Design and Installation of Horizontal Wick Drains for Landslide Stabilization

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One of the most effective options to stabilize landslides is to reduce the amount of water they contain by installing horizontal drains. A new type of horizontal drain material, geosynthetic wick drains, and a new installation method, driving drains rather than drilling them, were evaluated. Horizontal wick drains offer several advantages over conventional horizontal drains: They resist clogging, are inexpensive, may be deformed without rupture, and may be installed by unskilled laborers with a minimal investment in equipment. More than 100 drains were installed at eight sites in Missouri, Colorado, and Indiana using bulldozers, backhoes, and standard wick drain-driving cranes. Drains have been driven 30 m through materials with standard penetration test values as high as 28. Both experience and research indicate that drains should be installed in clusters that fan outward, aiming for average spacing of 8 m for typical clayey soils. As with drilled drains, initially some drains are expected to be dry, although these drains often become active during wet periods and serve as an important part of the overall slope stabilization scheme. Drain effectiveness is expected to build over the first few years as the effects of soil smear during drain installation are removed, peaking at 3 to 6 years after installation. The effectiveness is then expected to decrease as fine particles slowly clog the drain pores. From published tests, clogging appears to occur slowly enough in typical clay soils that the drain life is comparable with the project life.

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 4 mm $\times$ 100 mm in cross section and are shipped in 300 m rolls. They accelerate consolidation and settlement by an order of magnitude by significantly shortening the flow path for water to exit a soil layer (1). This study has developed equipment to install wick drains horizontally to drain landslides, and more than 100 drains were installed at eight sites in Missouri, Colorado, and Indiana to prove the effectiveness of the procedure.

Horizontal wick drains are intended to address several significant drawbacks experienced with the drilled horizontal drains currently used. Drilled drains, which consist of slotted polyvinyl chloride (PVC) pipes placed into drilled horizontal holes, tend to clog with fine material and require periodic cleaning because it is often impractical to place a filter pack over the slots. Because the PVC is inflexible, landslide movement can rupture the drains. Also drilled drains are expensive at approximately \$20 to \$36 per linear m (2, 3). Wick drains are encased in a fine mesh geotextile fabric that reduces

clogging and are economic to install. They may be deformed by as much as 60 to 100 percent before rupture (4, 5).

INSTALLATION PROCEDURE

To install drains, bulldozers or trackhoe excavators push a small-diameter steel pipe into the landslide mass. The pipe sections are preloaded with 3-m lengths of wick drain, which are rolled into long, tight cylinders and tied at $\frac{1}{2}$ -m (1-ft) intervals with electrical cable ties. The first pipe to be driven is faced with a drive plate (Figure 1) attached to the front end of the wick. Next, a drive head is slid over the back end of the first pipe, and the wick is folded out of the way (Figure 2a). The first pipe is then aligned and pushed into the slope.

Additional pipes are driven by splicing the protruding wick sections with a plier stapler, threading the pipes together, and pushing in the new piece of pipe. Pipe sections may be added until the desired drain length is reached or until the driving resistance causes refusal. Once the total length is driven, pipes are pulled from the ground by attaching a pulling head and a chain (Figure 2b) to the end of the protruding pipe and pulling each section smoothly out of the ground. The wick remains in the ground because the drive plate anchors the wick in place and resists withdrawal. A more detailed description of the installation procedure is provided in Santi and Elifrits (6).

Our time records show an experienced crew (with 2 to 3 days of site work) can install 12 to 21 m of wick drains in 1 h. A crew consists of an equipment operator and three laborers. Prices for wick drain vary by volume but typically range from \$0.80 to \$2.50 per linear m. The resulting cost for drain installation ranged from \$9 to \$20 per linear m (6).

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 1) is 19 cm² (3 in.²) and cut from 12- to 18-gauge (1.3- to 2.7-mm thickness) sheet steel. 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

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FIGURE 1 Drive plates with supporting washer (top) and carriage bolt used for driving (bottom).

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. Alternatively, a standard flat 6.4-cm (2½-in.) steel washer may be slid onto the re-bar to rest between the drive plate and the front of the lead pipe. A 13-cm (5-inch) long carriage bolt and washer may be substituted for the drive plate for very hard or rocky zones (Figure 1).

Drive Pipe

The drive pipe should have a minimum inner diameter of 32 mm (1¼ in.) to accommodate the rolled wick. The outer diameter is

FIGURE 2 Drive head to protect drive pipe (a). Pulling pipe (b) attaches to the drive pipes by threads at the left end and attaches to the trackhoe or bulldozer by a chain looped through the hooks on the right end.

only limited by the pushing force available from the driving machinery. This study used 3-m (10-ft) lengths of AQ wire-line drill rod, which is flush threaded both inside and out, with an inner diameter of 35 mm (1⅜ in.) and an outer diameter of 44 mm (1¾ in.; wall thickness of 4.8 mm or ⅜ in.). 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 in Figure 2 consists of a 45-cm (18-in.) section of 64-mm (2½-in.) 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 it can be attached to the exposed female end of each section of drill pipe still in the ground (Figure 2).

