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Diana Cook was born and raised in Las Cruces, New Mexico, the youngest of eleven children. She received triple Bachelor's degrees in Civil Engineering, Geological Engineering, and Geology from New Mexico State University in 2003. She completed a Master's degree in Civil Engineering from the University of Illinois in Urbana-Champaign in 2005. Diana is currently finishing her Ph.D. in Geological Engineering at the Colorado School of Mines, where she is researching improvement options for the design of horizontal drain systems.

Horizontal Landslide Drain Design: State of the Art and Suggested Improvements

Key Terms: ***Landslide, Horizontal, Drain, Design***

ABSTRACT

The removal of groundwater from the subsurface is one of the most common remediation practices in slope stabilization. The use of horizontal drains has often proved to be an efficient and economical dewatering option for slope stability. Despite their frequent use, a comprehensive review of the state of the art that includes modern research and contributions from related fields has not been performed for nearly 30 years. The objective of this paper is to provide a summary of the current state of practice, including application of recent research. In addition, this paper provides some suggestions for possible improvements to areas of current practice that have been identified as lacking complete answers. Recent research that may be applied to the design of horizontal drains includes (1) Zhou and Maerz's (2002) method for optimizing drilling directions to intersect as many discontinuities as possible in a rock mass, (2) Crenshaw and Santi's (2004) method for calculating an average drain spacing for designs implementing nonuniform drain spacing, and (3) Crenshaw and Santi's (2004) method for calculating an average two-dimensional groundwater profile representative of a corrugated three-dimensional groundwater table, which is low at drain locations and high between drains. Examples of issues that are not adequately addressed by current practice include (1) calculation of drain spacing values required to lower the groundwater level in a slope by a specific amount, (2) prediction of groundwater changes at various distances away from a drain, and (3) proper approaches to modeling complex landslide and groundwater geometries in two dimensions.

INTRODUCTION

In most cases of slope instability, water is one of the main contributors to slope movement. Water can affect slope stability in several ways: seepage forces may be introduced, the weight of the slide mass is increased, excess pore pressures may develop, and shear strengths are decreased (Smith and Stafford, 1957; Royster, 1977; FHWA, 1980; Smith, 1980; and Choi, 1983). Horizontal drains, when used appropriately, have often proved to be a fast and economical means of stabilization, either on their own or in conjunction with other stabilization methods (Royster, 1977; Coduto, 1999; Cornforth, 2005; and Hunt, 2005).

In order to remove subsurface water from a slope, horizontal drains are drilled into soil or rock at a slight positive inclination and extend beneath the phreatic surface of the slope beyond the rupture zone. The hole is typically cased with a small-diameter, perforated polyvinyl chloride pipe, although recently wick drains have also been used effectively in certain geologic environments (Santi et al., 2003; Cornforth, 2005; and Hunt, 2005).

A comprehensive review of the state of the art for horizontal drains has not been conducted since the work of Smith and Stafford (1957) and Royster (1980). A chapter in the recent book by Cornforth (2005) provides an excellent overview of many aspects of drain design and installation, but it does not include some of the more modern research or contributions from other related fields.

While some improvements have been made in the state of the art of horizontal drain design since they were first used in 1939 by the California Division of Highways (Smith and Stafford, 1957), the need for quantitative design guidelines that can be used effectively for emergency or near-emergency situations, in which the design must be established within a short amount of time, such as a few hours, has not been adequately addressed. Research efforts toward providing quantitative design guidelines have proved either too limited or too complicated to be widely used. Thus, the methods for designing a horizontal drain system are still largely those of trial and error. While the need for engineering judgment in the design of horizontal drain systems can never be replaced, quantitative design guidelines that could be applied quickly and easily would result in more efficient and economical horizontal drain systems, especially for emergency landslide repair. In order to create these design guidelines, several questions must first be answered. These questions include the following:

- How can an installation be planned so that it intersects the maximum number of discontinuities in a slope?
- What does the three-dimensional (3-D) groundwater table typically look like in a slope containing horizontal drains, and how can it be addressed in a two-dimensional (2-D) modeling program?
- What drain spacing is required to lower the groundwater level in a slope by a specific amount?
- If the groundwater surface within a drained slope is irregular, what should the water level be in a piezometer any given distance from a working drain?

