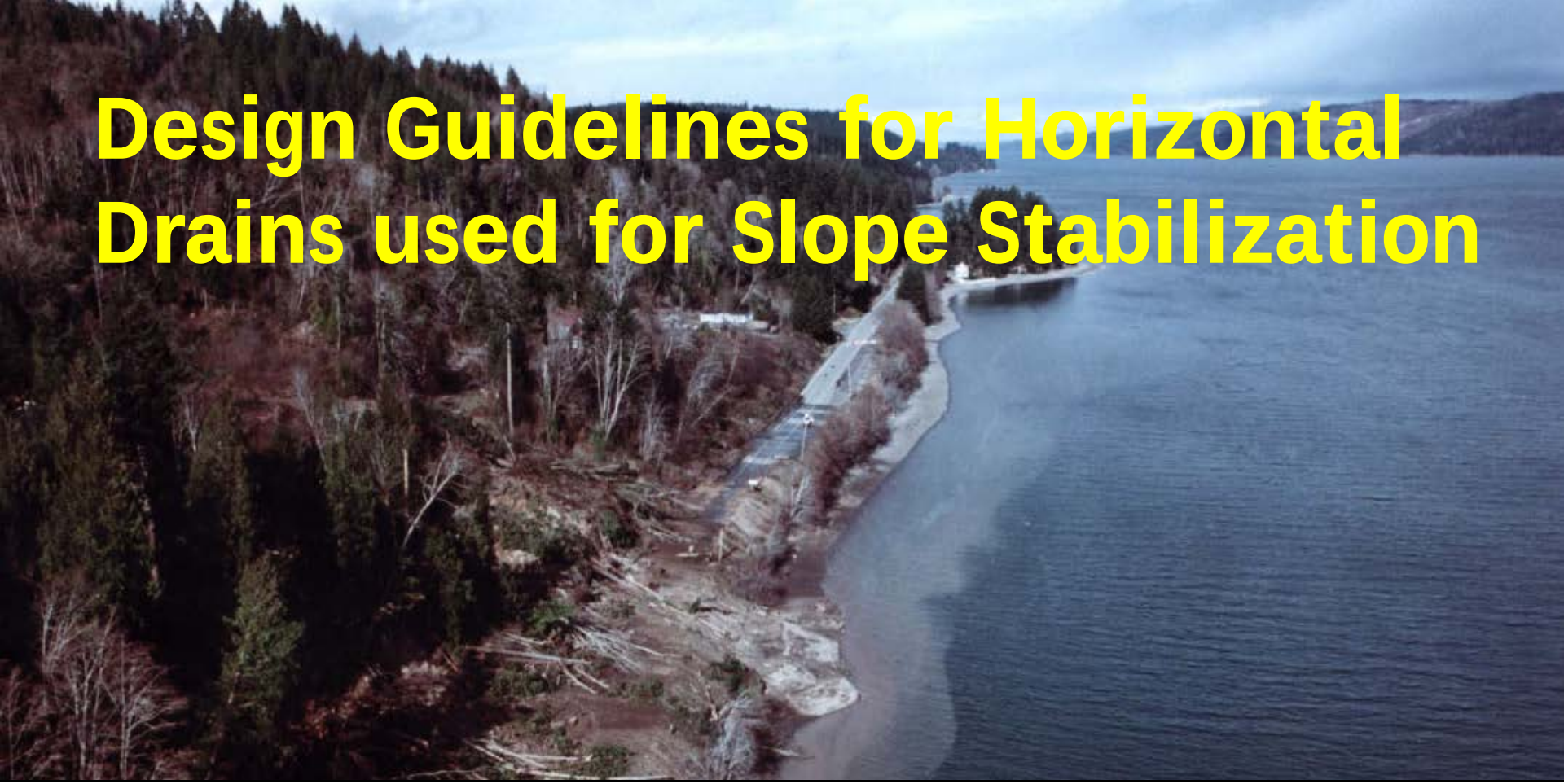

Design Guidelines for Horizontal Drains used for Slope Stabilization

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Rishi Parashar

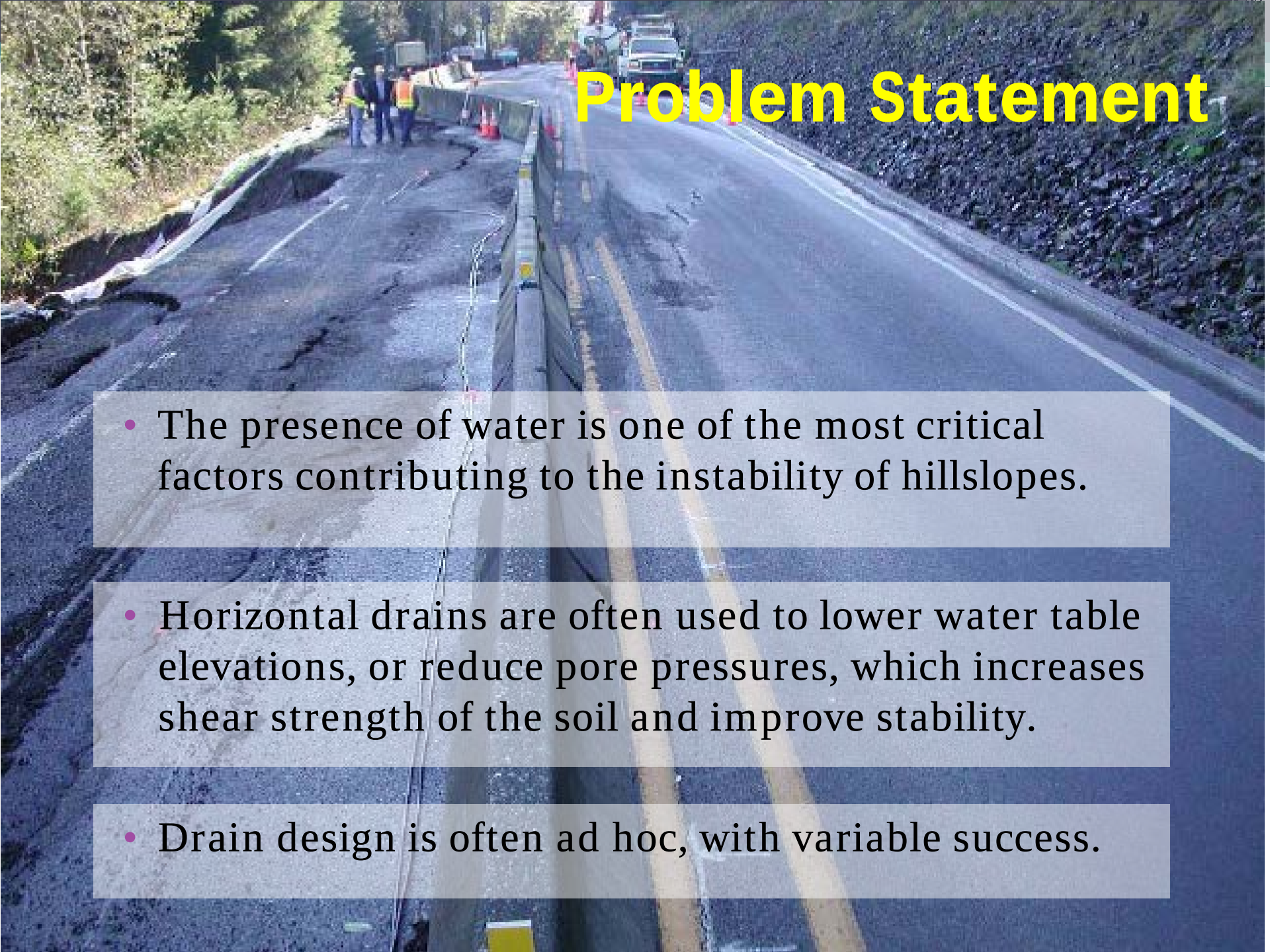
DRI Desert Research Institute

Washington State Department of Transportation

Acknowledgements

The research was a pooled-fund study with the following participating agencies with WSDOT being the lead agency:

