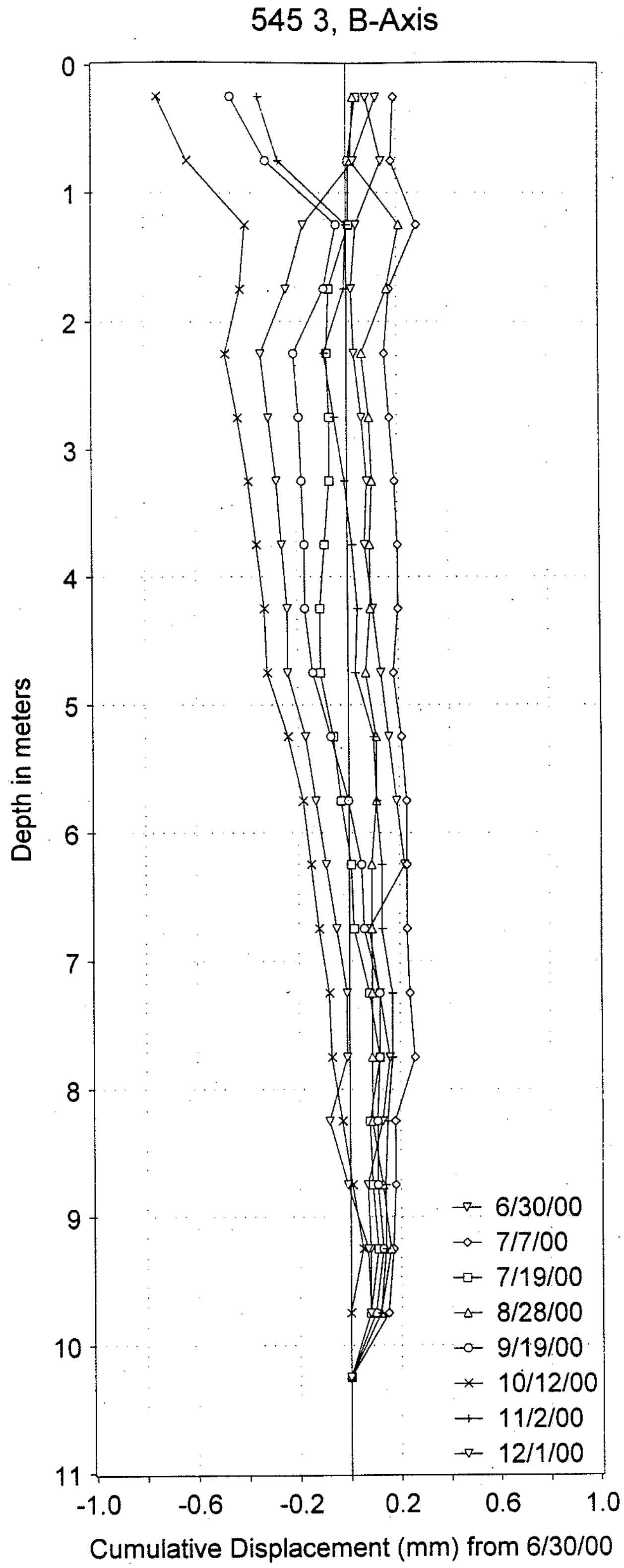
Summary of field and laboratory testing for Jasper, Indiana site





Inclinometer Readings





Inclinometer Readings

LOG OF TEST BORING

EARTH EXPLORATION Inc

Project	SR 545 Landslide
Location	Dubois County, Indiana
Client	Indiana Department of Transportation

7770 West New York Street · Indianapolis, Indiana 46214
317-273-1690 / 317-273-2250 (Fax)

Boring No.	1-P
Elevation	540.5
Datum	USC & GS
EEI Proj. No.	1-6161
Sheet	1 of 1

Proj. No.	SR 545 Slide	Station	101+30	Weather	Rain	Driller	J.M.
Struct. No.	---	Offset	95' Lt. of Centerline	Temp.	85 deg F	Inspector	D. Chase

