Exploration, Design, and Construction of Horizontal Drain Systems

MICHAEL T. LONG

Horizontal drain systems for landslide correction have historically been installed with varying degrees of success. This variability of success has also been apparent in preconstruction exploration, engineering design, and construction and postconstruction monitoring. The USDA Forest Service, Region 6 (Pacific Northwest Region), has accomplished a number of successful horizontal drain projects in the past 5 years. As a result, a system-and-method approach has been developed, along with several low-cost alternative technology tools, for completing the work. This paper is not intended to be an inclusive discussion of all methods, nor an in-depth summary of quantitative detail, but rather a summary and guide to the project approach and a supplement to the current body of literature on horizontal drain systems.

Horizontal drains have proven to be a cost-effective alternative to major slope stabilization repairs, such as unloading and buttressing, when subsurface water is involved in the mechanics of failure. The practice of installing horizontal drains into unstable slopes to lower the phreatic surface or to relieve confined groundwater pressures has been in use for some time (*1*). The California Department of Transportation (Caltrans) pioneered drilled installations in 1939 (*1*). Since then, California has installed over 1 million linear feet of horizontal drains, helping to develop current state-of-the-art horizontal drilling and installation methods (*2*). The list of successful case histories throughout the United States is extensive. Material and site conditions in these cases have varied from discontinuities in overconsolidated clays to silty sands with rock fragments larger than 1 cubic yard (*1–8*). Brawner (*9*) has documented cases in which an induced vacuum system has improved performance of horizontal drains in rock slope applications

Although the literature contains many case histories on horizontal drains, the number of papers relating to preconstruction investigative techniques and quantitative design methods, especially in anisotropic heterogeneous material, is lacking. In a 1984 case history, Long (*7*) discussed such methods on one project. During the past 5 years, the USDA Forest Service in Region 6 has accomplished a number of successful horizontal drain projects using contract as well as force account drill crews. As a result of these successes, methods and procedures for accomplishing the investigation and design of these types of projects have been refined. The project planning process now includes a variety of techniques, including geophysical, geochemical, and drilling exploration methods; groundwater and drain system modeling using Darcy's Law and Mannings' Equation; and a method of drain end spacing developed by Prellwitz (*10*). A number of low-technology, inexpensive, and reliable exploration and installation techniques have also been developed (*11–14*).

These methods and procedures, as well as a summary of several case histories from the Forest Service in Region 6 and a 1958 case history from the Oregon Department of Transportation (DOT), are discussed in the following paragraphs. The groundwater modeling results obtained using the outlined approach are not intended to be precise; however, back calculations from postconstruction records of drain system discharge, groundwater levels, and rainfall have established a close correlation between initial design parameters and final system discharge.

USDA Forest Service, Region 6, Willamette National Forest, 211 E. 7th Ave., P.O. Box 10607, Eugene, Oreg. 97440.

PRECONSTRUCTION INVESTIGATION TECHNIQUES

The success or failure of any geotechnical project depends on the degree of accuracy of the subsurface model (soil and rock characteristics and horizontal and vertical distributions) and on the groundwater regime (distribution, volume, and flow characteristics). The most sophisticated analysis and design efforts are useless, within reasonable economic limits (regarding overconservative design parameters), unless an equal effort is employed toward technical confidence in the subsurface investigation phase. The following techniques can be considered for any geotechnical exploration effort but especially in drainage design for slope stabilization. Depending on the project scope and budget, some methods may not be economical but are presented as a suggested list of available techniques:

Area Reconnaissance

Area reconnaissance includes a complete literature search and aerial photo review as well as a general field reconnaissance to determine the history, process, and origin relating to the previous geologic and construction events that produced the present morphology. In particular, rock and soil units should be designated and classified, and point sources for groundwater infiltration should be identified.

Ground Control Survey

A ground control survey is best accomplished by a survey crew using an electronic distance measuring (EDM) device for precision accuracy in control-point or hub-line monitoring of surface movements. The centerline and lateral cross sections should be surveyed under the supervision of a qualified engineering geologist or geotechnical engineer who can identify features relative to interpretation and stability analysis. These will be staked on the ground for future reference and included on the plan map and as cross-section points. Aerial photography targets can be set and tied in if the scope of the project warrants photogrammetric mapping. A topographic map and an adequate number of cross sections for analysis and design should be generated from the survey. Periodic control-point and hub-line resurveys should then be planned.