The purpose of this paper is to provide a summary of the current state of practice, including application of recent research, and to identify questions still unanswered by the current drain design science. In addition, this paper will attempt to provide some suggestions for possible improvement in these areas.

CURRENT DESIGN PRACTICES

The following sections provide a brief summary of the main parameters involved in the design and installation of horizontal drains. Many of these are covered in more detail by Cornforth (2005).

Installation of Piezometers

A piezometer is a small-diameter well or tube used to measure the hydraulic head of groundwater. When circumstances allow, between four and 10 piezometers are installed in a slope before drain installation begins (Cornforth, 2005). The piezometers are used to estimate initial water heights in the slope for stability modeling purposes and to measure average drawdown over time so that there is some means of judging the effectiveness of the drainage system (Hoek and Bray, 1981). However, when using piezometers to judge the effectiveness of a drainage system, it is important to note that water levels can change rapidly over short distances, which can be an issue in areas with sparse piezometer coverage (Lau and Kenney, 1984; Santi et al., 2003). Head differences on the order of a few meters over a horizontal distance of a few meters have been documented (Santi et al., 2003; Crenshaw and Santi, 2004).

Slot Sizes

Slots, or perforations, allow water in the slope to enter the horizontal drain pipe, which then carries the water out of the slope. The slots are located in two longitudinal rows spaced 120° apart on the circumference and are generally 0.25, 0.5, or 1.3 mm in width. The wider slots are intended for use in coarse sand or gravel and will allow fine sand and silt to pass into the drain before bridging. The finest slots are more easily plugged and require cleaning to unplug them, but will pass fewer particles and may be used in fine-grained host material. The middle width is most commonly used (Cornforth, 2005). This is generally the case because of time limitations, a lack of samples for testing, and/or high variability in grain sizes within the slide mass.

When possible, selection of the appropriate slot size for a drain installation is based on sediment analysis for the site in question. According to Forrester (2001), the filter requirement typically used is

$$slot\ width < \frac{d_{85}\ of\ soil}{1.2} \tag{1}$$

Circular holes, while not as common as slots, may also be used to perforate the pipe. For a pipe with circular holes, the filter requirement used is

$$hole\ diameter < d_{85}\ of\ soil \tag{2}$$

Additional filtering can be achieved by surrounding the pipe with a fiber filter (Choi, 1983).

Drain Penetration of Permeable Zones

Horizontal drains are most effective when located where they will intercept water before it reaches the zone of instability. With this in mind, several factors should be noted during the investigation of a specific slope. These include the source and direction of groundwater movement in the area, the character of the transporting strata or stratum, the presence of any brecciated zones or open discontinuities, interconnected fissures in clay, and any perched layers of water (Smith and Stafford, 1957; FHWA, 1980; Hoek and Bray, 1981; Nonveiller, 1981; Dharmawardene and Weimer, 1988; and Mekechuck, 1992).

In areas where the geological structure is relatively simple, the Federal Highway Administration (FHWA, 1980) recommends aligning horizontal drains normal to the strike or trend of steeply dipping beds in order to intercept the maximum number of water-bearing planes. Where geologic structure is more complicated, such an alignment may not be possible. In such cases a drain orientation that intersects the maximum number of discontinuities would be the most efficient means of transporting water out of the slope (Figure 1). A method developed by Zhou and Maerz (2002) for identifying the optimum drilling direction for characterizing a mass of discontinuous rock may prove applicable to such cases. The method might also be applied in soil, where stratigraphic layering, fissures, and other zones of high permeability might be tapped. The method is based on the analysis of linear sampling bias and uses a calculated linear sampling bias index (LSBI) to establish an optimum drilling direction. The optimum azimuth of the borehole is found when the LSBI is minimized by considering all possible borehole azimuth angles (φ). For uniform spacing of discontinuity sets, the LSBI is calculated as follows:

$$LSBI_{\varphi} = \sum_{i=1}^{n} \left(\frac{1}{\sin \alpha_i} \right) \tag{3}$$