- 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

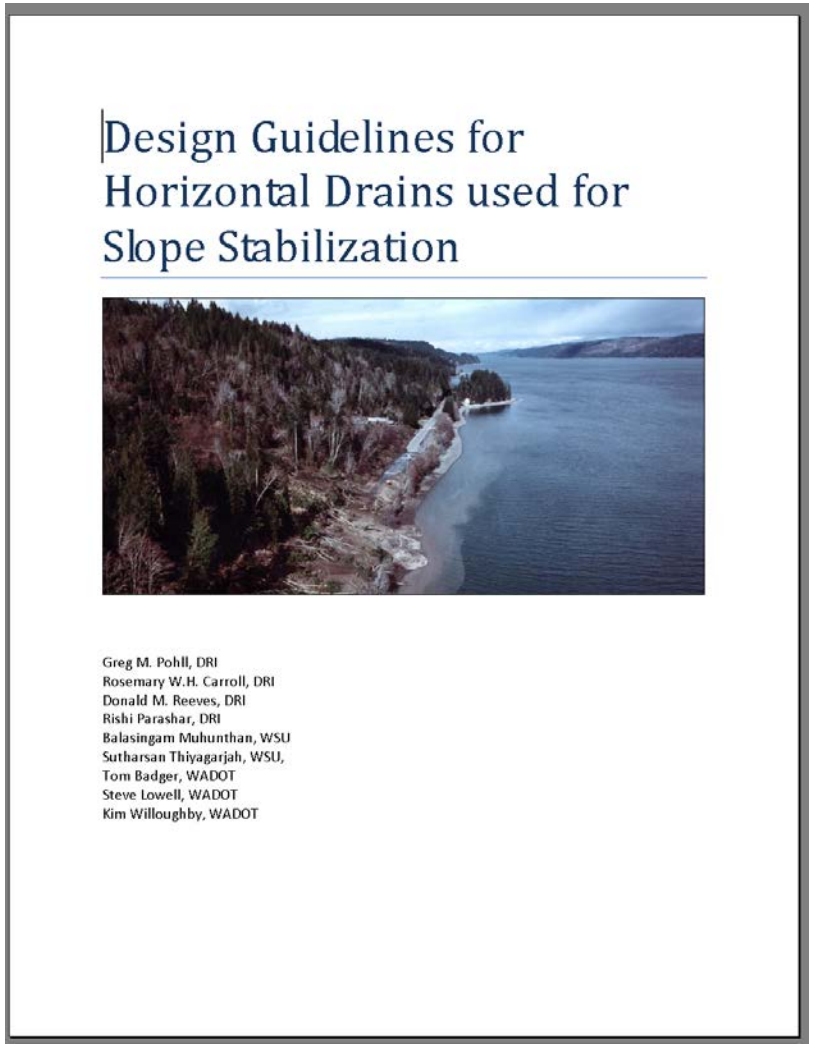
1. To develop a standard protocol for proper hydrogeologic site characterization

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



Design Guidelines for Horizontal Drains used for Slope Stabilization

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Tom Badger, WADOT
Steve Lowell, WADOT
Kim Willoughby, WADOT