SAMPLE / DESCRIPTION/CLASSIFICATION and REMARKS / SOIL PROPERTIES

No.	Type	Rec %	Blow Counts	Description	q_p tsf	q_u tsf	γ_d pcf	W %	LL %	PL %	PI %
SS-1	X	80	2 2 2		1.5						
SS-2	X	20	2 2 3	SS-2 = Driving a stone, reddish-brown, moist, soft, Clay with sandstone fragments A-7-6 (14) Lab. #: 00-5958							
1PT-1	■	71									
SS-3	X	80	2 2 3								
				Brown and gray mottled, very moist to moist, soft Clay A-7-6(14) Lab #: 00-6002							
SS-4	X	100	18 50/.2	Gray and brown, weathered Shale and Shaley Sandstone, soft to medium hard, moist (bedrock)							
SS-5	X	100	29 50/.4	Gray, dry Shale (bedrock)							

Depth scale: ft 0–40; m 0–12.

End of Boring at 19.4'

Piezometer

0' – 2.0' --	Protective Cover
2.0' – 7.5' --	Bentonite Pellets
7.5' – 9.0' --	#4 Sand
9.0' – 11.0' --	#7 Sand
11.0' – 14.0' --	#4 Sand
14.0' – 19.4' --	Bentonite Chips

WATER LEVEL OBSERVATIONS

Depth ft	While Drilling	Upon Completion	2 Hr. After Drilling
To Water	NW	NW	NW
To Cave-in			

The stratification lines represent the approximate boundary between soil/rock types and the transition may be gradual.

GENERAL NOTES

Start 7/5/00 End 7/5/00 Rig D-120
Drilling Method 4-1/4" I.D. HSA ATV
Remarks Borehole equipped with piezometer.

LOG OF TEST BORING

EARTH EXPLORATION

7770 West New York Street · Indianapolis, Indiana 46214
317-273-1690 / 317-273-2250 (Fax)

Project	SR 545 Landslide
Location	Dubois County, Indiana
Client	Indiana Department of Transportation

Boring No.	2-P
Elevation	539.1
Datum	USC & GS
EEI Proj. No.	1-6161
Sheet	1 of 1

Proj. No.	SR 545 Slide	Station	102+00	Weather	Sunny	Driller	J.M.
Struct. No.	---	Offset	85' Lt. of Centerline	Temp.	80 deg F	Inspector	D. Chase

SAMPLE					DESCRIPTION/CLASSIFICATION and REMARKS	SOIL PROPERTIES						
No.	Type	Rec %	Blow Counts	Depth ft m		q_p tsf	q_u tsf	γ_d pcf	W %	LL %	PL %	PI %
				0–15 ft	See Boring 2-SI for description of materials							
2PT-1		75										
				15 ft	End of Boring at 15.0'							

WATER LEVEL OBSERVATIONS

Depth ft	While Drilling	Upon Completion	After Drilling
To Water	NW	NW	
To Cave-in			

The stratification lines represent the approximate boundary between soil/rock types and the transition may be gradual.

GENERAL NOTES

Start 6/30/00 End 6/30/00 Rig D-120
Drilling Method 4-1/4" I.D. HSA ATV
Remarks Borehole equipped with piezometer.