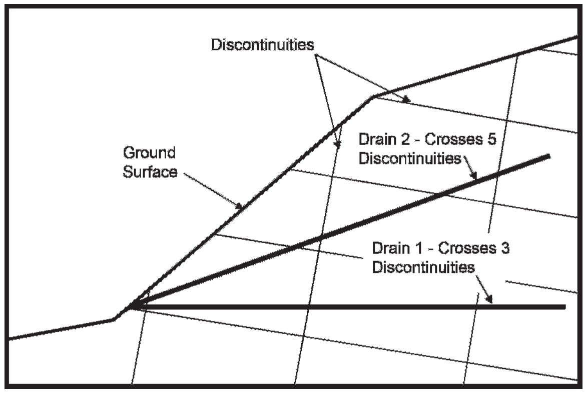


Figure 1. Cross section of a theoretical slope showing how the number of discontinuities intersected by a drain can vary depending on drain inclination. For slopes with closed discontinuities, intersecting the maximum number of discontinuities would maximize drain efficiency.

where $LSBI_{\varphi}$ is the LSBI of a given borehole azimuth, n is the number of discontinuity sets, and α_i is the angle between the borehole azimuth φ and the strike of the ith discontinuity set. In the case that one of the n discontinuity sets has a perfect horizontal orientation, $n - 1$ discontinuity sets need to be considered, since the strike of a horizontal discontinuity set is undefined.

For nonuniform spacing of discontinuity sets, the equation includes a weighting factor to account for the varying contributions of each set:

$$LSBI = \sum_{i=1}^{n} \left(\frac{\lambda_i}{\sum_{i=1}^{n} \lambda_i} \times \frac{1}{\sin \gamma_i} \right) \tag{4}$$

where λ_i is the average frequency (spacing) of the ith discontinuity set and γ_i is the angle between the borehole direction and the angle of the ith discontinuity set. For more information about the method, or to see example calculations, Zhou and Maerz (2002) should be referenced.

Drain Spacing

Since more than one drain will be necessary to dewater a slope, some spacing value between drains needs to be established for installation. Spacing is frequently established at the time of installation, often involves a significant amount of trial and error, and is usually dependent on access and site layout (Crenshaw and Santi, 2004). A few researchers have attempted to provide quantitative methods for estimating drain spacing, but these methods either do not provide the most economic and efficient solution or still require some trial and error to achieve a desired phreatic drawdown (Hoek and Bray, 1981;

Resnick and Znidarcic, 1990). In addition, Resnick and Znidarcic (1990) noted that though the need for rational design methods for horizontal drains has been addressed by some researchers (Choi, 1974; Kenney et al., 1977; Prellwitz, 1978; Nonveiller, 1981; Stanic, 1984; and Aigle et al., 1987), even the design charts and diagrams developed with physical modeling (Choi, 1974; Kenney et al., 1977) were limited by a lack of adequate experimental verification.

In addition to the lack of physical modeling, Crenshaw (2003) notes that many of the techniques are based on oversimplification of assumptions and subjective analyses and/or are theoretically or mathematically complex and require an unreasonable investment in time to implement. For example, Cai et al. (1998) proposed a procedure that uses the elasto-plastic shear strength reduction finite element method to establish drain spacing, as well as other drain design parameters, but this procedure does not provide drain spacing directly and would require a relatively lengthy iterative modeling process before a viable drain spacing value could be obtained. In addition, it is unclear how the initial drain spacing for the model is established. Thus, lacking more definitive means of establishing drain spacing, the standard practice still relies upon general guidelines based on engineering experience. Several examples are provided.

Hunt (2005) states that drain spacing depends on the type of material being drained. For fine-grained soils, a spacing of 3–8 m may be required. For more permeable materials, a spacing of 8–15 m may be adequate. Huculak and Brawner (1961) give similar recommendations: when the locations of high-permeability zones are unknown, horizontal drains may be installed on an exploratory basis at a spacing of 9–12 m. When water is encountered, at least one additional drain should be placed between drains of the initial exploratory set. Cornforth (2005) states that parallel drains are typically spaced 1–3 m apart and are drilled normal to the slope in the direction of slide movement. The wide range of spacing recommendations emphasizes the lack of agreement as to a specific design standard.

With the more recent use of fan configurations (see section below), additional drains have been installed in areas of high water flow at angles of 5–10° away from the original drain, about 1 m or less apart at the base (Santi et al., 2003). The question, then, is how many drains should be installed in a fan to achieve a desired spacing? Crenshaw and Santi (2004) assessed the inhomogeneity of drain spacing in fan configurations by calculating the average drain spacing for 3-m intervals into a slope (Figure 2). This method produces an average drain spacing for the entire slope.