A lower-accuracy-level survey may be accomplished using the field developed cross section method (*11*), developed in Region 6 for internal geotechnical project support. This method uses a cloth tape, handheld compass, and clinometer and gives the investigator freedom of scale and the ability to operate independently of a survey crew. One limitation of this method is compounded errors in cross sections over 200 ft long. This method is ideal for small organizations without survey support, or with modest budgets, who need to begin or complete a project without delay.

Subsurface Interpretation

Before further exploration efforts, an initial approximation of the subsurface material distribution and slope failure geometry should be made on the centerline and lateral cross sections. This procedure compels the engineering geologist or geotechnical engineer to use the scientific approach of multiple working hypotheses leading to commitment to a working model. This, in turn, promotes confirmation or revision of the hypothesized model. As exploration proceeds, subsurface interpretation facilitates preliminary slope stability analysis and helps define further exploration efforts. This method has proven valuable for learning interpretation as well as giving management personnel a tool for serial review.

Drive Probe Exploration

Another low-technology exploration device developed in Region 6 is the Portable Drive Probe Assembly (*12*). The probe assembly is inexpensive, lightweight, and retrievable. It consists of 4-ft sections of ½-in. threaded galvanized pipe that are advanced below the surface by an 11-lb sliding hammer free-falling 41 in. The lead section is closed-end, by means of a pipe plug, and perforated with ³⁄₁₆-in. drilled holes so water levels can be checked as the pipe is advanced. Normally, blow counts are recorded at 6-in. intervals. An increase or decrease in blow counts indicates a change in density and shear strength, relative to the overlying or underlying soil profile. These data will assist in making an initial interpretation of the subsurface. Measuring for free water in the hole through the pipe using a resistivity meter will also allow the investigator to determine exactly where groundwater was encountered. When apparent refusal is reached, additional dynamic force (accomplished by physically adding acceleration to the hammer) may be applied to ensure that a rock fragment has not been encountered. The pipe may be left in place as an open stand pipe piezometer, which will provide an extension to the data obtained from more costly efforts of core drilling. This device has been used effectively to depths of 30 ft.

Electrical Resistivity Profiling

A portable electrical resistivity instrument with a simple Werner configuration can extend the exploration efforts and help define areas of subsurface water concentrations. The profiles can also be used as an inexpensive way to plan drilling exploration for optimum placement of boreholes to intercept saturated zones. Profile lines with electrode spacings of 60 ft, recording drops in apparent resistivity 25 ft below the surface, have been used effectively.

Drilling Exploration

Hollow-stem augers and continuous standard penetration test sampling should be used to obtain subsurface samples and soil strength estimates without introducing drilling fluids into the borehole. The hole should be advanced far enough beyond the interpreted failure plane, using a core barrel assembly if necessary, to properly seat and seal any borehole instrumentation such as inclinometer casing or piezometers. At a minimum, open stand pipe observation wells should be installed. Observation wells must be installed within the failed mass at points near or adjacent to analysis cross sections to determine the effectiveness of the horizontal drains and the final calculated factor of safety (F.S.) achieved through reduction in pore water pressure. Additional borings and wells are suggested beyond the lateral failure limits to fully define the groundwater model and to obtain data for constructing lateral cross-section end areas. These additional borings and data will also facilitate horizontal flow net construction to determine the most effective drain locations. As the borings and observation well installations are being completed, the design must be considered relative to in situ permeability testing. Slug tests, or maintained head tests, have proven to be efficient. This testing should be completed to obtain the coefficients of permeability for hydraulic analysis. The up- and downslope boreholes and measured static water levels should be plotted on the appropriate cross sections to determine the hydraulic gradient for the model. All drilling exploration should be completed with a qualified engineering geologist or geotechnical engineer on-site as inspector.

Permeability Testing

In situ permeability tests should be performed in the material to be drained (*12*). If, from the exploration borings, the material is determined to be hydraulically zoned, containing perched water tables or pockets of isolated water, testing in an adjacent borehole is preferable so each zone can be tested separately. Testing can be accomplished in the observation wells if care is taken in placement and sealing of the wells within the zone to be tested, or pneumatic borehole packers can be used.