LOG OF TEST BORING

EARTH EXPLORATION Inc

Project	SR 545 Landslide
Location	Dubois County, Indiana
Client	Indiana Department of Transportation

7770 West New York Street · Indianapolis, Indiana 46214
317-273-1690 / 317-273-2250 (Fax)

Boring No.	3-P
Elevation	551.8
Datum	USC & GS
EEI Proj. No.	1-6161
Sheet	1 of 1

Proj. No.	SR 545 Slide	Station	102+20	Weather	Sunny	Driller	J.M.
Struct. No.	---	Offset	131' Lt. of Centerline	Temp.	80 deg F	Inspector	D. Chase

SAMPLE No.	Type	Rec %	Blow Counts	Depth ft / m	DESCRIPTION/CLASSIFICATION and REMARKS	q_p tsf	q_u tsf	γ_d pcf	W %	LL %	PL %	PI %
3PT-1		92		8–10	See Boring 3-SI for description of materials							
3PT-2		88		13–15								
				26.7	End of Boring at 26.7'							

WATER LEVEL OBSERVATIONS

Depth ft	While Drilling	Upon Completion	16 Hr. After Drilling
To Water		10	9.2
To Cave-in			

The stratification lines represent the approximate boundary between soil/rock types and the transition may be gradual.

GENERAL NOTES

Start 6/29/00 End 6/29/00 Rig D-120
Drilling Method 3-1/4" I.D. HSA ATV
Remarks Borehole equipped with piezometer.

LOG OF TEST BORING

EARTH EXPLORATION Inc

Project	SR 545 Landslide
Location	Dubois County, Indiana
Client	Indiana Department of Transportation

7770 West New York Street · Indianapolis, Indiana 46214
317-273-1690 / 317-273-2250 (Fax)

Boring No.	4-P		
Elevation	552.3		
Datum	USC & GS		
EEI Proj. No.	1-6161		
Sheet	1	of	1

Proj. No.	SR 545 Slide	Station	102+50	Weather	Partly Sunny	Driller	J.M.
Struct. No.	---	Offset	180' Lt. of Centerline	Temp.	80 deg F	Inspector	D. Chase

SAMPLE No.	Type	Rec %	Blow Counts	DESCRIPTION/CLASSIFICATION and REMARKS	q_p tsf	q_u tsf	γ_d pcf	W %	LL %	PL %	PI %
				Brown, moist, soft, Silty Clay Loam							
SS-1	X	80	2 2 3	Yellowish-brown, moist, soft, silty Clay Loam	1.5						
SS-2	X	90	4 4 7	Brown and gray mottled, moist, medium stiff, Silty Clay Loam	2.0						
SS-3	X	90	3 6 6	Reddish brown, slightly moist, Clay Loam with Sandstone fragments	3.0						
SS-4	X	40	2 2 5	Red, moist, soft, Clay with gray mottles, with Sandstone fragments	2.0						
4PT-1	■	75									
SS-5	X	90	3 4 7	Brown and gray, moist, medium stiff to stiff, Silty Clay with Weathered Shale fragments, wet seam at 14.0' in sample	2.5						
SS-6	X	100	5 6 10		4.5						
				Dark brownish red, Clay							
SS-7	X	90	6 11 32	Gray, slightly moist, soft, Weathered Shale							
				Gray, Shaley Sandstone, medium to hard							
SS-8	X	100	47 50/.5								
				End of Boring at 29.2'							

Piezometer

0.0' – 2.0' --	Protective cover
2.0' – 9.5' --	Bentonite Chips
9.5' – 18.0' --	# 4 Sand
18.0' – 29.2' --	Bentonite Chips

Depth scale: ft 5, 10, 15, 20, 25, 30, 35, 40; m 1–12

WATER LEVEL OBSERVATIONS

Depth ft	▽ While Drilling	▼ Upon Completion	▽ 24 Hr. After Drilling
To Water	14.5	NW	1.4
To Cave-in			

The stratification lines represent the approximate boundary between soil/rock types and the transition may be gradual.

GENERAL NOTES

Start 6/27/00 End 6/27/00 Rig D-120

Drilling Method 4-1/4" I.D. HSA ATV

Remarks Borehole equipped with piezometer.