Clearly there is no hard-and-fast rule for drain spacing, but general guidelines might be summarized as follows:

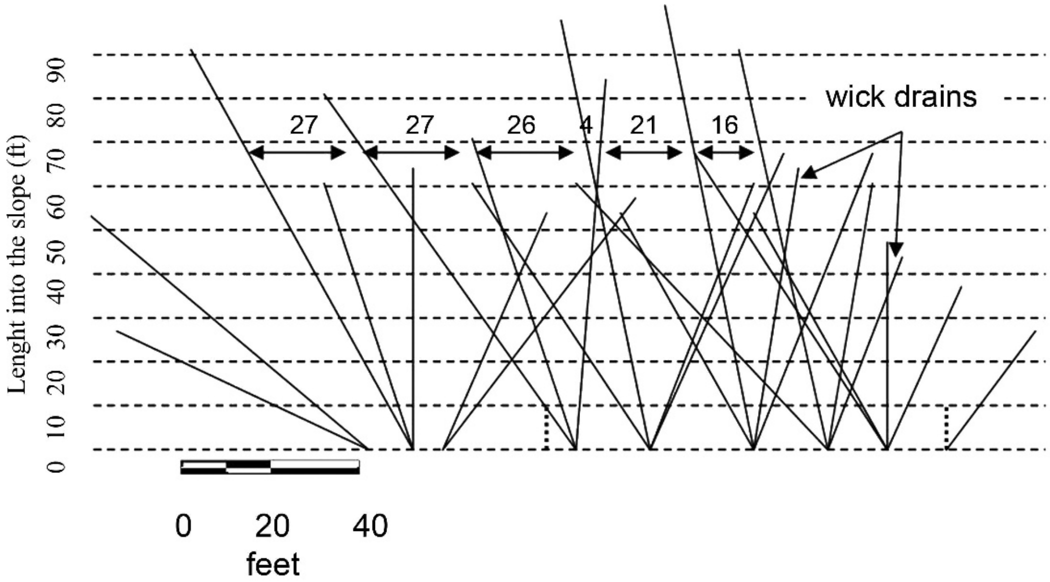
- For parallel drains in high-permeability soils, initial drains should be spaced at 8–15-m intervals.
- For parallel drains in fine-grained soils, initial drains should be installed at 1–8-m intervals.
- Additional drains may be necessary depending on site conditions and to tap zones that produce substantial amounts of water.
- For fan configurations, enough drains should be installed to result in an average spacing equivalent to the guidelines given for parallel drains.

Drain Length

Drains need to extend far enough into the slope to achieve the desired drawdown throughout the slope. Since water needs to be removed from the slip zone, drains are installed to penetrate through this zone. Royster (1980) stated that drains should not extend more than 3–5 m past the slip surface, and according to Lau and Kenney (1984), no additional benefits may be achieved by installing drains that extend beyond where the critical slip surface intersects the top of the slope. This finding was supported by Nakamura (1988), whose research showed that the maximum reduction in subsurface water is not affected by changes in drain length beyond a critical length, and by Cai et al. (1998), who showed that increases in safety factors became smaller the further drains extend beyond a critical length. In fact, installing drains that significantly exceed the slip surface is uneconomical and may actually cause more water to be conveyed into the failure zone (Royster, 1980).

Drain Inclination

Horizontal drains are inclined upward from the drain outlet in order to maintain a positive hydraulic gradient, allowing water to flow out of the slope more effectively (Smith and Stafford, 1957; Cornforth, 2005). The drains are typically installed at an inclination between 2° and 10° from the horizontal, though installation at 25° or more is possible (Cornforth, 2005). Low angles are preferable because they result in lower elevations at the back ends of the drains. This increases the potential groundwater drawdown the drains may induce (Santi et al., 2001a, b). If necessary, drains can be installed with no inclination and will be effective as long as positive hydraulic gradient exists from the back to the front of the drain. While the same principal would apply to



At each interval, drain spacing values are summed. At a depth of 70 ft into the drain field, the average spacing is:

$(\sum_{(70)})$/# of drain spacings at 70 ft, or

(27+37+26+4+21+16) / 6 = 20.1 ft

This calculation is made for every 10 ft. interval in the slope.

To estimate the average drain spacing for the entire drain field:

$S_{avg} = (\sum_{(0)} + \sum_{(10)} + \ldots + \sum_{(1)})$/# of drain spacings

This calculation is made once.