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

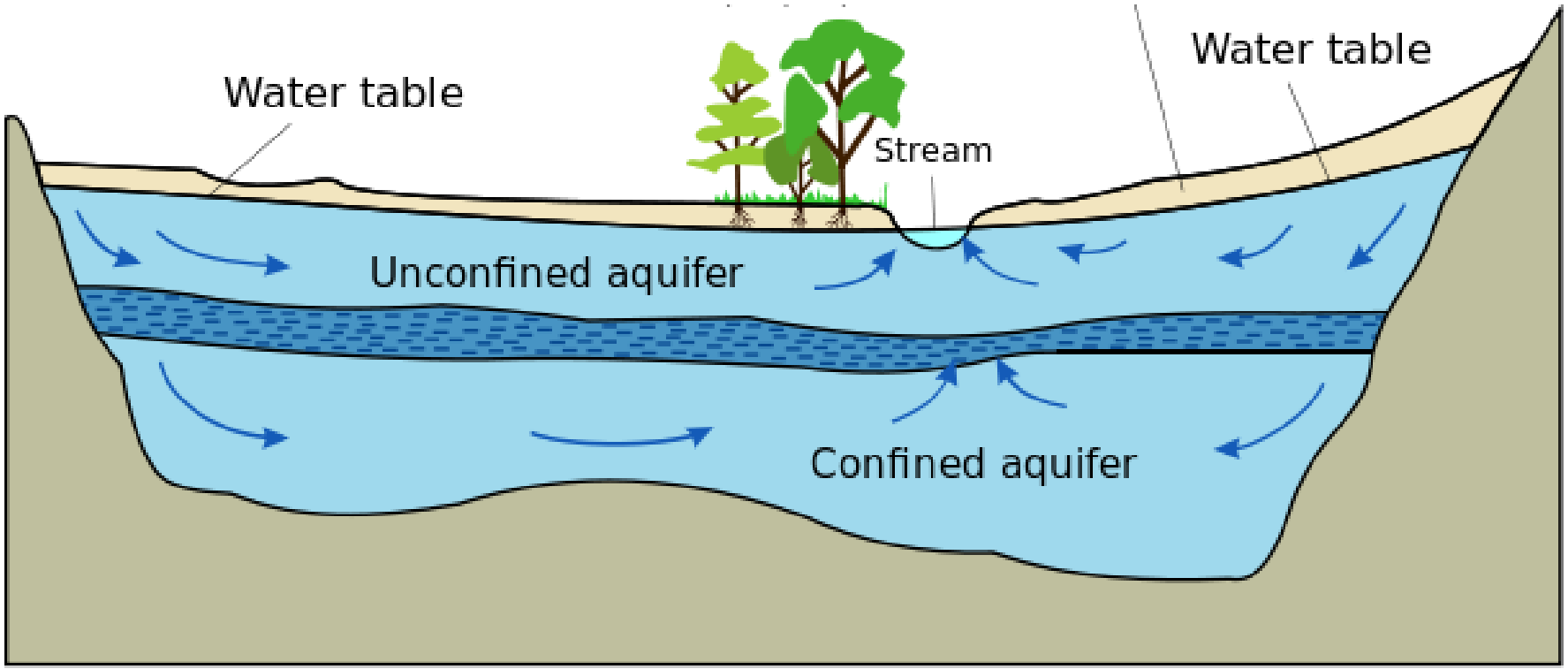
Design Manual

- 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

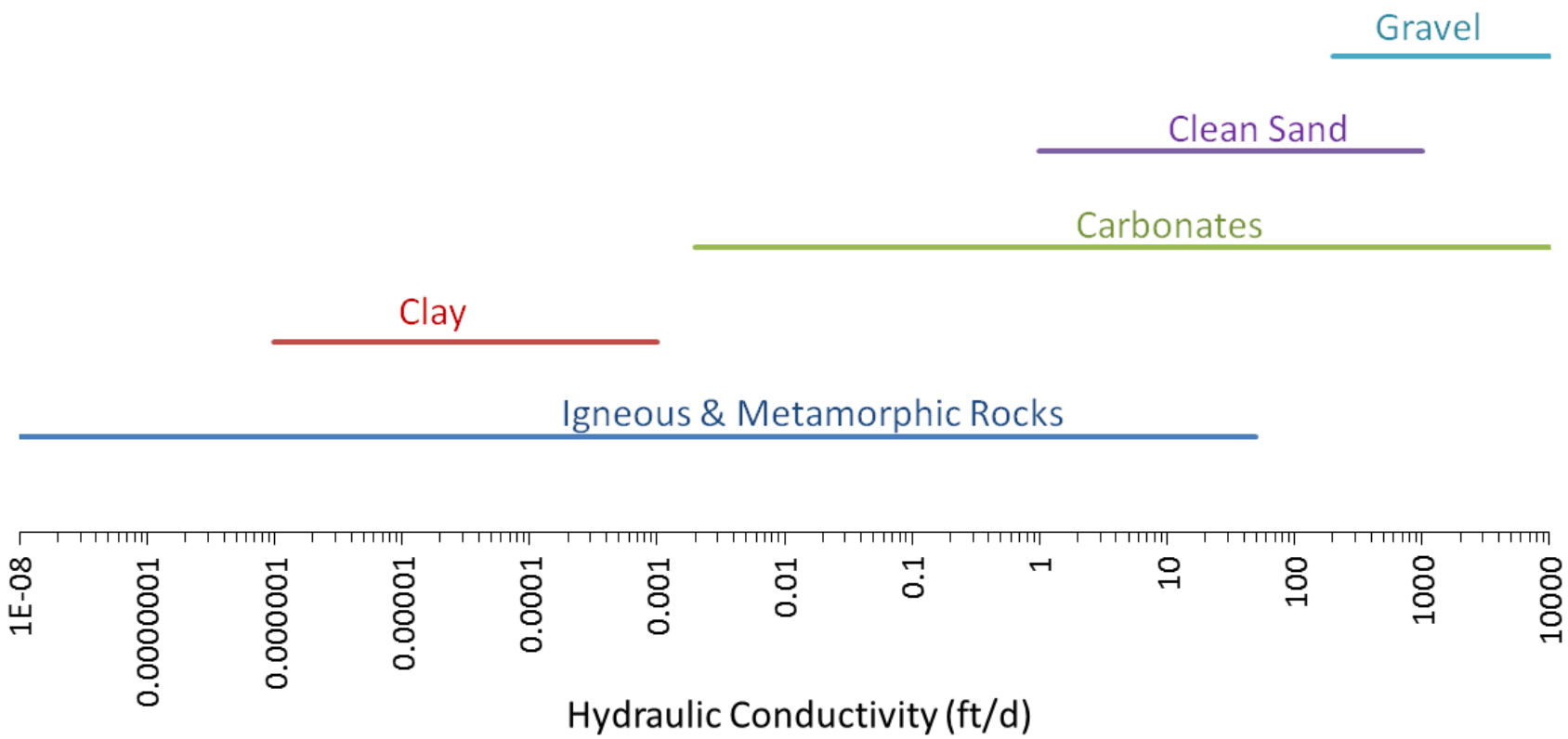


Hydrogeologic Terms

- **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



Hydrogeologic Terms

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

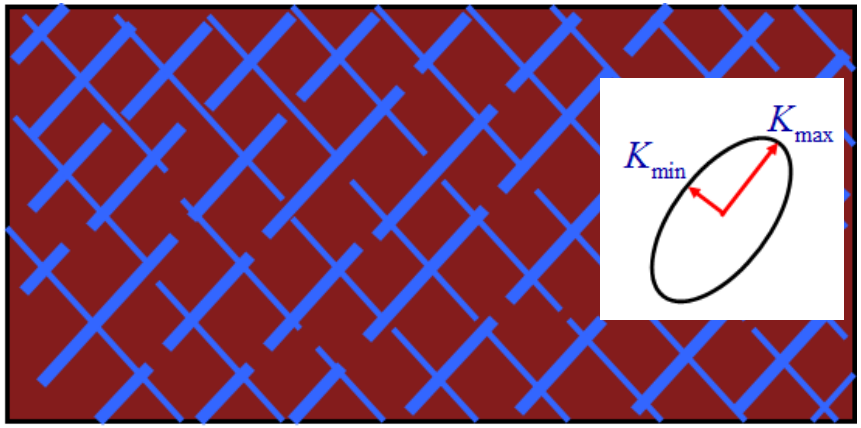
- **Transient:** – System stresses are changing with time, which causes changes in storage