LOG OF TEST BORING

EARTH EXPLORATION LLC

Project	SR 545 Landslide
Location	Dubois County, Indiana
Client	Indiana Department of Transportation

7770 West New York Street · Indianapolis, Indiana 46214
317-273-1690 / 317-273-2250 (Fax)

Boring No.	5-P
Elevation	547.6
Datum	USC & GS
EEI Proj. No.	1-6161
Sheet	1 of 1

Proj. No.	SR 545 Slide	Station	103+12	Weather	Sunny	Driller	J.M.
Struct. No.	---	Offset	125' Lt. of Centerline	Temp.	80 deg F	Inspector	D. Chase

SAMPLE No.	Type	Rec %	Blow Counts	Depth	DESCRIPTION/CLASSIFICATION and REMARKS	qp tsf	qu tsf	γd pcf	W %	LL %	PL %	PI %
SS-1	X	100	1 2 2		Brown, moist, soft, Silty Loam A-4(3) Lab #: 00-6053	3.0						
SS-2	X	100	2 3 3	5 ft	Brown, moist, medium stiff Silty Clay Loam A-4(4) Lab #: 00-6055	1.5						
5PT-1	■	100										
5PT-2	■	50			Reddish brown, moist, soft, Clay with Sandstone fragments (Vis.)							
SS-3	X	80	1 3 8	10 ft	Reddish brown, very moist, soft to medium stiff, Clay, with Sandstone fragments, wet seam at 10.5'	1.5						
					Weathered Sandstone							
SS-4	X	10	28 7 5	15 ft	Brown, moist, stiff, Silty Clay Loam (Vis.)							
SS-5	X	100	6 10 16	20 ft	Gray and brown to gray, soft, Weathered Shale	4.0						
					Dark reddish brown Clayey Shale							
					Sandstone and Sandy Shale, medium Hard gray							
SS-6	X	80	37 50/.2									
				25 ft	End of Boring at 24.2'							

Depth scale: ft 5, 10, 15, 20, 25, 30, 35, 40; m 1–12.

Piezometer

0.0' – 2.0' --	Protective cover
2.0' – 6.5' --	Bentonite Chips
6.5' – 7.5' --	Bentonite Pellets
7.5' – 10.0' --	# 4 Sand
9.5' – 11.5' --	# 7 Sand
11.5' – 13.3' --	# 4 Sand
13.3' – 24.2' --	Bentonite Chips

WATER LEVEL OBSERVATIONS

Depth ft	∇ While Drilling	▼ Upon Completion	∇ 24 Hr. After Drilling
To Water	10.5	NW	3.5
To Cave-in			

The stratification lines represent the approximate boundary between soil/rock types and the transition may be gradual.

GENERAL NOTES

Start 6/29/00 End 6/29/00 Rig D-120
Drilling Method 4-1/4" I.D. HSA ATV
Remarks Borehole equipped with piezometer.

Earth Exploration, Inc.

LOG OF TEST BORING

Project	SR 545 Landslide
Location	Dubois County, Indiana
Client	Indiana Department of Transportation

7770 West New York Street · Indianapolis, Indiana 46214
317-273-1690 / 317-273-2250 (Fax)

Boring No.	2-SI
Elevation	539.2
Datum	USC & GS
EEI Proj. No.	1-6161
Sheet	1 of 1

Proj. No.	SR 545 Slide	Station	102+06	Weather	Cloudy	Driller	J.M.
Struct. No.	---	Offset	85' Lt. of Centerline	Temp.	80 deg F	Inspector	D. Chase

SAMPLE No.	Type	Rec %	Blow Counts	Depth ft	DESCRIPTION/CLASSIFICATION and REMARKS	q_p tsf	q_u tsf	γ_d pcf	W %	LL %	PL %	PI %
SS-1	X	90	1 1 2	0–10.5	Reddish-brown, moist and very moist. Very soft to soft, Clay with some rock fragments. A-7-6 Lab. #: 00-5998							
SS-2	X	70	2 2 3			2.0						
SS-3	X	80	1 3 8			2.0						
SS-4	X	20	3 3 3									
					Gray, moist, soft, Weathered Shale							
SS-5	X		30 50/.5		Brown and gray, moist, Weathered Shaley Sandstone							
RC-1		100	RQD=40%	15–25	Gray, Shaley Sandstone Rock Core dia. 2"							
RC-2		92	RQD=75%									
				25	End of Boring at 25.0' ** Installed Slope-Indicator Casing backfilled with neat cement grout							

WATER LEVEL OBSERVATIONS

Depth ft	While Drilling	Upon Completion	After Drilling
To Water	NW		
To Cave-in			

The stratification lines represent the approximate boundary between soil/rock types and the transition may be gradual.