Groundwater Tracing

There are several methods used to confirm a point source or sources of water infiltration into a system and to determine hydraulic conductivity between observation wells. The tracer dyes rhodamine WT and fluorescein have been used successfully in groundwater modeling efforts by the Forest Service in Region 6 (*7,15–17*). Both dyes can be used concurrently to determine separate point sources at the surface (which could discharge at the same location) or introduced into observation wells. Water samples can be collected directly or by placing a packet of activated charcoal at discharge points in the failed mass. Charcoal packets can also be connected to a line lowered into a borehole. Sodium chloride has been used to trace groundwater and to determine hydraulic conductivity by measuring the relative electrical conductivity at the discharge point (*18*). However, this method is limited to shorter travel distances because of the lower concentrations of sodium chloride achievable and detectable. A weir should be constructed at all springs and seeps observed at the slide scarp, lateral margins, and toe. This can be accomplished using natural material and fitting a 1-in. polyvinyl chloride (PVC) overflow pipe through the weir so flow measurements can be taken of all the seeps and then summed for water budget estimates. The weir discharge must be directed away from the failed mass.

Water Surface Contours

A general water surface contour map should be constructed from the static water level (SWL) readings, converted to elevations, from the observation wells. The water surface contours can then be superimposed on the topographic contours and used to plan the drainage design. The water surface contours can generally be considered equipotential lines, and the general subsurface flow path or paths can be estimated by constructing flow lines perpendicular to the equipotential lines.

Test Drain Installation

Test drains should be installed to confirm final drain locations. The test drains should be located according to the water surface contour model in areas that suggest piezometric valleys (concentrations or convergence of flow lines).

DRAINAGE SYSTEM DESIGN

In order to design a horizontal drainage system, the data obtained from the subsurface investigation and subsequent interpretation must be used to obtain the variable values necessary for Darcy's Law, Mannings' Equation, and drain end spacing equation parameters. The following is a recommended approach to the design (the number of drains needed, inclination, length, and maximum end spacing).

Groundwater Recharge Capacity

To determine the volume of water entering the failure area, which ideally corresponds to the desired interception volume, Darcy's Law states

$$Q = kia \qquad (1)$$

where

Q = discharge (gal/min),
k = coefficient of permeability (ft/day),
i = hydraulic gradient (10^{-2}), and
a = cross-sectional area (ft^2).

The cross-sectional area is determined from the interpreted cross sections perpendicular to the long axis of the slide, taking into consideration the current (steady-state flow) and potential (transient-state flow) rainfall recharge areas. The hydraulic gradient can be obtained from the difference in head and horizontal distance between upslope and downslope observation wells. Coefficients of permeability are determined by borehole falling and maintained head tests performed in the exploration phase.

This process should be used for each water zone if possible, and summed for the total discharge. Current cross-sectional area discharge calculations should then be compared with the sum of all seep discharge points to determine if there is a reasonable correlation. If the correlation is not reasonable (e.g., the sum of all seeps does not represent the total discharge, or values assigned to the model parameters are high or low), engineering judgment or further investigation must be used to resolve the discrepancy.

Number of Drains Needed

The number of drains necessary to accommodate the computed volume is based on Mannings' Equation, which states

$$V = \frac{1.486}{N} R^{\frac{2}{3}} S^{\frac{1}{2}} \qquad (2)$$

where

V = velocity (ft/sec);
N = roughness coefficient = 0.009 (7);
S = percent slope, range 2 to 15 percent (7); and
R = hydraulic radius = area/wetted perimeter = 0.031 ft (for 1½-in. pipe flowing full).

The capacity of 1½-in. inside diameter (ID) slotted PVC pipe flowing full in various slope gradient configurations can then be calculated by

$$Q = VA \qquad (3)$$

where

Q = discharge, and
A = end area of 1½-in. drain pipe (0.012 ft^2).

Drain grades and lengths are then determined from cross-section analysis to optimize the drain length in the saturated zones. An array of grades and lengths will likely be necessary to accommodate each site-specific geometry.

On the basis of case history experience, it is suggested that the number of drains in the preliminary design be based on 25 percent flow capacity to compensate for nonfunctional or low-performing drains in the system. Consideration should be given to incorporating interceptor drains above the failed mass, if possible, as well as relief drains within the failed mass.