Drive Equipment

The estimated pushing load required for the drive pipe used is less than 4500 to 6800 kg (10,000 to 15,000 lb). We estimate that bulldozers or trackhoe excavators in the 11,000 to 20,000 kg (25,000 to 45,000 lb) range are best suited for this task. Substantially larger equipment 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 problem was most serious when a new pipe was first being driven and the full 3 m was exposed and not confined by the soil of the hillside. The buckling generally subsided once at least 1 m of the pipe had been driven into the hill. However, the pipe also buckled 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 our work. We have also used another larger pipe as a sleeve around the drive pipe to prevent buckling. The sleeve may be pushed into the hillside along with the pipe and then pulled out to be reused with the next pipe section. 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 3).

FIGURE 3 Control of pipe buckling by timber support from underneath.

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, recognizing that these parameters may need to be altered in the field.

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) suggested that drains should not extend more than 3 to 5 m (10 to 15 ft) beyond the shear zone, as they may convey water into the landslide mass. Lau and Kenney (8) also concluded there was 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 30 m (100 ft) through materials as stiff as 66 to 92 blows/m (20 to 28 blows/ft). With more robust equipment, we believe drains 45 to 60 m (150 to 200 ft) long may be driven through similar soils.

Angle

Drilled drains have typically been installed at a large range of angles above horizontal, from as low as 2 to 3 percent grade (9) to as high as 20 percent grade (10, 11). In our experience, wick drains at low angles, even horizontal, are the most effective. Physically, there is no less gravitational force pushing the water out of the slope than by sloping drains, and low-angle drains will lower the water table and pore-water pressures to a greater degree farther 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.

Spacing

Several research efforts have focused on calculating ideal drain spacing as a function of soil permeability, slope geometry, and drain position (12–15). Judging the validity of these studies is difficult because they require soil homogeneity and isotropy and preciseness

in drain location, which are seldom available in the field (7). Royster suggested that drain spacing and location in practice are largely matters of "trial and adjustment" and depend on site accessibility, topography, and the suspected internal drainage of the landslide.

The early experience of the California Department of Highways led Smith and Stafford to space drains roughly 8 m (25 ft) apart in areas where high quantities of water were produced and roughly 30 m (100 ft) apart elsewhere to detect the producing zones (10). FHWA guidelines suggest that rather than using an even spacing, which results in both productive and nonproductive drains, spacing should be based on the location of productive zones (16).

Drain Pattern

Two general approaches to drain layout are used: a fan pattern radiating from a single installation point or a parallel layout from a line of evenly spaced installation points. Using finite element modeling of drain patterns, Nakamura concluded that for a given area of coverage, there is no difference between fan and parallel drain layouts (17). Mekechuk noted that on the basis of 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 (18). Kazarnousky and Silagadze proposed that rather than draining an entire landslide, draining only alternate thick slices of the hillside can achieve many benefits (19).

From 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 8 m (measured at approximately one-half the drain length).

Water Levels Between Drains

Assuming drains are spaced 8 m (25 ft) apart in productive areas, a simplified analysis may be conducted to calculate the effects of the drain on the water table. In general, the water table surface between two drains is an inverted parabola, with low points at the drains and 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), and

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.

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 ft),
Flow rate (Q) = 2 to 20 L/day (0.5 to 50 gal/day), and
Drain spacing (L) = 8 m (25 ft),

it follows that

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

From a number of plots using the equation above, the average water table height in the landslide, h_{avg} , is about $\frac{2}{3}h_{max}$ for clayey soils and about h_{max} for sandy soils.

Filter Size and Clogging

Selection of Wick Drain Filter Size

Clogging is generally caused by the 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 0.05 mm).

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

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

and

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

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

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

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

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

Because the number of options for wick drain filter sizes is limited, it may not always be realistic to meet all of these criteria. The criteria proposed by Chen and Chen were developed exclusively for

wick drains as proposed by Hansen (22) whereas the other criteria should be viewed as desirable, but not critical. A cursory examination of these recommendations indicates that the 70-mesh filter will be effective for silt and clay soils with a significant sand component ($D_{85(\text{soil})} > 0.15$ mm and $D_{50(\text{soil})} > 0.02$ mm) and the 100- and 200-mesh filters are more effective for almost pure silt and clay soils ($D_{85(\text{soil})} > 0.05$ mm and $D_{50(\text{soil})} > 0.007$ mm).

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 nondisplacement 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 $\frac{1}{10}$ 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 (24–26). Atkinson and Eldred concluded that this thickness of smear zone is comparable with the thickness of the natural filter created by piping, so for properly sized filter fabric, the effects of the smear zone are eventually removed (23). Welsh suggested that static pushing of the mandrel results in less disturbance than driving or vibrating the mandrel (27). 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 calculated reduction in cross-sectional area of up to 17 percent 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 15 m of natural soil (28). This reduction in drain area, coupled with migration of soil fines into the filter, resulted in flow rates as low as 4 percent of maximum within 6 months. Note that their tests assumed constant drainage, which is not expected for truly effective drains (as discussed in the section on water drainage). Moreover, they used a compacted soil with a permeability of 10^{-8} cm/s, 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 et al. recommended 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 (29).