GENERAL NOTES

Start 6/30/00 End 6/30/00 Rig D-120
Drilling Method 4-1/4" I.D. HSA ATV
Remarks Borehole equipped with slope inclinometer.

EARTH EXPLORATION, INC.

LOG OF TEST BORING

Project: SR 545 Landslide
Location: Dubois County, Indiana
Client: Indiana Department of Transportation
7770 West New York Street · Indianapolis, Indiana 46214
317-273-1690 / 317-273-2250 (Fax)

Boring No. 3-SI
Elevation 550.9
Datum USC & GS
EEI Proj. No. 1-6161
Sheet 1 of 1

Proj. No.	SR 545 Slide	Station	102+19	Weather	Cloudy	Driller	J.M.
Struct. No.	---	Offset	126' Lt. of Centerline	Temp.	75 deg F	Inspector	D. Chase

SAMPLE No.	Type	Rec %	Blow Counts	Depth ft	DESCRIPTION/CLASSIFICATION and REMARKS	q_p tsf	q_u tsf	γ_d pcf	W %	LL %	PL %	PI %
SS-1	X	90	6 5 8		Reddish-brown, moist, stiff, Clay Loam with Sandstone fragments A-6-(7) Lab. #: 00-6022	3.5						
SS-2	X	70	5 4 5			4.5						
SS-3	X	70	4 5 6		Reddish and yellow-brown, moist, medium Stiff, Clay, with Sandstone fragments A-7-6 Lab. #: 00-5998	3.0						
SS-4	X	60	4 5 5			2.5						
SS-5	X	60	1 2 5		Reddish-brown and mottled gray to gray moist, soft to medium stiff Clay A-7-6 Lab. #: 00-6002	3.0						
SS-6	X	70	3 4 6			>4.5						
				▽ 21	Very moist, gray, Clay (Vis.)							
					Dark reddish-brown, Clay (Vis.)							
SS-7	X	90	9 15 50/.3		Gray and brown, moist, Weathered Shale	>4.5						
					Gray and brown, slightly moist, medium hard, Shaley Sandstone (Vis.)							
RC-1		92	RQD=18%		Gray and light gray, Shaley Sandstone, medium hard, with a few calcareous streaks Rock Core dia. 2.0"							
RC-2		100	RQD=93%									
					End of Boring at 36.2'							

Depth scale: ft 5, 10, 15, 20, 25, 30, 35, 40; m 1–12

WATER LEVEL OBSERVATIONS

Depth ft	▽ While Drilling	▼ Upon Completion	▽ After Drilling
To Water	21		
To Cave-in			

The stratification lines represent the approximate boundary between soil/rock types and the transition may be gradual.

GENERAL NOTES

Start 6/27/00 End 6/27/00 Rig: D-120
Drilling Method: 4-1/4" I.D. HSA ATV
Remarks: Borehole equipped with slope inclinometer, backfilled with neat cement grout