Slot Size

The slot size of the drain pipe must be small enough to prevent piping of fines through the opening but large enough to prevent clogging. FHWA (*19*) recommends that the slot size be equal to one-third of the D_{85} of the soil for slotted underdrain systems. Cedergren (*20*) suggests that

$$\frac{D_{85} \text{ soil}}{\text{Slot width}} < 1.2 \qquad (4)$$

where "D_{85} is defined as the decimal number of the size of soil particles for which 85 percent of the soil is finer. . . ." (*17*). On the basis of observation and performance, the Cedergren estimate has given values for slot sizes larger than desirable, which has produced piping. It is recommended that the FHWA value be used.

Maximum End Spacing

The minimum phreatic surface drawdown that will produce an increased shearing resistance for a desired F.S. is determined by the distance between drains in parallel installations. If the drains are installed in a fan array, the maximum end spacing should be calculated to ensure that the minimum required drawdown is being affected within the failure mass. Prellwitz (*10*) outlined a method for determining end spacing on the basis of a modification of the Hooghoudt Equation for transient-state flow and the site-specific slope and phreatic surface geometries.

Collector System

The collector system for a large array of drains may consist of several options. For example, 12- or 8-in. corrugated pipe anchored above ground with steel posts and ¼-in. wire rope, with 2-in. feeder hoses clamped to the drain ends, has been used successfully (see Figure 1). A buried pipe may be considered if further movement is not expected, which would make it difficult to locate a break.

Corrugated polyethylene pipe can be used in a subsurface installation. Surface installations should incorporate material that is strong enough to withstand animal traffic or vandalism. If freezing conditions are likely at the site, a covered manifold system with a concrete drop collection box at the drain discharge points can be designed. Access to each individual drain must be provided to allow monitoring of postconstruction discharge and to facilitate cleanout. A sudden decrease or increase in flow, or a change in water color, may indicate further movement.

FIGURE 1 Collector system intake point.

STANDARD CONSTRUCTION

Rotary drilling is the common method of horizontal drain construction. Installation is accomplished by advancing a 4-in. drill casing to the desired length using a knock-off tri-cone roller bit. At the end point, the casing is rotated in the reverse direction, and PVC pipe slotted in two rows on 120-degree centers is inserted through the casing, thereby knocking off the bit. As the casing is removed, the PVC pipe and roller bit remain in the drill hole.

Suggested Construction Practices

Suggested construction practices include the following:

- The collector system should be constructed before drilling to accommodate anticipated drain flow.
- If excavation is necessary to construct drilling pads, steps must be taken to ensure that the drill pad cutslope will continue to be stable under leaky drainage conditions. If necessary, a rock buttress should be designed and constructed for local stability before drilling. If the cutslope fails after construction, the drains can be sheared off and cause system failure.
- If possible, drilling should take place during wet weather to allow field judgments to be made for modifications on drain locations, concentrations, direction, and inclination on the basis of observed discharge from completed drains.
- Drain end elevation should be determined using the manometer method (a hose connected to the end of a flowing drain, elevated to equilibrium) or a pressure meter to check for up or down casing drift. The next hole should then be corrected as necessary.
- Absorbent wipes, stream booms, silt fences, and straw bales are effective in controlling sediment from drill cuttings and machine fluid leaks. If adjacent to an environmentally sensitive area, a spill plan may be necessary.

- Slots have previously been installed in both the up and down positions successfully; however, consideration must be given to segments of blank pipe in the drain. Blanks should be installed in any segment that is not penetrating the water-bearing zone to prevent migration of groundwater into otherwise dry areas. The blanks should be installed in at least the last 20 ft of drain if toe or cutslope stability is a concern. Drains should not penetrate further than 15 ft beyond the failure surface or the drainage barrier.
- For discharge end protection, and to prevent root growth in the drain, a 3-in. galvanized metal pipe should be installed over the discharge end into the drill hole to a minimum of 5 ft, then grouted in place.

Inspector Duties

A qualified engineering geologist or geotechnical engineer should direct the drilling installation to ensure that design criteria (such as angle, elevation, and location) are met and to make any field modifications. Routine duties should include

- Setting fore and aft site stakes for hole alignment before any large metal objects arrive that would affect compass bearings;
- Measuring the drill casing slope as the hole is collared in;
- Recording advance rate, water return, and water color;
- Monitoring the path of the drill casing for surface indications of drilling fluids in any adjacent or upslope tension cracks;
- Noting material changes with casing advancement;
- Sampling the drill cuttings to determine when the failure surface or the soil and rock interface has been reached;
- Having on-hand predictive tools (such as interpreted cross sections and drill logs) to assist with estimating failure plane and material boundaries;
- Recording final length, slope, end elevation, and discharge rate for each completed drain; and
- Ensuring that the drain number is marked on the galvanized sleeve with a metal stamp for future reference.