Figure 2. Example calculation of average drain spacing (1 ft = 0.305 m) (modified from Santi et al., 2003).

drains inclined downward from the drain outlet, this is not advised, as such an orientation has the potential for conveying water backwards along the drain from the drain outlet and into the slope.

Drain Configuration

Either parallel or fan-shaped (array) configurations may be used in a horizontal drain system; there is no difference in the maximum amount of water reduction between the two (Nakamura, 1988). However, each has its own advantages.

There are many reasons to install several drains in a fan shape from a single location. One reason is that suitable locations for drilling are rare on sloping terrain and have to be prepared ahead of time. Also, the slope can be weakened to the point of movement if too many drill sites are prepared (Mekechuk, 1992; Santi et al., 2003; and Cornforth, 2005). An additional advantage is that the installation process is faster because the time required for resetting the equipment after each drain installation is reduced (Dharmawardene and Weimer, 1988; Mekechuck, 1992). In addition to benefits related to cost and site access, a fan configuration also makes it easier to collect water from several drains at once for conveyance off the slope (Figure 3) (Mekechuk, 1992; Santi et al., 2003;

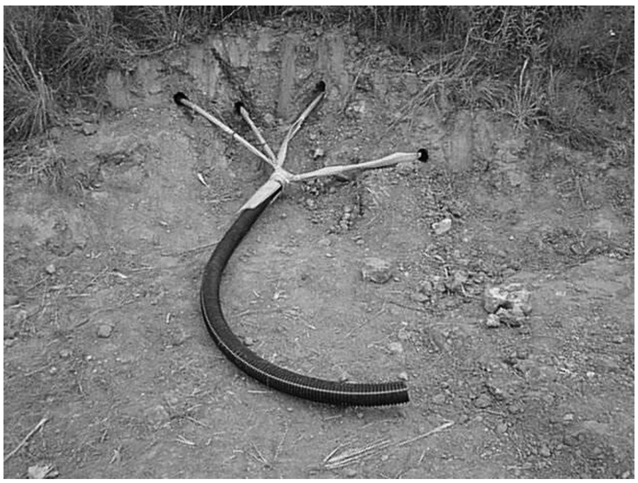


Figure 3. Multiple wick drains connected to a collector pipe used to convey water off of a slope.

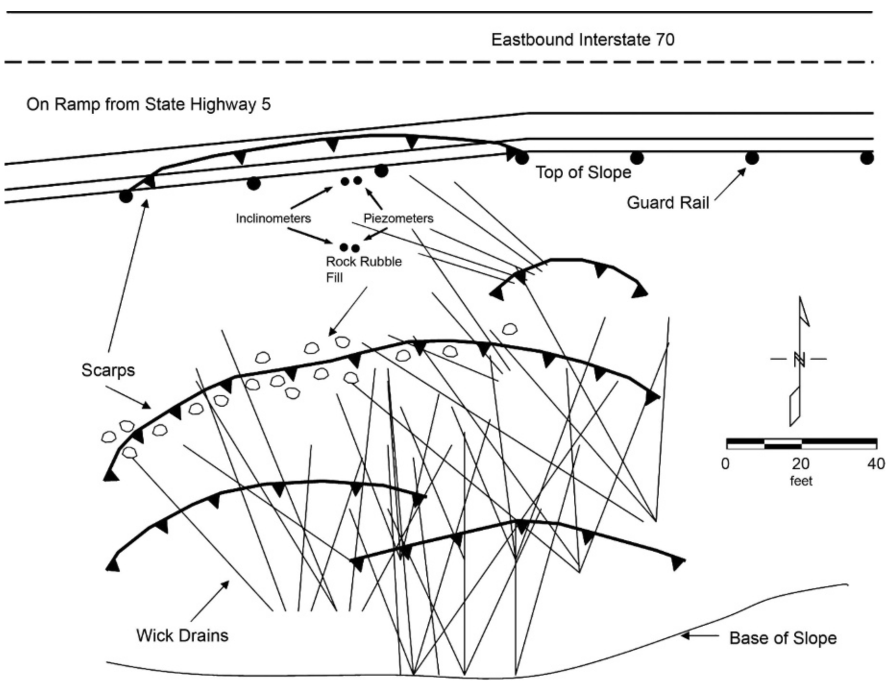


Figure 4. Wick drains installed at different levels in a fan configuration (Santi et al., 2003).

and Cornforth, 2005). Finally, with an array configuration, the likelihood of intersecting previously unrecognized open discontinuities or perched layers of water is higher since the drains are installed at several different orientations within the slope.