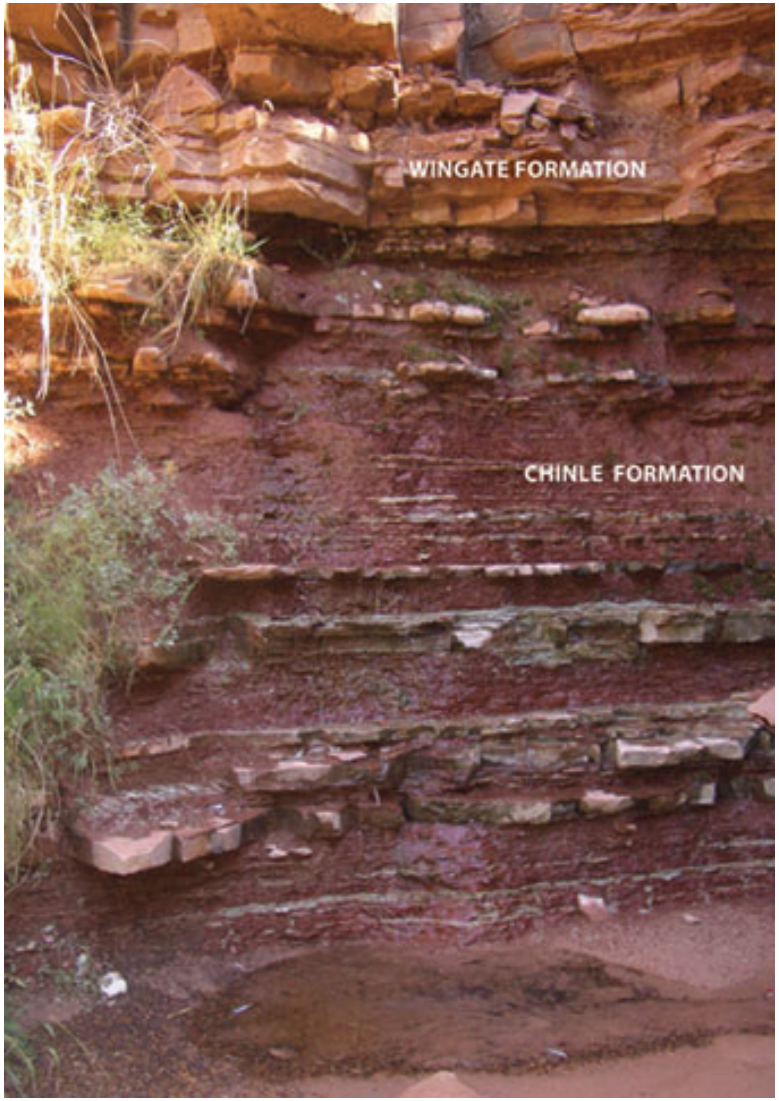
Hydrogeologic Terms

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

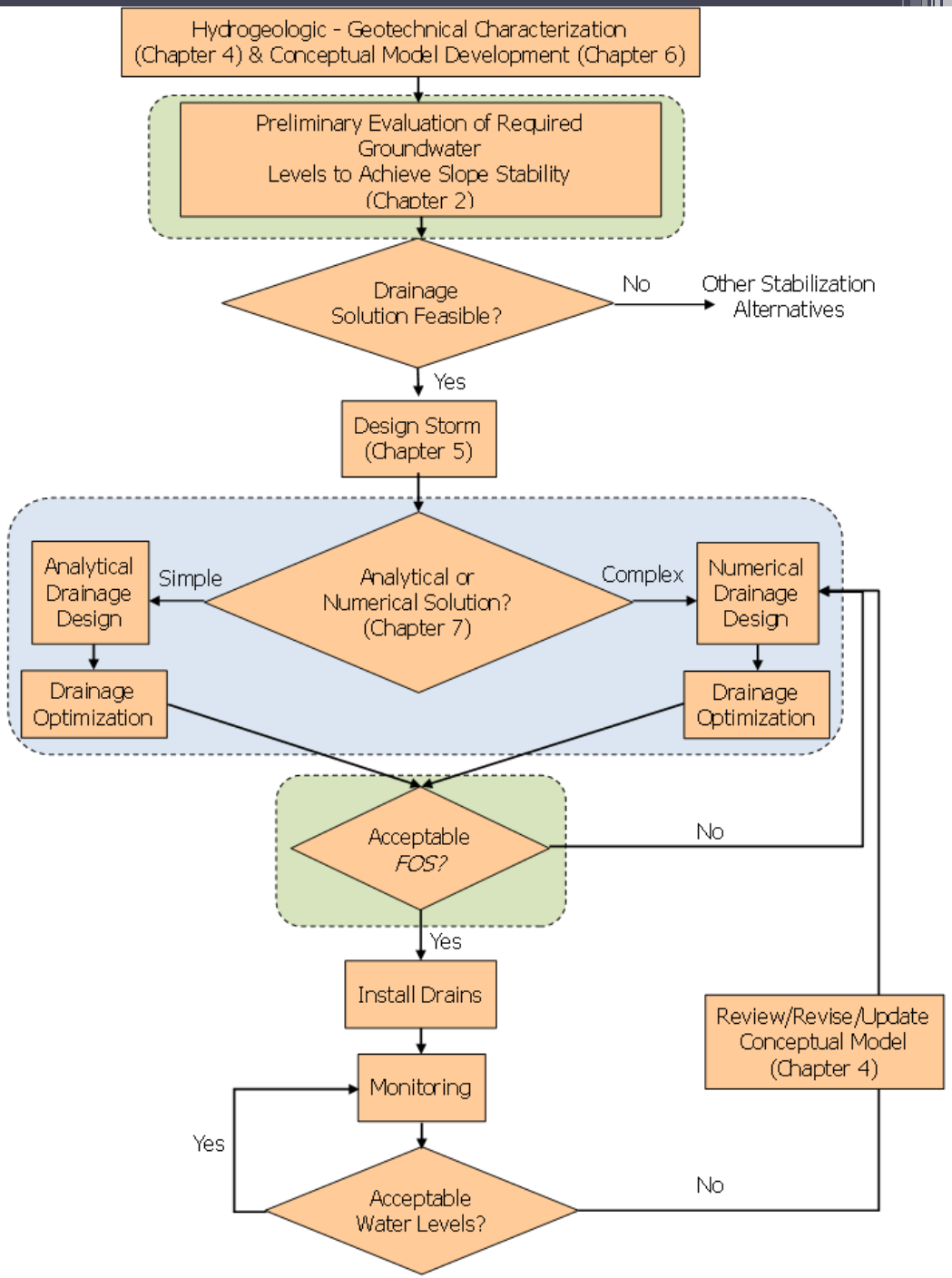
- **Anisotropic:** – A property changes with direction

Anisotropy





Drainage Design



Site Characterization

Geotechnical

- Friction angle*
- Cohesion*
- Unit weight soil*
- Saturated soil weight*
- Slope angle*
- Slope length*
- Depth to barrier layer*

Hydrogeologic

- Site topography (DEM)
- Watershed delineation
- Geologic survey*
- Soil survey*
- Vegetation type/condition*
- Hydraulic conductivity*
- Specific yield*
- Average annual rainfall*
- SCS 100-yr 24-hr storm total and type*
- Site specific precipitation
- 1 observation well*
- Additional wells
- Drain location
- Drain discharge

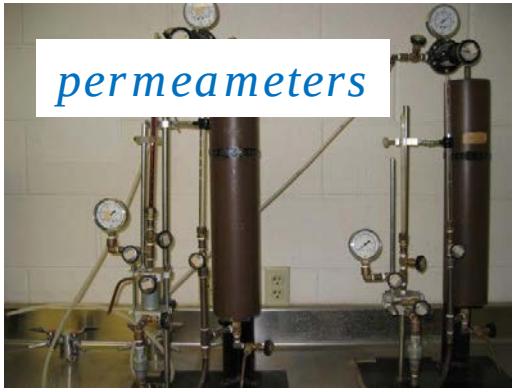
* *Needed for preliminary analysis: for a first cut, much of this information can be obtained via literature, government agencies and rudimentary site surveys.*