ALTERNATIVE CONSTRUCTION METHOD

The State of Oregon, Department of Forestry, has experimented with driven horizontal well points as an alternative low-technology method of installing horizontal drains into slopes. The technique uses sections of ½-in. steel pipe inserted into a perforated 1-in. PVC pilot sleeve with a hard plastic well point. The well point is then advanced into the slope by means of a slide hammer acting against the ½-in. steel pipe (similar to the drive probe method). Sections of PVC and drive pipe are added as the drain is advanced. The drive pipe is then rotated and removed from the PVC upon completion. This system has been used effectively with horizontal advancement up to 40 ft. With some modification, it could be used with a head frame assembly and power cathead to drive steel well points and galvanized pipe to even greater depths with faster penetration rates.

POSTCONSTRUCTION MONITORING

Postconstruction monitoring of a drainage system should be calculated into the project budget and scheduling. Monitoring should continue on a weekly basis for the first month after the project and monthly thereafter until there is a high degree of confidence regarding long-term stability. Monitoring frequency may be increased during periods of excessive rain, rain-on-snow events, or spring runoff. The following is a list of recommended monitoring activities:

- Measuring static water levels in all observation wells,
- Obtaining inclinometer readings,
- Resurveying hub lines and control points,
- Measuring the discharge from each individual drain,
- Measuring total system discharge, and
- Installing a rain gauge on site and recording precipitation.

All water levels, total system discharge, and rainfall can be recorded automatically using pressure transducers calibrated to the head of water in a casing, flume, or rain gauge and connected to a battery-powered automated data logger. Prellwitz (*14*) provides detailed instructions on construction of these devices.

A low-technology device for recording the highest water level reading in an observation well is to place finely ground cork in a length of ⅜-in. clear flexible-plastic tubing (equal to the depth of the borehole) with a piece of sponge to close the bottom end. The riser tube is then lowered to the bottom of the observation well and fastened in place with tape. As the water rises in the observation well, the cork in the plastic tubing rises to the highest level in the riser tube. As the water level decreases, the cork adheres to the sides. The tubing can then be removed from the observation well at any time, with the highest level of cork representing the highest level of water that has been in the well. The cork can then be flushed back to the bottom of the riser tube, and the tubing reinserted in the well.

Drain effectiveness is often reduced within 5 to 10 years due to root growth, piping of fines, and bacteria. Caltrans (*2*) recommends that an ongoing inspection program be initiated, and that a cleaning schedule be established if reduced discharge volume is noted. Cleaning is accomplished using a high-pressure water pump with a self-propelling jet nozzle attached to a length of hose inserted the full length of each drain.

CASE HISTORY SUMMARIES

The five case histories summarized below represent between $300,000 and $400,000 cost savings over the next lowest cost stabilization alternatives considered.

Camp 5 Slide

Location:	Willamette National Forest, Oakridge, Oregon
Failure mass:	250,000 yd^3
Install dates:	December 1983 to January 1984
Linear feet:	7,800 ft

No. drains:	52
No. locations:	7
Drain length:	65 to 240 ft
Drain slope:	2 to 15 percent
Slot size:	0.050 in.
Soil type:	Silty sand (SM)
SWL drop:	14 ft
Total discharge:	High = 576 gal/min
Install cost:	$107,000
Final F.S.:	1.20
Investigation:	
Drill holes:	21
Drive probe:	0
Other:	Resistivity profiling, dye tracing, permeability testing, EDM survey, aerial photogrammetry
Comments:	At least three previous attempts to stabilize the slide were unsuccessful (unloading and buttressing). The slide increased in size from 30,000 to 250,000 yd^3 in the final failure before drain installation.