Parallel placement of drains is less common, given the advantages of array configurations, but such an arrangement is still used often on relatively linear features such as highways, canals, and railroads (Cornforth, 2005). In addition, parallel configurations provide more confidence in measuring spacing of drains and in representing the slope with simplified models.

For both configurations, drains are often installed from more than one level, provided the subsurface water can be reached from various levels and provided that the terrain permits access to different levels (Smith and Stafford, 1957). Such a layout (Figure 4) has the advantage of draining perched zones and isolated water pockets.

In cases where access is especially poor as a result of site or geologic constraints, Kazarnovsky and Silagadze (1988) demonstrated that many slope stabilization benefits may still be achieved, even when only thick slices or wedges of the hillside can be drained, rather than the entire landslide.

Drain Protection and Water Redirection

After the drain has been installed, a protective sleeve of galvanized pipe is usually installed and grouted in place to protect the lower 1.5–6 m from invasion by tree roots and to prevent soil erosion at the outlet. The sleeve also protects the pipe from impact by straying vehicles, rockfall events, etc. A collector pipe may be attached to the sleeve to direct water to a designated discharge point off of the landslide (Smith and Stafford, 1957; Cornforth, 2005). In extreme climates, drain outlets should be buried in sand or gravel to protect them from ice buildup or blockage (Santi et al., 2001b).

Drain Markers and Location Records

The final step in a drain installation involves identifying the drain with some kind of sign or marker (Smith, 1980). Likewise, the location of drains with respect to survey monuments or permanent landmarks is recorded. Marking the location of a drain is an important step that in the past was commonly overlooked. Discharge water from a drain often results in ample vegetation growth, which obscures outlet locations. Having drain markers and a record of drain locations facilitates drain repairs and cleaning (FHWA, 1980) and is useful for slope stability evaluations.

Drain Cleaning and Inspection

Drains require some maintenance in order to remain effective. Over time they become clogged with root growth, sediments, or mineral deposits and need to be cleaned. High-pressure water systems are used to clean the slots and to scour away sediments or mineral

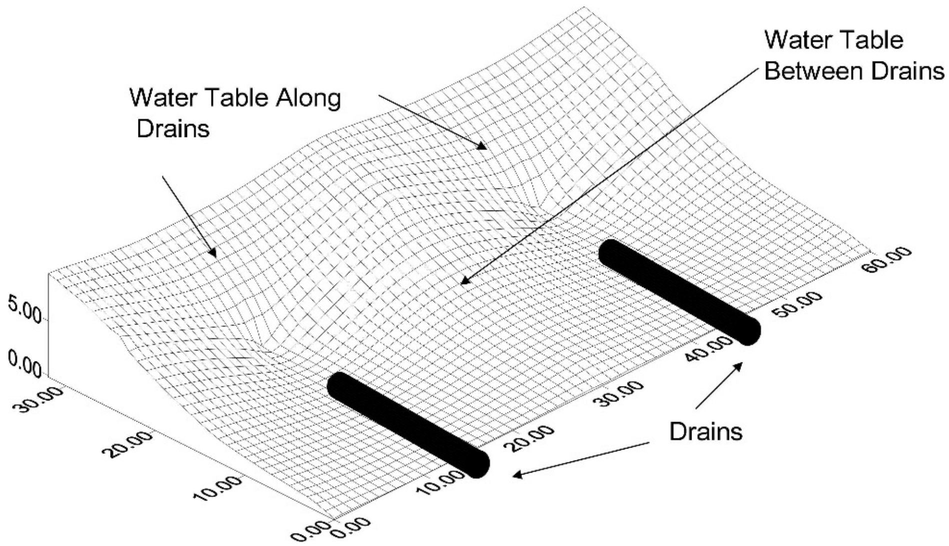


Figure 5. Shape of water table within a drain field. Note troughs corresponding to drain locations and ridges located between drains (Crenshaw and Santi, 2004).

deposits (FHWA, 1980; Cornforth, 2005). The use of chemical treatments is sometimes necessary to clean especially stubborn mineral deposits. A cutter head is used to remove root growth and other obstructions that cannot be removed with a forward-pointing jet (Cornforth, 2005). Wick drains tend to resist clogging (Santi et al., 2003), but once clogged, they cannot be easily cleaned. In this case new drains will need to be installed.