9/14/00

SUMMARY OF CLASSIFICATION TEST RESULTS

DES. NO. 9137165
PROJECT NO. SR545 SLIDE
STRUCTURE NO. N/A
COUNTY DUBOIS

LABORATORY NUMBER	PART	BORING NUMBER	STATION	OFFSET LINE	SAMPLE NUMBER	SAMPLE DEPTH	TEXTURAL/ UNIFIED	AASHTO	NO. 10	NO. 40	NO. 200	GRAVEL 76.2 - 2.00 mm	SAND 2.00- 0.074 mm	SILT 0.074- 0.002 mm	CLAY BELOW 0.002 mm	BELOW 0.001 mm	LL	PL	PI
007078805998		1-P	101+30	95' LT	SS 1-T	1.0'-2.5'	CLAY	A-7-6(14)	97.2	96.7	67.9	2.8	29.3	28.1	39.8	35.9	41.9	18.6	23.3
007078806002		1-P	101+30	95' LT	SS 3-T	8.5'-10.0'	CLAY	A-7-6(14)	100.0	99.9	75.1	0.0	24.9	32.9	42.2	35.9	41.5	22.3	19.2
007078806022		3-SI	102+19	12.6' LT	SS 2-T	3.5'-5.0'	CLAY LOAM	A-6(7)	88.8	87.1	59.5	11.2	29.3	32.1	27.4	24.9	33.2	17.3	15.9
007078806053		5-P	103+12	125' LT	SS 1-T	1.0'-2.5'	SILTY LOAM	A-4(3)	98.1	97.2	74.2	1.9	23.9	54.9	19.3	16.5	24.9	18.8	6.1
007078806055		5-P	103+12	125' LT	SS 2-T	3.5'-5.0'	SILTY CLAY LOAM	A-4(4)	99.7	99.0	73.9	0.3	25.8	50.0	23.9	21.5	26.6	17.9	8.7