Eg. Characterization of Hydraulic Conductivity

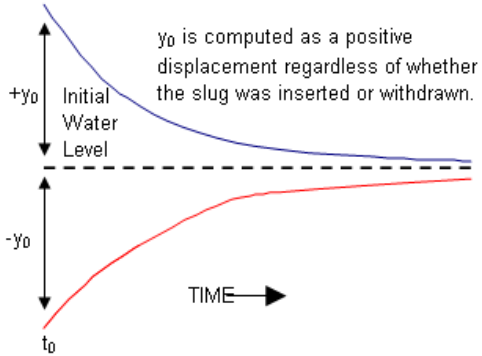
Type of Measurement

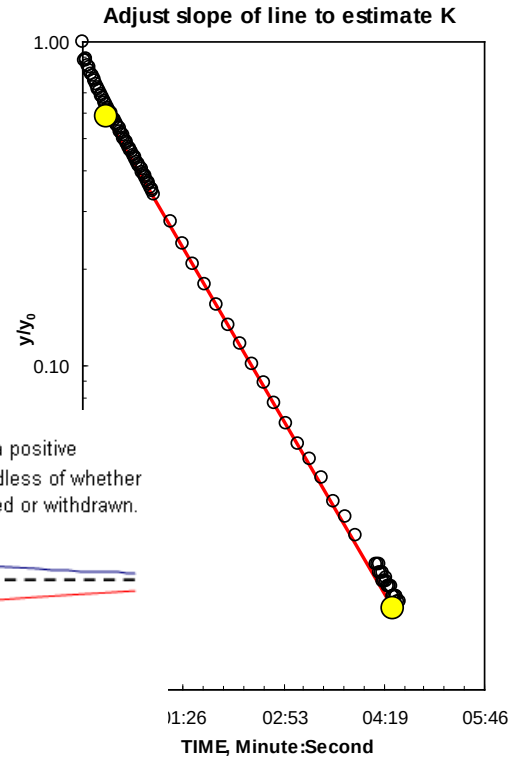
Increased Scale, Accuracy, Cost

- 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



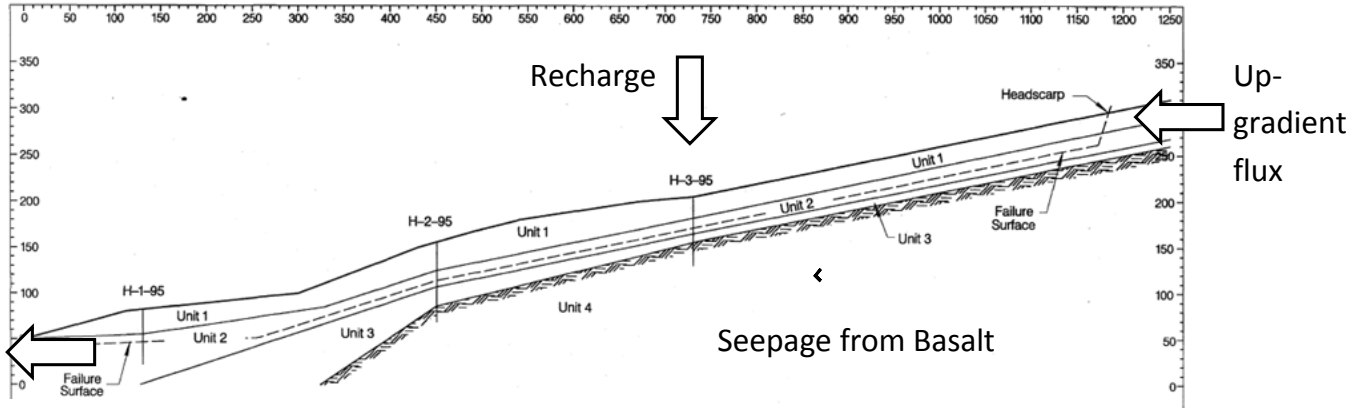
Slug Test





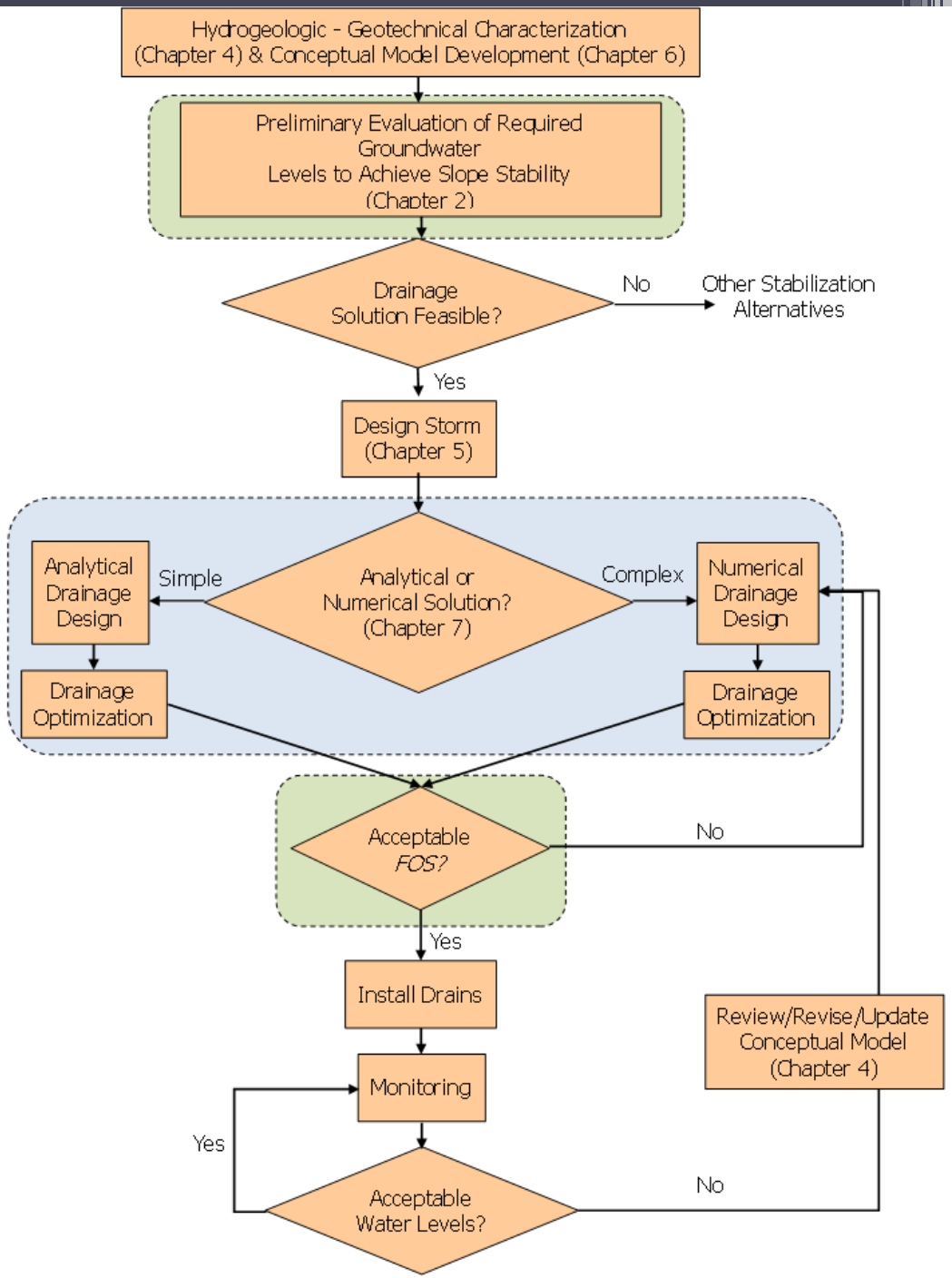
Conceptual Model

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



Unit 1	Outwash Sands and Gravels
Unit 2	Glacio-lucustrine Silts and Clays
Unit 3	Glacial Till
Unit 4	Basalt Bedrock

Drainage Design



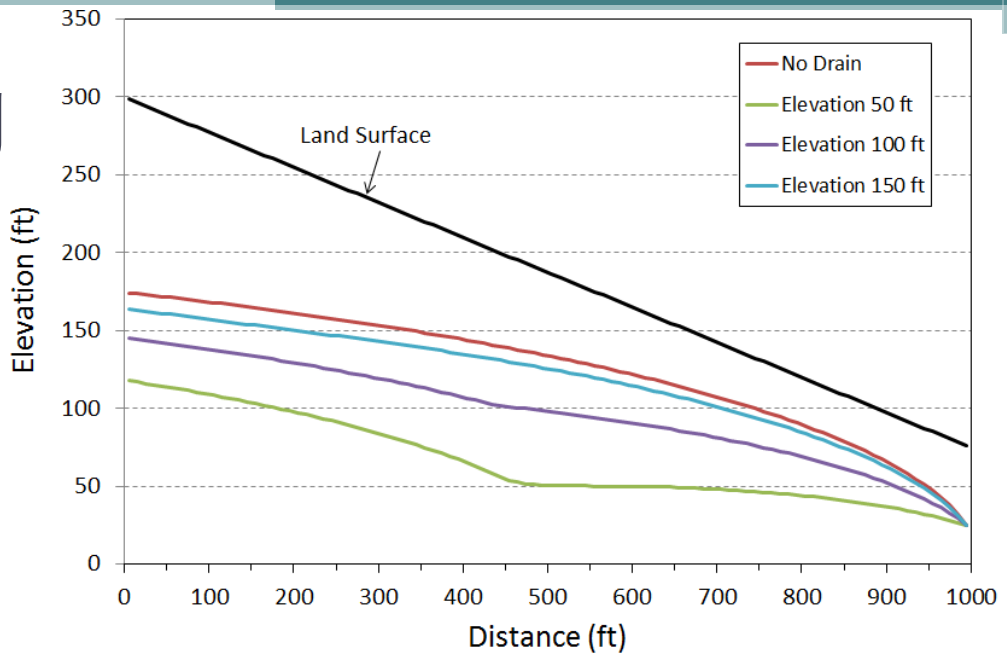
After an Initial Geotechnical Analysis its ….

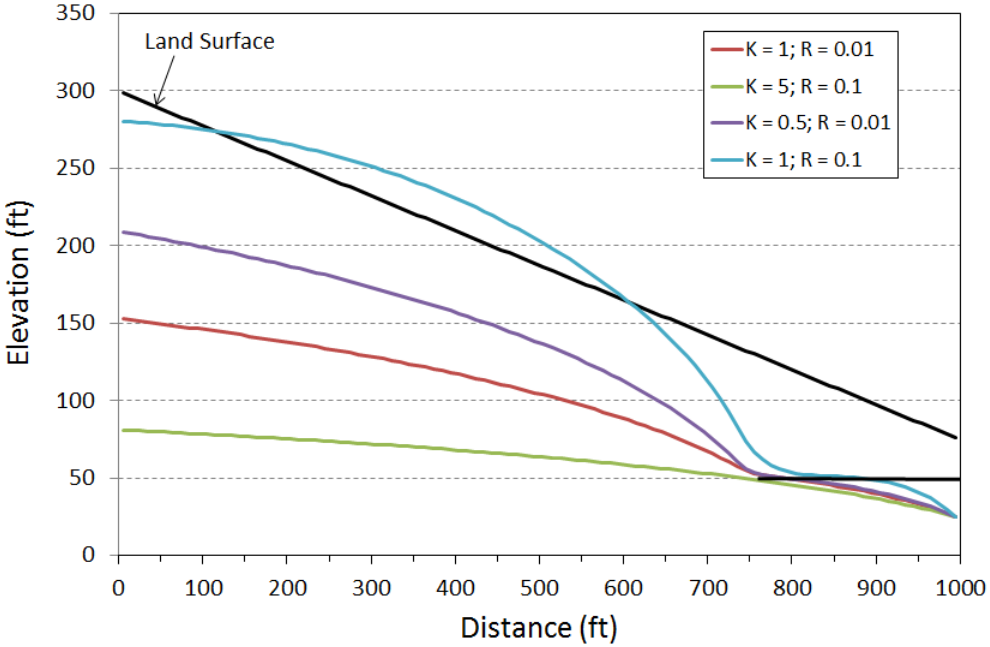
Decision Time!