The frequency at which drains will need to be cleaned will depend on climate, local geology and vegetation, and other factors (Smith and Stafford, 1957). The general recommendation is for drains to be cleaned and inspected every 3 months for the first year, once the following year, and once every 4 years thereafter, except in the case of frequent calcium carbonate clogging, in which case cleaning and inspection should take place every 2 years (Cornforth, 2005).

For each drain cleaning and inspection, the following should be recorded (Smith, 1980; Cornforth, 2005):

- flows before and after cleaning,
- type and quantity of materials flushed during cleaning,
- obstructions and their location in the drain,
- repairs made or required,
- depth of cleaning, shearing, or damage of drains due to slide movement or external forces, and
- the person responsible for the cleaning and inspection.

Sheared Drains

It is frequently necessary to install drains in stages over a period of time (Hunt, 2005). Continued movement of the slope often shears some of the drains, at which point they cease to function. Shearing is especially likely to occur when horizontal drains have been installed in an emergency situation. Flexible drain materials, such as wick drains, may stretch and deform significantly without rupturing, but the geologic environments in which they can be installed are limited (Santi et al., 2003).

Modeling of Drained Slopes

A common assumption in slope stability modeling is that the groundwater surface is fairly level across the slope. This is not the case when horizontal drains have been installed. The water surface is lowest at the drain location and rises between drains (Figure 5). The groundwater table may be located several centimeters above the drain in silty and clayey soils and may rise substantially near the uphill end of the drain (Figure 6) (Crenshaw and Santi, 2004). Accounting for the 3-D groundwater profile in a slope stability model can alter the calculated safety factor by as much as 10 percent (Santi et al., 2003).

During their research into the stabilization of clay slopes using horizontal drains, Lau and Kenney (1984) developed a program to convert 3-D output from the groundwater program "Trust" (Narasimhan and Witherspoon, 1978) into an equivalent 2-D array for use in a 2-D slope stability modeling program. Since this was not the point of the research, the particulars are not well documented, and the program was not made widely available. Software packages such as GEO-SLOPE International's (2007) GeoStudio can be used to analyze changes in groundwater

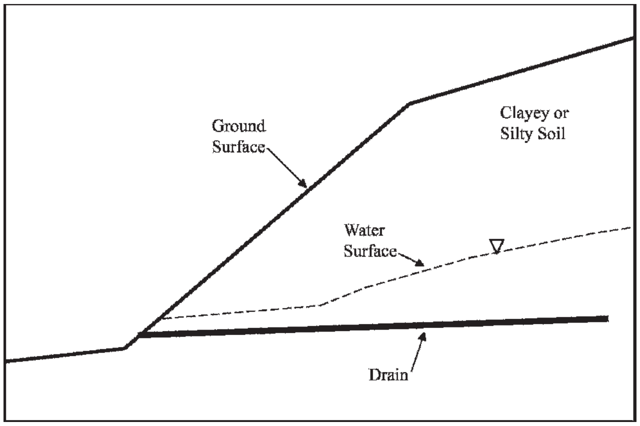


Figure 6. Cross section showing change in water-table profile along a drain in fine-grained soils.

flow and to integrate the results into slope stability analyses, but only in two dimensions. Programs such as RockWare's (2008) Groundwater Modeling System (GMS) can be used to analyze groundwater flow in three dimensions, but these programs do not provide an automated means of averaging the 3-D water surface into a 2-D profile that can be used for slope stability analyses.

Several methods for analyzing slope stability in three dimensions have been established over the last several years (Griffiths and Marquez, 2007). The finite element methods in particular might be extended to analyze the irregular 3-D water surface within a drained slope, but there is no current standard for this. Indeed, while finite element methods would be very beneficial for aiding the design of drainage systems, it is unlikely that they would prove a panacea for all drainage design needs. The most significant reason for this is that horizontal drains are often installed in emergency or near-emergency situations, in which cases the design is required in a very limited amount of time. This would preclude the use of finite element analyses, which are more time-consuming than traditional slope stability analyses, and would require special care to be performed effectively (Duncan, 1996). In addition, while accounting for a 3-D water surface can make a significant difference in factors of safety, this is not the case for 3-D slope stability analyses. Provided a critical cross section has been chosen for the analyses, the 2-D factors of safety are conservative and do not vary significantly from the 3-D values (Griffiths and Marquez, 2007). Cornforth (2005) suggests that the cost increase between 3-D and 2-D data needs is likely to cause a decrease in site exploration quality. Thus, for engineers in State Departments of Transportation especially, a simple method for averaging a 3-D groundwater surface to a 2-D profile for use in 2-D slope stability analyses would be best.