9/14/00

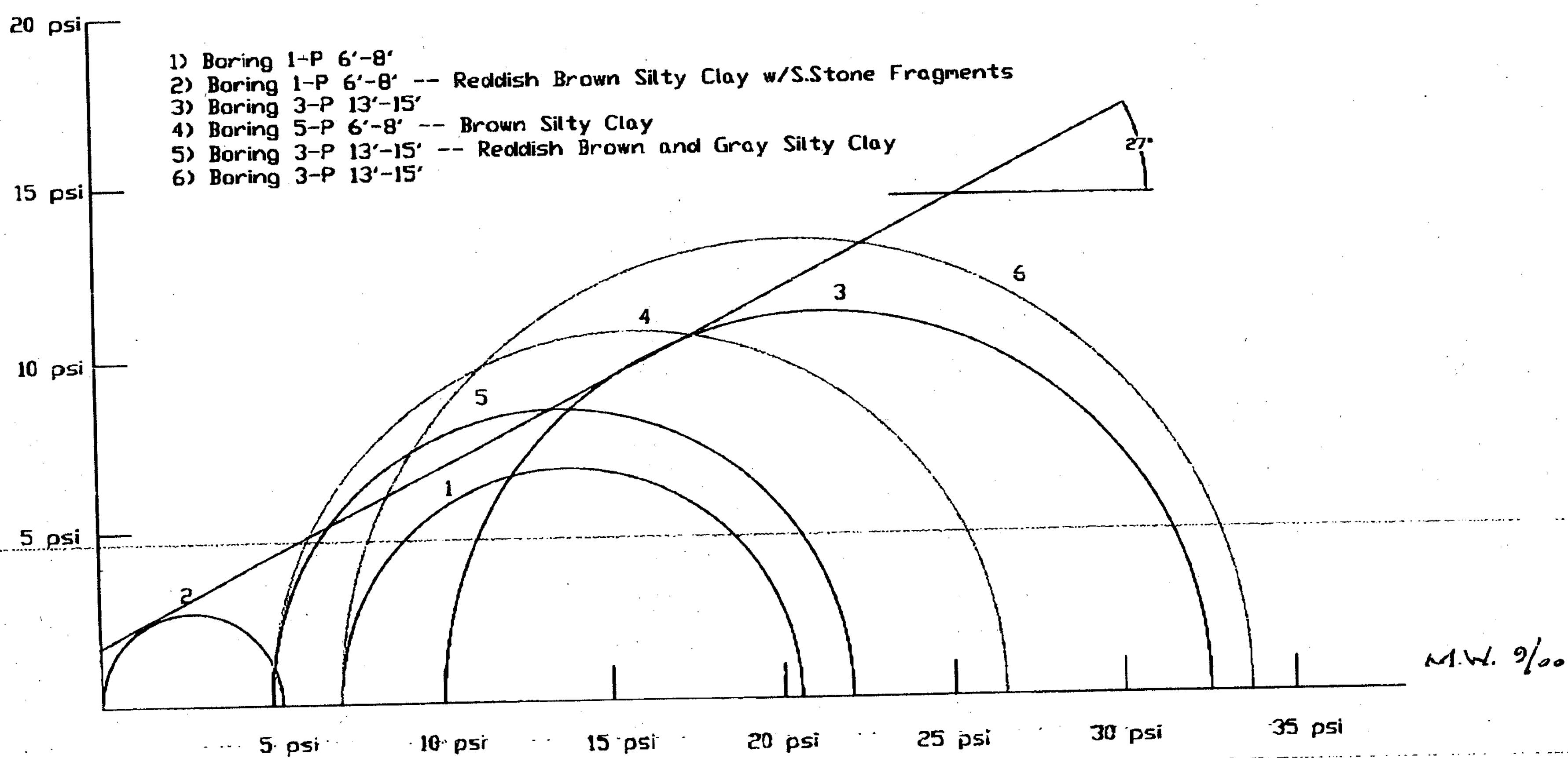
DES NO. 9137165

SUMMARY OF SPECIAL LABORATORY TEST RESULTS

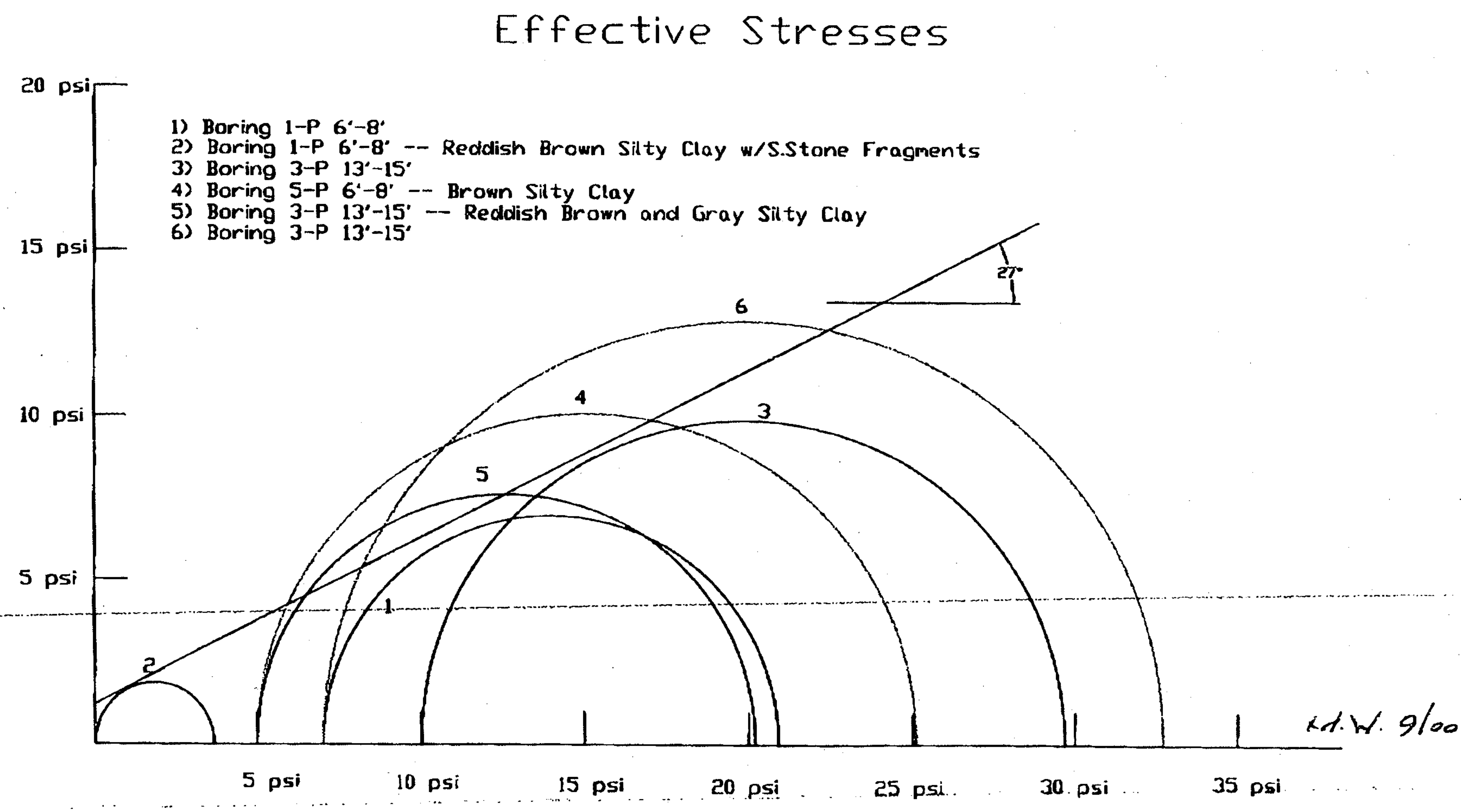
DES. NO. 9137165
PROJECT NO. SR545 SLIDE
STRUCTURE NO. N/A
COUNTY DUBOIS