- 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?

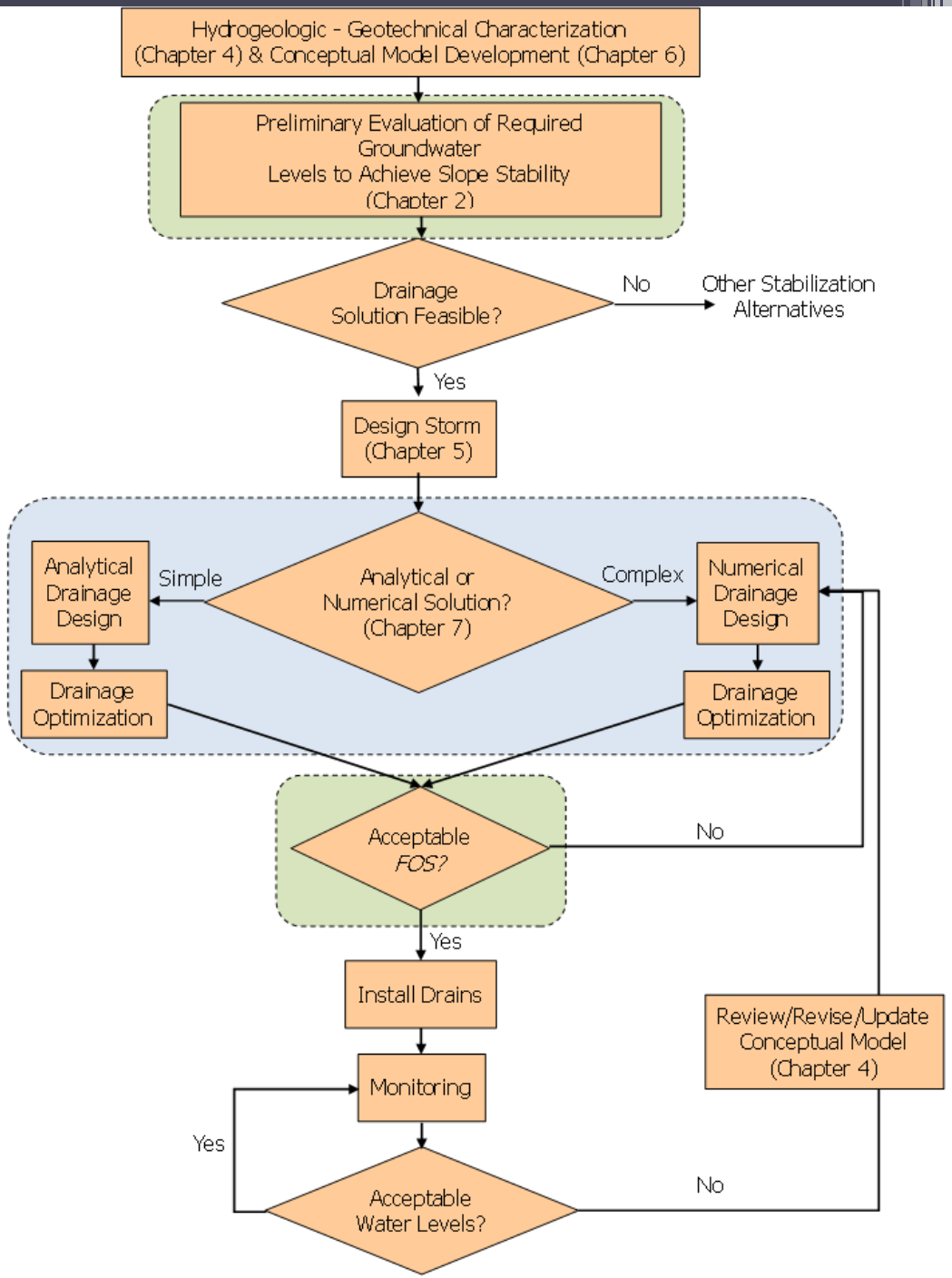
Factors Controlling Drainage Design

- Aquifer Characterization
- Aquifer Recharge/Response to Precipitation
- Drain length, spacing and elevation