Crenshaw and Santi (2004) developed a calculation for the water-table height between drains in a slope based on Hooghoudt's (1940) research on agricultural drainage, as translated by Luthin (1966). Since, as mentioned previously, most computer programs used for slope stability analysis evaluate a 2-D cross section of a slope, Crenshaw and Santi developed a method for averaging the 3-D water surface to create a representative 2-D water-table profile. Though this work was based on a range of materials and was designed to be used with easily measured field and laboratory data, it is still fairly unwieldy.

UNANSWERED QUESTIONS

While horizontal drain systems have proved highly effective for slope stabilization, the design process as it currently exists is based largely on generalized recommendations and a trial-and-error approach. Complete answers to the following unanswered, or only partially answered, questions would improve the design process, thereby improving design efficiency and economy. The following sections address the importance of the questions and how they might be answered.

How Can an Installation Be Planned So That it Intersects the Maximum Number of Discontinuities in a Slope?

This question has been partially answered through the use of the optimum drilling direction method developed by Zhou and Maerz (2002). This method could potentially be used to identify the optimum drain orientation to intersect a maximum number of discontinuities, bedding planes, fissures, and other zones of high permeability in a rock or soil mass. Further study may be required to confirm or modify the use of this method for horizontal drains, which are installed within a small range in inclination and orientation.

What Does the 3-D Groundwater Table Typically Look Like in a Slope Containing Horizontal Drains, and How Can it Be Addressed in a 2-D Modeling Program?

This question can best be addressed through Crenshaw and Santi's (2004) calculation for the water-table height between drains in a slope. Though this work is not currently in a form that allows efficient use, it could be streamlined and simplified to be more effective.

What Drain Spacing Is Required to Lower the Groundwater Level in a Slope by a Specific Amount?

As shown earlier, drain spacing is generally established as the installation progresses. While the great variation in geology and the geometry of different slopes will probably always require some flexibility in drain installation, it seems reasonable that the level of trial and error could be reduced, saving time and money. This might be accomplished with a quick, quantitative method for predicting drain spacing using site-specific parameters.

Crenshaw and Santi's (2004) work, mentioned in the previous section, comes closest to answering this question. This method, which can be applied to both fan and parallel drain configurations, requires an iterative process wherein average drain spacing is provided and the output is an average water-table height. Instead, the average groundwater level required to achieve a specific factor of safety could be estimated from a slope stability analysis. A modification of this work, either mathematically or through changes in parameter estimation methods, could then be used to more accurately estimate the average drain spacing required to achieve this groundwater level.

If the Groundwater Surface Within a Drained Slope Is Irregular, What Should the Water Level Be in a Piezometer Any Given Distance from a Working Drain?

One means of evaluating the effectiveness of a drain installation involves monitoring piezometer levels near the drains. If the drains are working as expected, the piezometer levels should match the desired drawdown. However, if the desired drawdown is expected to be level across the site when in actuality the groundwater profile exhibits a corrugated shape, with low levels near the drains and higher levels between drains, the effectiveness of the drains will be misjudged. The height of the water in a piezometer will depend on its location relative to the horizontal drain. The question asked in this section might best be answered by a set of charts or a spreadsheet, which could quickly be used in the field to compare actual drawdown to expected drawdown in a slope.

FUTURE WORK

Based on the current state of practice, it appears reasonable to assert the need for better design charts or analyses that can be used quickly and easily by any engineering geologist or geological engineer. In order to address this need and answer some of the questions mentioned previously, focus should be placed on the following:

- Modification of Crenshaw and Santi's (2004) work to answer the question "What drain spacing is required to lower the groundwater level in a slope by a specific amount?"
- Development of the modifications to Crenshaw and Santi's work into easily used spreadsheets or design charts for various typical site situations.
- Creation of design charts or a spreadsheet relating piezometer locations to water-table heights in order to establish drain efficiency.
- Incorporation of the new work into a manual that includes design, installation, inspection, and maintenance practices.

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