Fairview Sanitary Landfill

Location:	Bureau of Land Management, Coquille, Oregon
Failure Mass:	80,000 yd^3
Install dates:	April 1987 to May 1987
Linear feet:	3,337 ft
No. drains:	19
No. locations:	3
Drain length:	175 ft
Drain slope:	3 degrees
Slot size:	0.051 in.
Soil type:	Sandy silt (ML)
SWL drop:	5 ft
Total discharge:	10 gal/min
Install cost:	$45,000
Final F.S.:	1.25
Investigation:	
Drill holes:	9
Drive probe:	0
Other:	Survey
Comments:	Drains were placed to intercept subsurface water in siltstone. Drains were also placed into landfill pits to drain infiltrated water. The majority of the flow was from intercepted subsurface water. An immediate maintenance concern arose because of buildup of iron bacteria in the drains.

Powder Creek Slide

Location:	Willamette National Forest, Oakridge, Oregon
Failure mass:	55,500 yd^3
Install dates:	August 1988 to October 1988
Linear feet:	2,754 ft
No. drains:	20
No. locations:	1
Drain length:	110 to 225 ft
Drain slope:	3 to 10 percent
Slot size:	0.090 in.
Soil type:	Silty sand (SM)
SWL drop:	10 ft
Total discharge:	4 to 16 gal/min
Install costs:	$30,000
Final F.S.:	1.35
Investigation:	
Drill holes:	22
Drive probe:	2
Other:	Survey
Comments:	Drill pad construction at the toe of the slide was difficult due to saturated conditions. The drains have effectively stabilized the road prism, which has been moving for 20 years despite previous attempts at stabilization (piles, relocation, syphon wells). The drill pad backslope was not buttressed, and drain slots were installed the entire length. As a result, the pad backslope failed and sheared all drains 15 ft behind the discharge point. The drains are still effective; however, the toe will have to be restabilized.

Quentin Slide

Location:	Willamette National Forest, Blue River, Oregon
Failure mass:	66,600 yd^3
Install dates:	February 1987 to March 1987
Linear feet:	4,087 ft
No. drains:	19
No. locations:	2
Drain length:	215 to 296 ft
Drain slope:	2 to 14 percent
Slot size:	0.050 in.
Soil type:	Silty sand (SM)
SWL drop:	10 ft
Total discharge:	High = 40 gal/min
Install cost:	$60,000
Final F.S.:	1.05
Investigation:	
Drill holes:	13
Drive probe:	10
Other:	In situ permeability testing
Comments:	The system has not been monitored since installation. To obtain the original road alignment, further stabilization methods need to be considered.

Highlands Interchange Slide

Location:	Sunset Highway, Portland, Oregon, Oregon DOT
Failure mass:	300,000 yd^3
Install dates:	October 1958 to November 1958
Linear feet:	5,900 ft
No. drains:	22
No. locations:	7
Drain length:	80 to 450 ft
Drain slope:	3 to 5 percent
Slot size:	½-in. drilled holes
Soil type:	Sandy silt (MH)
SWL drop:	30 ft
Total discharge:	100 gal/min
Install costs:	Unknown
Final F.S.:	Unknown
Investigation:	
Drill holes:	17
Drive probe:	None
Other:	Unknown
Comments:	This system was installed in 1958 using 2-in. iron pipe with drilled holes to stabilize a slope failure in a residential neighborhood caused by highway widening. The drains are still operational today after 31 years of service. Maximum discharge from one drain is still 15 gal/min.

CONCLUSIONS

Horizontal drains are a cost-effective alternative to slope stabilization when elevated pore water pressures must be reduced. The chances of success for any geotechnical project depend as much on the quality of exploration and interpretation as on the design. This premise is even more important when groundwater variables are the focus. By applying a system-and-method approach with working hypotheses, the probability of success is greatly increased. Lower-cost technology exists and is being refined, which will allow an agency or organization with modest resources to successfully complete several or all phases of a project.

ACKNOWLEDGMENTS

The author would like to thank the many workers responsible for the cumulative level of technical expertise in the field of horizontal drain exploration, design, and installation. Special recognition is extended to the following individuals for information on specific topics: René Renteria of the Willamette National Forest for Fairview and Powder Creek slides, Richard Kennedy of the Willamette National Forest for Powder Creek Slide, Peter Bolander of the Willamette National Forest for Camp Five and Quentin slides, Donald Turner of the Oregon DOT for Highlands Interchange Slide, David Michael of the Oregon Department of Forestry for the driven well point method, Douglas Williamson (retired) of the Willamette National Forest for the drive probe method, Kenneth Neal of the Olympic National Forest for the Field Developed Cross Section, and Rodney Prellwitz of the Forest Service, Intermountain Research Station, for information on the ground cork and riser tube method of obtaining remote high-water levels.