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 in Figure 4, which indicates that for typical clayey soils with permeability on the order of 10^{-7} cm/s,

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 et al. (29) showed that because of smear, 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 for a $K=10^{-4}$ 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 4 Expected long-term flow rates from horizontal wick drains.

clogging is not expected to be an issue for many years. Figure 4 assumes drainage during 3 to 10 percent of the time after the initial 2 months.

Effects of Root Growth and Ice

As with 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 to 5 m 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 reported 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" (30, p. 393).

WATER DRAINAGE FROM WICKS

Because of the heterogeneity of most landslide masses, the flow of groundwater through the landslide is difficult to predict, and the flow appears 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 suggested that landslide groundwater may concentrate in "water lenses," which are most frequently created as voids caused by dilation of the landslide during slope movement (17). He reported 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/min (5 gal/min) 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 more than 4 L/min (1 gal/min) immediately after installation].

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. Many case studies have confirmed that a significant number of drilled PVC and steel pipe drains are initially and sometimes permanently dry. Royster described several projects in Tennessee with the following numbers of dry drains (11): 6 of 31 (19 percent), 3 of 52 (6 percent), 33 of 75 (44 percent), 4 of 17 (24 percent), and 22 of 44 (50 percent). Royster noted that many of these drains became active in the wet seasons. Nakamura reported that 55 percent dry drains for a site in Japan (17). Krohn reported that 5 of 16 (31 percent) of the drains installed at a site in Pacific Palisades, California, were

permanently dry (31). 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 has 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 percent of the Jasper, Indiana, drains were wet or dripping following installation, but all of the drains produced water after a rainstorm 2 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) cautioned against judging the success of a drainage program on the basis of 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 evaluated different flow graphs plotting drain output over time and concluded that the most successful drains for slope stabilization are those that show decreasing flow rates over time (indicating that they have lowered groundwater levels to their inlet level) and those that show drainage only after rainfall events (indicating that they are removing rapidly infiltrating rainwater) (17). Drains with relatively constant flow rates may be tapping groundwater that is not contributing to landslide movement.

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

to affect the entire slide mass (Figure 5). A summary of each site is included in Table 1.

Horizontal wick drains were first installed and tested in 1998 in an instrumented embankment in Rolla, Missouri. The embankment was approximately 45 m³ in volume with a 1:1 front slope face; it was instrumented with 6 piezometers, 16 nested soil moisture meters, and 20 survey markers. One-half of the slope was stabilized with six wick drains (each 6 m long); the other half of the slope was not stabilized so that it could be used as a control point in the experiments. The influence of the wick drains was tested by inducing groundwater infiltration through a trench at the back of the slope and then simulating a 100-year, 24-h rainfall using sprinklers (1, 32).

The results of the testing showed that the drains removed a substantial volume of water from the slope (almost 40 L/h apiece), lowering groundwater levels by more than 0.3 m. Furthermore, the survey stakes showed substantially less movement within the drained half of the slope (1, 6, 32).

Following the installation of wick drains at the test embankment, drains were placed at several locations with varying geology and various types of driving equipment. Drains were driven through a variety of natural and fill materials with standard penetration test (SPT) values as high as 92 blows/m (28 blows/ft), although 20 blows/ft appears to be the realistic limit for longer drains. Drains were driven through rocky or hard zones greater than 1 m in width, although these zones sometimes deflected the drain pipe toward the ground surface or completely halted the driving progress.

Wick drains have visibly reduced water levels at the Meeker South and Jasper landslides, and water drainage has been observed at the Boonville, St. Joseph, Meeker North and South, and Jasper landslides (Figure 6). Flow rates from a single drain have been as high as 20 L/min at Meeker North and 4 L/min at Jasper (6).

Drains at the Rio Blanco landslide were installed too high to intercept groundwater because of limited access points to the landslide. Drains at the Rye landslide were too short to intercept groundwater, and later installation of an uphill cutoff trench lowered the groundwater table below wick levels (the maximum length of the Rye drains was limited to 12 m because a standard wick drain driving crane was used to push the drains horizontally into the hillside) (6).

FIGURE 5 Layout of drains at the Jasper, Indiana, landslide (base map prepared by Dan Chase of IDOT).

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. 6800 kg 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 6 Water exiting from wick drains installed in a fan pattern (left). Note wet soil surrounding drains and puddle of accumulated water in front. The third drain from the right produced 20 L/min for several days before drainage slowed to a trickle. Close-up view of discharge from a wick drain shown on right.

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

Continued monitoring of the drains 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 by eight piezometers and two inclinometers.

SUMMARY

Since 1998, more than 100 drains totaling almost 1500 m 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 (12 to 21 m/h), inexpensive (\$9 to \$20 per linear m), and easily learned by untrained crews.

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

From our experience and other studies reported in technical literature, we suggest the following guidelines for drain design:

1. Drains should not extend more than 3 to 5 m 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 that fan outward, aiming for a typical average drain spacing of 8 m 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 to 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 by pounding or vibrating them in place. The cross-sectional area of the pipes also should 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 in sand or other highly permeable medium. 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 30 m for harder soils and 45 to 60 m 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.

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