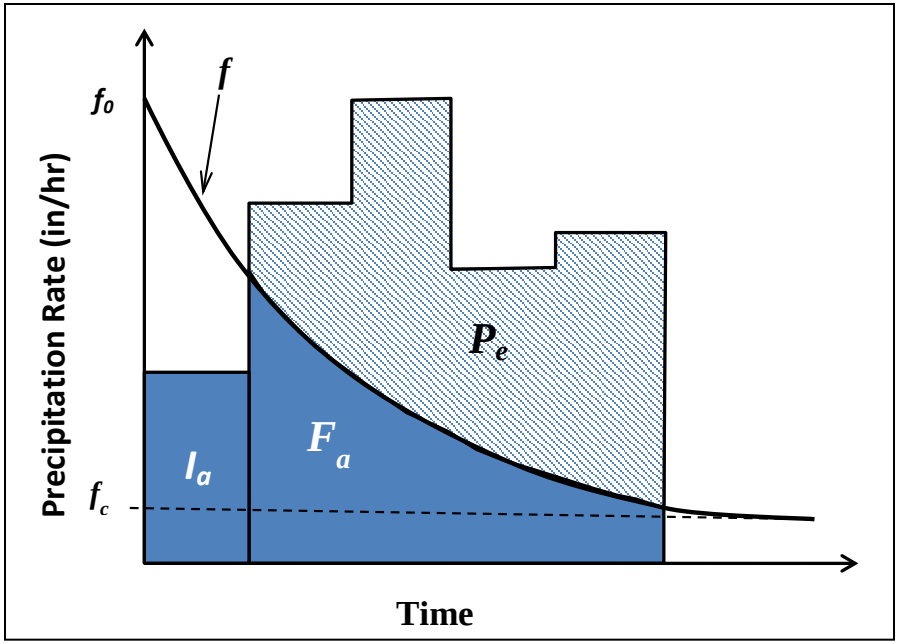




Drainage Design

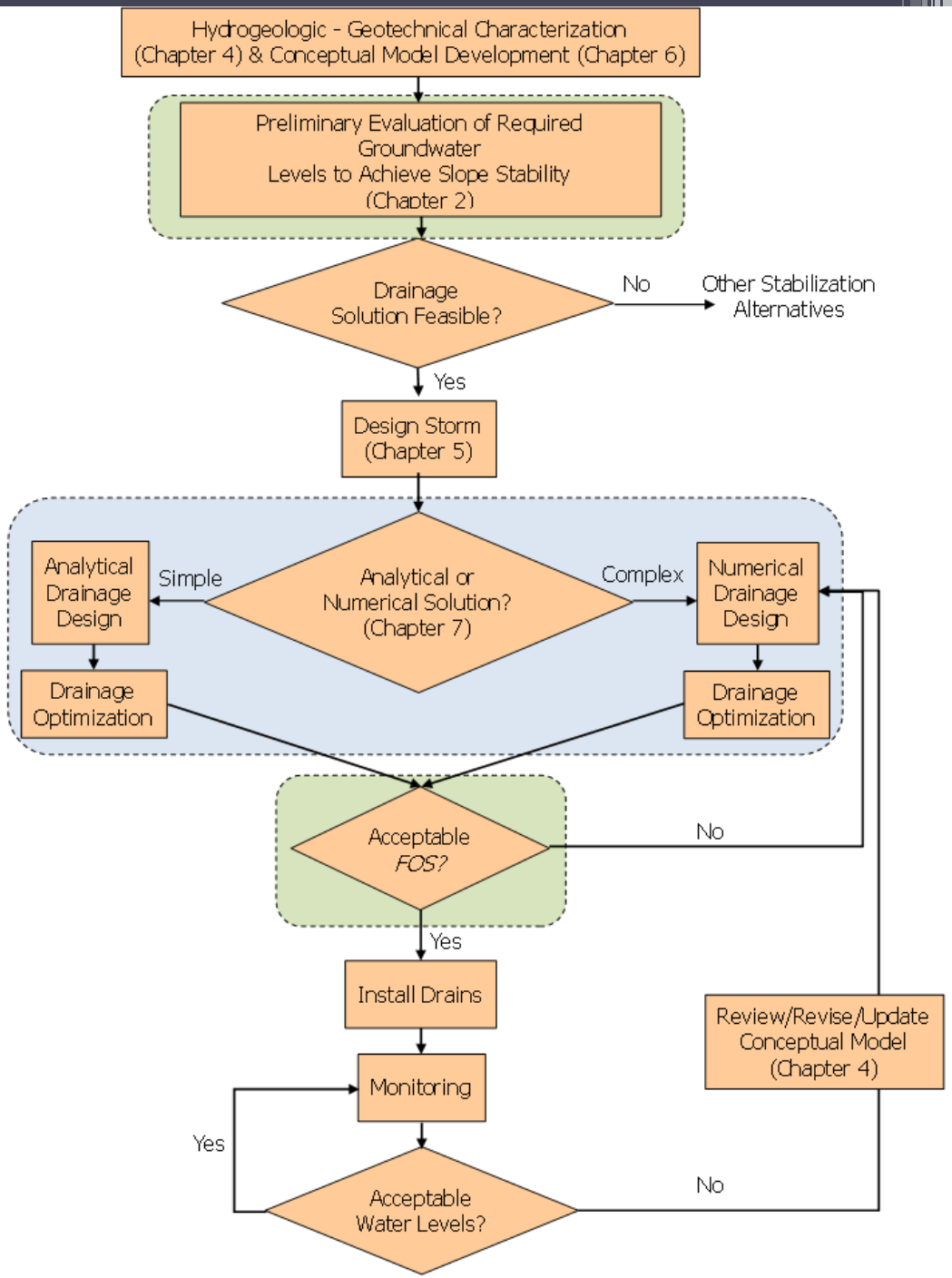


Recharge & Design Storm



- 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



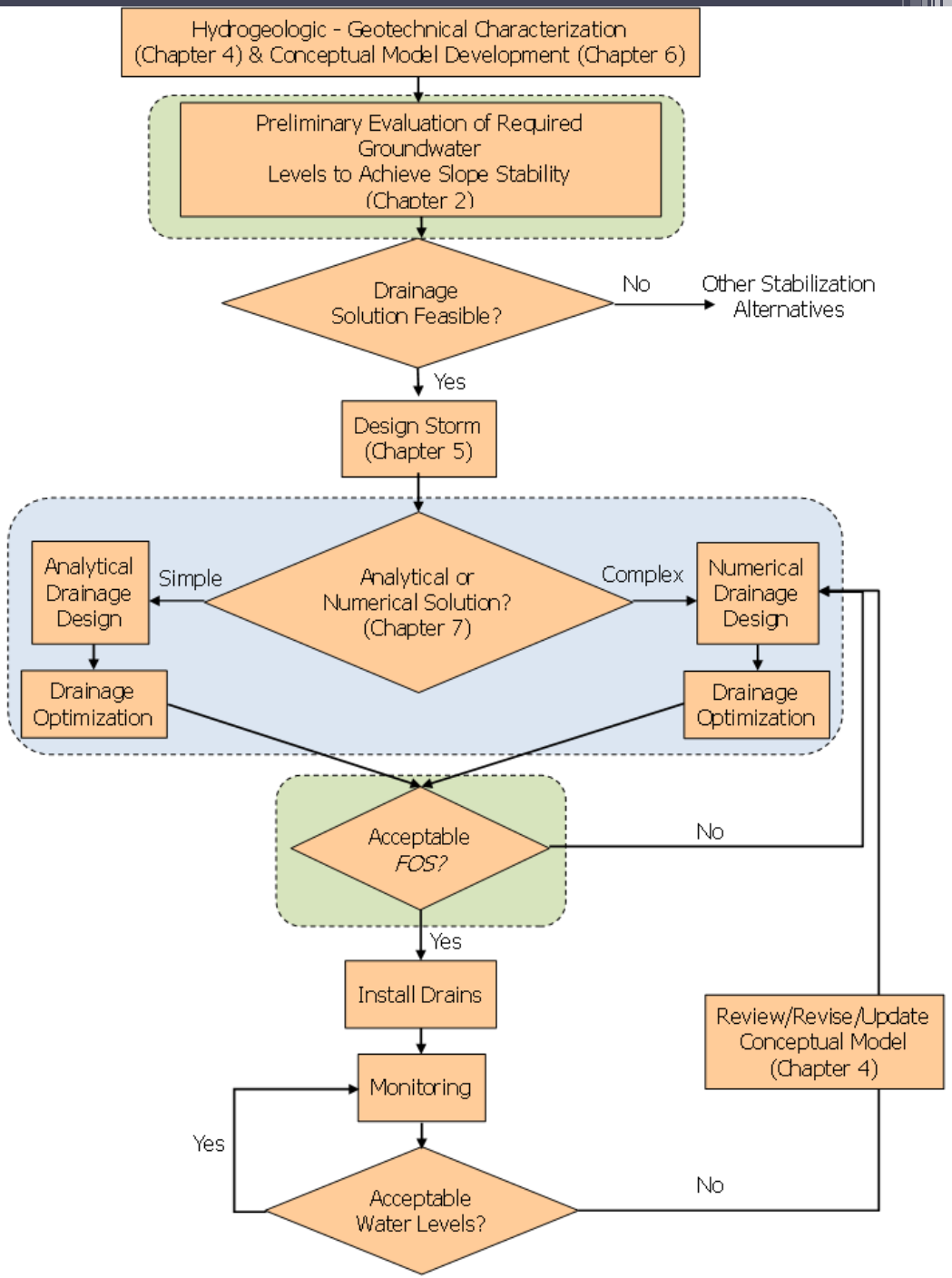
Analytic Model

- 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

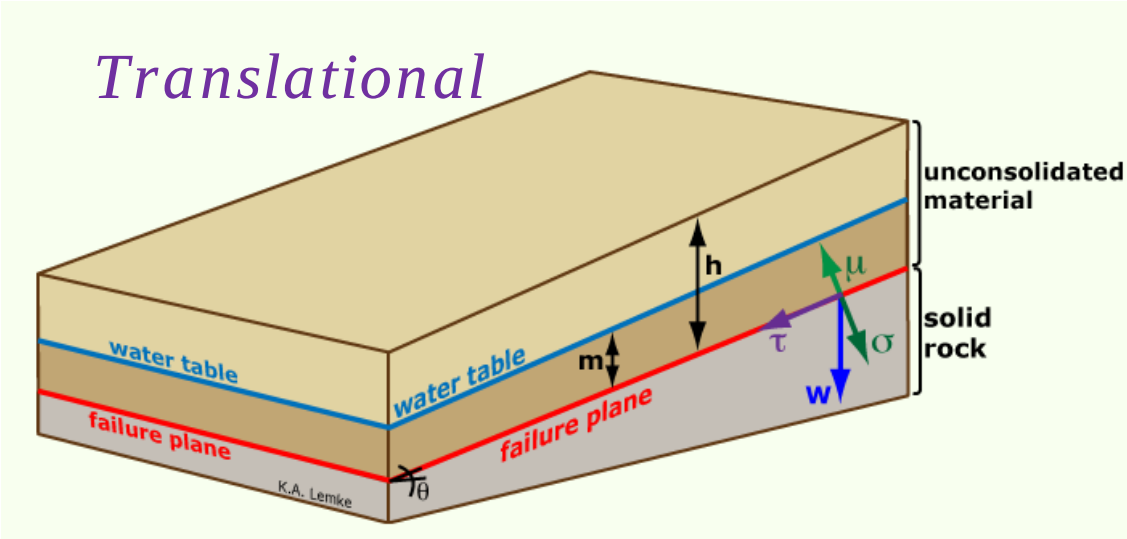
- Numeric models solve the groundwater flow equation using algebraic techniques
- Can simulate just about any real-world situation including complex geology and drainage networks
- More data required and increased user expertise
- Manual proposes the use of MODFLOW which is the industry standard
- Manual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