REFERENCES

1. D. L. Royster. Some Observations on the Use of Horizontal Drains in the Correction and Prevention of Landslides. Presented at 28th Annual Highway Geology Symposium, Rapid City, S. Dak., 1977.
2. D. D. Smith. *The Effectiveness of Horizontal Drains*. Report FHWA/CA.TL-80-16. California Department of Transportation, Sacramento, 1980.
3. B. C. Vandre. A Case History of a Landslide Caused by Confined Groundwater. *Bulletin of the Association of Engineering Geologists*, Vol. XII, No. 4, 1975, pp. 261–273.
4. R. K. Barrett. Use of Horizontal Drains: Case Histories from the Colorado Division of Highways. In *Transportation Research Record 783*, TRB, National Research Council, Washington, D.C., 1980, pp. 20–25.
5. W. D. Trolinger. Rockwood Embankment Slide 2001+00–2018+00: A Horizontal Drain Case History. In *Transportation Research Record 783*, TRB, National Research Council, Washington, D.C., 1980, pp. 26–30.
6. D. L. Royster. Horizontal Drains and Horizontal Drilling: An Overview. In *Transportation Research Record 783*, TRB, National Research Council, Washington, D.C., 1980, pp. 16–20.
7. M. T. Long. Camp Five Slide—Exploration, Design and Construction of a Horizontal Drain Solution. *Proc., 22nd Annual Engineering Geology and Soils Engineering Symposium*, Boise, Idado, 1986, pp. 246–264.
8. R. H. Spitzer, G. T. Jirak, and S. L. Pawlak. Landslide Stability Achieved with Horizontal Drains. *Proc., 22nd Annual Engineering Geology and Soils Engineering Symposium*, Boise, Idado, 1986, pp. 266–280.
9. C. O. Brawner, R. Pilkalnis, and J. Balmer. Vacuum Drainage to Stabilize Rock Slopes on Mining Projects. Presented at 1st International Mine Water Conference, Budapest, Hungary, 1982, pp. 1–20.
10. R. W. Prellwitz. Analysis of Parallel Drains for Highway Cut-Slope Stabilization. In *Transportation Research Record 705*, TRB, National Research Council, Washington, D.C., 1979, pp. 2–7.
11. K. G. Neal and D. A. Williamson. *The Field Developed Cross Section: A Systematic Method of Dimensional Portrayal*. Internal Memo, U.S. Department of Agriculture, Forest Service, Region 6, Eugene, Oreg., 1980, pp. 1–34.
12. D. A. Williamson. *Geotechnical Field Methods*. Engineering Field Notes, Vol. 21, U.S. Department of Agriculture, Forest Service, 1989, pp. 31–36.
13. *1982 Soil Mechanics*. NAV-FAC DM 7.1. U.S. Department of the Navy, Naval Facilities Engineering Command, Washington, D.C.
14. R. W. Prellwitz and R. E. Babbitt. Long Term Ground Water Monitoring in Mountainous Terrain. In *Transportation Research Record 965*, TRB, National Research Council, Washington, D.C., 1984.
15. H. Stables. Tracing Waters Underground, Fluorescein Disodium Salt. *Eastman Organic Chemical Bulletin*, Vol. 51, No. 3, 1979, pp. 1–2.
16. *Determination of Algae in Natural Waters by Fluorometry, Fluorometry Reviews, Chlorophyll*. G. K. Turner and Associates, Palo Alto, Calif., 1973, pp. 1–4.
17. *Fluorometry in Studies of Pollution and Movement of Fluids, Fluorometry Reviews, Fluorescent Tracers*. G. K. Turner and Associates, Palo Alto, Calif., 1971, pp. 1–11.
18. W. F. Megahan and J. L. Clayton. Tracing Subsurface Flow on Roadcuts on Steep Forested Slopes. *Soil Science Society of America Journal*. Vol. 47, No. 6, 1983, pp. 1063–1067.
19. *Slotted Underdrain Systems, Implementation Package 769*. FHWA, U.S. Department of Transportation, 1976, pp. 1–7.
20. H. R. Cedergren. *Seepage, Drainage and Flow Nets*, 2nd ed. John Wiley, New York, pp. 324–329.