LABORATORY NUMBER	PART	BORING NUMBER	SAMPLE NUMBER	DEPTH	NATURAL WATER CONTENT (%)	pH VALUE	LOI (%)	CA & MG (%)	NATURAL WET DENSITY (PCF)	NATURAL DRY DENSITY (PCF)	MAX DRY DENSITY (PCF)	OPT. MOIST (%)	CBR @93%	CBR @97%	COHESION (Qu/2) (KSF)
007078805998		1-P	SS 1-T	1.0'-2.5'	18.0	5.1			126.1	106.9					
007078806002		1-P	SS 3-T	8.5'-10.0'	24.4	6.2			120.1	96.6					
007078806008		2-SI	SS 1-T	1.0'-2.5'	15.3				124.1	107.6					
007078806010		2-SI	SS 2-T	3.5'-5.0'	14.3				132.1	115.6					
007078806013		2-SI	SS 3-B	6.0'-7.5'	13.1				136.4	120.6					
007078806020		3-SI	SS 1-T	1.0'-2.5'	19.9				118.1	98.5					
007078806022		3-SI	SS 2-T	3.5'-5.0'		4.7									
007078806025		3-SI	SS 3-B	6.0'-7.5'	12.9				122.5	108.5					
007078806026		3-SI	SS 4-T	8.5'-10.0'	15.6				127.5	110.3					
007078806028		3-SI	SS 5-T	13.5'-15.0'	20.1				127.9	106.5					4591
007078806036		4-P	SS 1-T	1.0'-2.5'	16.6				116.9	100.3					
007078806038		4-P	SS 2-T	3.5'-5.0'	17.0				128.1	109.5					
007078806040		4-P	SS 3-T	6.0'-7.5'	16.6				123.8	106.2					
007078806042		4-P	SS 4-T	8.5'-10.0'	19.0				130.2	109.4					
007078806053		5-P	SS 1-T	1.0'-2.5'	16.2	4.8			123.1	106.0					
007078806055		5-P	SS 2-T	3.5'-5.0'	16.2	5.4			120.3	103.5					

Total Stresses



Triaxial Strength Test Results



Triaxial Strength Test Results