Design Guidelines for Horizontal Drains used for Slope Stabilization

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- California DOT
- Maryland DOT
- Mississippi DOT
- Montana DOT
- New Hampshire DOT
- Ohio DOT
- Pennsylvania DOT
- Texas DOT
- Washington State DOT
- Wyoming DOT
Problem Statement

• The presence of water is one of the most critical factors contributing to the instability of hillslopes.

• Horizontal drains are often used to lower water table elevations, or reduce pore pressures, which increases shear strength of the soil and improve stability.

• Drain design is often ad hoc, with variable success.
Objectives

1. To develop a standard protocol for proper hydrogeologic site characterization

2. Select design guidelines that utilize both analytical and numerical models to cover a wide range of field conditions.

3. Validate selected design methodologies against field data.

4. Provide charts, equations, and useful numerical models for the optimal design of a subsurface drainage system.
Design Manual

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Design Manual

- Chapter 1 – Introduction
- Chapter 2 – Slope Stability Analysis
- Chapter 3 – Groundwater Hydrology
- Chapter 4 – Site Characterization
- Chapter 5 – Groundwater Recharge
- Chapter 6 – Groundwater Modeling
- Chapter 7 – Drainage Design
- Chapter 8 – Fracture Flow
- Chapter 9 – Concluding Remarks
Design Manual

• Appendix A – Definition of Symbols
• Appendix B – MODFLOW Tutorial
• Appendix C – Groundwater Modeling Example
• Appendix D – Soil Characterization in the U.S.
Focus of Today’s Presentation

- Hydrogeologic concepts and terms
- Drainage design procedure
- Idealized example to show thresholds of drainage design
- Illustrate approach with a demonstration site
Hydrogeologic Terms

- Water table
- Unconfined aquifer
- Confined aquifer
- Stream
Hydrogeologic Terms

• **Hydraulic conductivity** – A measure of an aquifer’s ability to transmit water

• **Specific Yield** – Drainable porosity
  ▫ Clay: 1 – 5%
  ▫ Silt: 3-19%
  ▫ Sand: 10-35%
Hydraulic Conductivity

- **Gravel**
- **Clean Sand**
- **Carbonates**
- **Clay**
- **Igneous & Metamorphic Rocks**

Hydraulic Conductivity (ft/d)
Hydrogeologic Terms

- **Steady-state**: A system is in equilibrium with inputs and outputs in balance

- **Transient**: System stresses are changing with time, which causes changes in storage
Hydrogeologic Terms

• **Heterogeneous**: – A property changes with location

• **Anisotropic**: – A property changes with direction
Anisotropy
Drainage Design

Hydrogeologic - Geotechnical Characterization (Chapter 4) & Conceptual Model Development (Chapter 6)

Preliminary Evaluation of Required Groundwater Levels to Achieve Slope Stability (Chapter 2)

Drainage Solution Feasible?

Yes

Design Storm (Chapter 5)

Analytical Drainage Design

Simple

Drainage Optimization

Acceptable FOS?

No

Review/Revise/Update Conceptual Model (Chapter 4)

Acceptable Water Levels?

Yes

Install Drains

Monitoring

Yes

No

Complex

Numerical Drainage Design

Drainage Optimization

No
* Needed for preliminary analysis: for a first cut, much of this information can be obtained via literature, government agencies and rudimentary site surveys.
Eg. Characterization of Hydraulic Conductivity

Type of Measurement

- Literature
  - Specific to aquifer or rock type.
- Grain Size Distribution and Sorting
- Laboratory Estimate
  - Constant head permeameter
  - Falling head permeameter
- Field Site
  - Slug Test
  - Pump Test

Increased Scale, Accuracy, Cost

Adjust slope of line to estimate K

 Slug Test

\[ \frac{y}{y_0} \]

\( y_0 \) is computed as a positive displacement regardless of whether the slug was inserted or withdrawn.

TIME

11:26 01:26 00:00 01:26 02:53 04:19 05:46
Conceptual Model

- Define basin boundary
- Define hydrostratigraphic units
- Delineate important water budget components
- Define flow paths in the system

![Diagram showing seepage from basalt, recharge, and exit to Hood Canal.](image)
Drainage Design
After an Initial Geotechnical Analysis it's ....

**Decision Time!**

- Will drains work to stabilize this hill slope?
- Is it worth further analysis?
  - If Yes, Analytic or Numeric?
- Expert Opinion counts!
- Questions to ask:
  - Have we considered site complexity?
  - Does the system appear highly anisotropic (e.g. large variability in the vertical direction)
  - Are K-values extremely low or high?
  - What are the risks & costs associated with failure?
Factors Controlling Drainage Design

- Aquifer Characterization
- Aquifer Recharge/Response to Precipitation
- Drain length, spacing and elevation
Drainage Design
Recharge & Design Storm

- Recharge is defined as that proportion of precipitation that reaches the water table.

- USDA – SCS (1972) curve number (CN) approach is explained in detail in the manual.

- The CN has been defined over a wide range of geographic, soil and land management conditions. Easily assessable.

- Drain design considers the 100-yr 24 hour storm event.
Drainage Design
Analytic Model

- Analytic models provide simple solutions to estimate groundwater levels under drained conditions given the following:
  - Layer cake geology
  - Uniform slope
  - Homogenous/isotropic conditions.
  - Drains are placed orthogonal to slope (not realistic).
  - Spatial and temporal distribution of water table/pore pressures are not explicitly calculated.
Numeric Model

- Numeric models solve the groundwater flow equation using algebraic techniques
- Can simulate just about any real-world situation including complex geology and drainage networks
- More data required and increased user expertise
- Manual proposes the use of MODFLOW which is the industry standard
- Manual includes step-by-step tutorial for building and executing models
Drainage Design
Factor of Safety (FOS)

Translational

Slope failure assumed
FOS \leq 1.0
Stability assumed
FOS \geq 1.2

Rotational

Images courtesy UMR
IdealizedSites

Translational
Fractured Systems
Rotational
Why present Idealized Sites?

- Test sensitivity of drain design to hydraulic properties.
- Provide practitioner guidance in making decisions after preliminary analysis.
Translational Failure

Assume a thin soil unit over impermeable material

soil thickness 20 ft
Silt, Sandy Silt, Clayey Sand or Till ($K_x = 0.1 \text{ ft/d}$)

Isotropic
FOS = 1.24

### Numeric Model Results

- Higher storage ($\geq 5\%$) and isotropic conditions represent the only situations for this soil class that drains are effective.

- Length of drain is more important than drain density. For this example, stability is achieved with long drains of wide spacing,

- Whole slope is stable, despite gw seepage in slope toe.

- Failure limited to the toe region not tested.

- Shorter drains in the toe region, even with dense spacing cannot stabilize the entire slope.

- No drain array tested works for anisotropic conditions (e.g. $K_x/K_v = 10$), though long drains of dense spacing are close (FOS = 1.15)
Silty Sands and Fine Sands
\( (K_x = 1 \text{ ft/d}) \)

- Drains only necessary for low storage (1%) and isotropic to slightly anisotropic (VKA ≤ 2) conditions in this soil class.
- Short, slope toe drains of medium spacing are able to promote slope stability.
- Longer drains may be necessary for more anisotropic conditions (i.e. VKA = 5), but no drain array tested can stabilize a slope with higher levels of anisotropy (i.e. VKA = 10).
- Slopes with high storage (10%) do not need drains. FOS = 1.43 given no drains.
- Drains are not needed for well sorted sands and glacial outwash \( (K_x = 10 \text{ ft/d}) \).

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Fractured Systems

- Bedrock typically has little or no primary porosity and permeability, and networks of fractures serve as primary conduits for fluid flow.

- These networks are spatially discontinuous and highly irregular in geometry and hydraulic properties.

- Statistical analysis of collected fracture data – fracture location, orientation, spacing, length, aperture, hydraulic conductivity/transmissivity and values of network density – can be used to generate representative, site-specific fracture networks.
Fractured Systems

These discrete fracture networks can then be used for two purposes: (1) compute equivalent permeability tensor values for use in numeric modeling approach, and (2) maximize the probability for drains to intersect flowing fractures to sufficiently reduce pore pressures.

Drainage networks based on site-specific fracture data where drain laterals vary in length according average distance to conductive fractures.
Demonstration Site

MP 69.8
Located in Western Washington
Rotational Failure
Emergency Drains installed February 2006

Landslide Toe Drains installed August 2006
Geotechnical Analysis
(Bishop Simplified Method)
Numeric Modeling Approach

Steady State
Calibrate $K$ to match observed WL

Transient (pre-drains)
Calibrate Storage Terms to match WL

Transient (post-drains)
Calibrate drain conductance to drain flow

OR

Transient (post-drains)
Hypothetical/No Drains

Run Model in Steady State (Not emergency situation)
Run 100-yr 24 hour Storm
Calculate FOS for maximum water level
Is FOS < 1.2?

Design Storm

No
Modeled Peak Water Level

100-yr, 24-hr Design Storm

With no drains, failure is likely above and below hwy.
How well do modeled drains work during a design storm?

- **Upslope emergency drains do little to lower water levels, and become obsolete after toe drains installed.**

- **Landslide toe drains responsible for most/all water level reduction**
Concluding Remarks

- Every drainage problem is unique, and expert opinion cannot be superseded.

- However, our manual provides a quantitative analysis to reduce *ad hoc* decision making.

- This approach requires a conceptual model that includes a proper assessment of data collection, the water balance and the site’s complexity.

- Feasibility, location, length and spacing of drains considered.

- In hydrogeologic terms, drainage design is heavily influenced by amount of recharge, thickness of soil, hydraulic conductivity, storage and anisotropy.

- Numeric models should be used if the system is complex, heterogenous and/or anisotropic and risk/cost of failure is high.