Drainage Design



Factor of Safety (FOS)

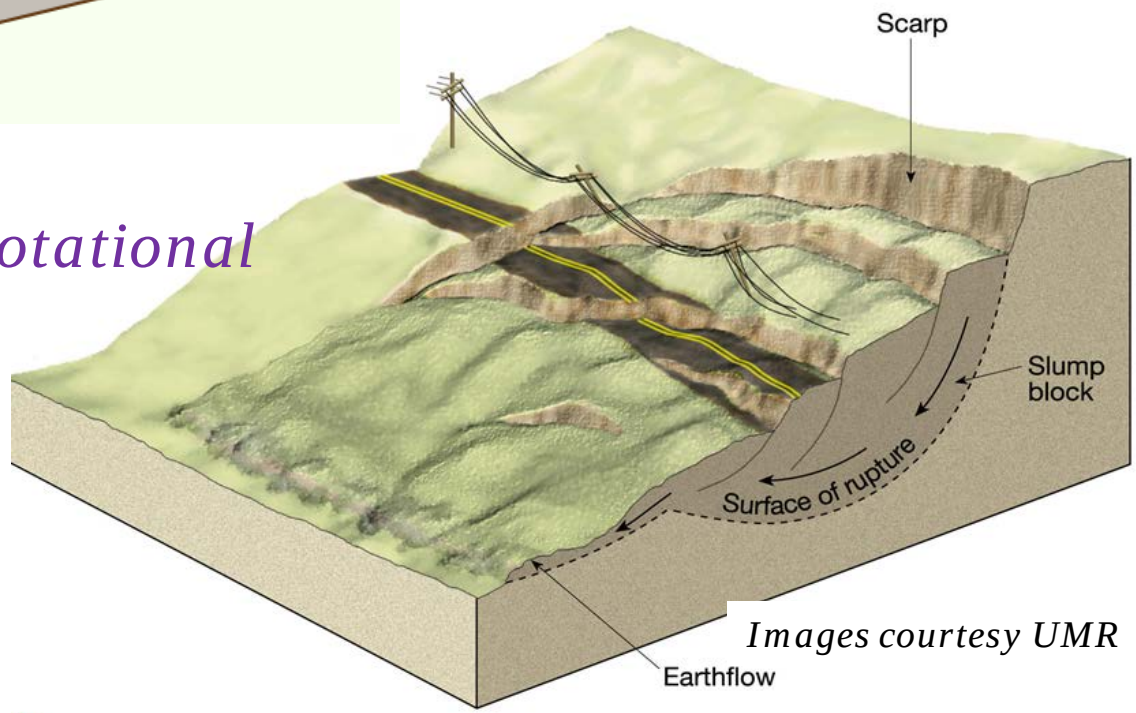
Translational



Slope failure assumed
FOS ≤ 1.0

Stability assumed
FOS≥1.2

Rotational



Images courtesy UMR

Idealized Sites

Translational

Fractured Systems

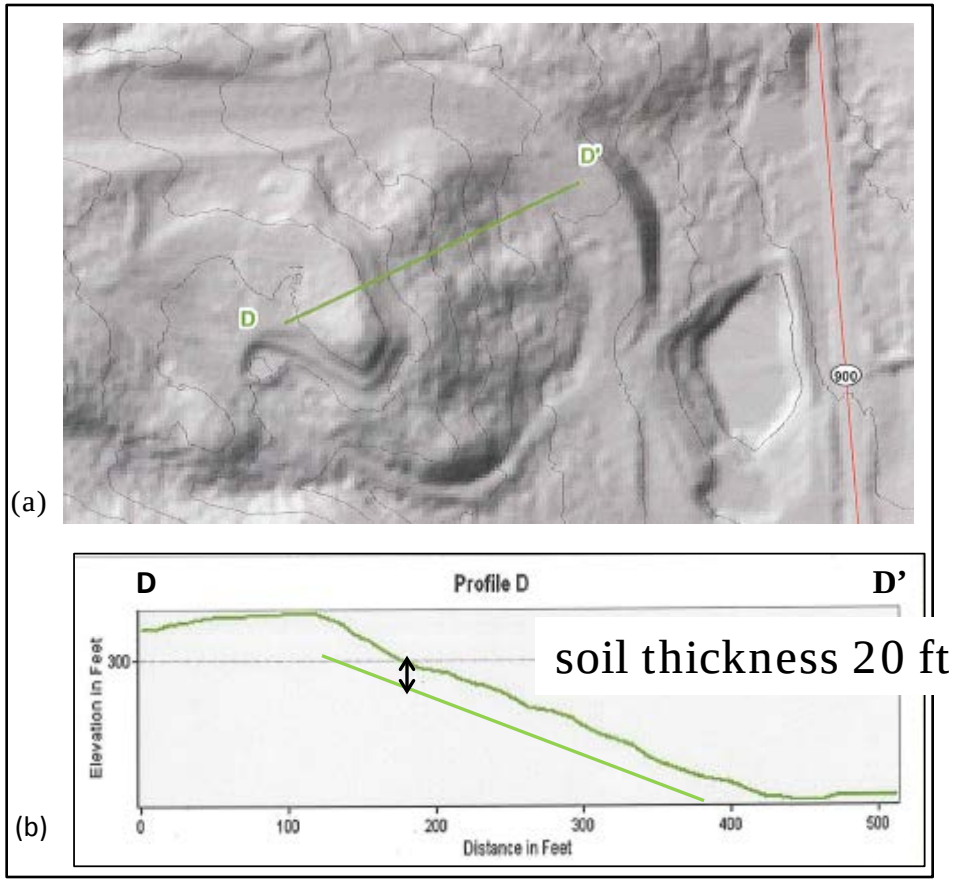
Rotational

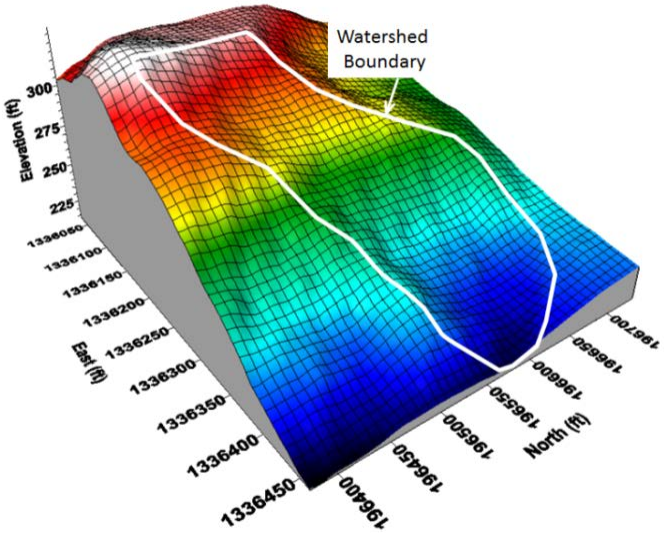
Why present Idealized Sites?

- Test sensitivity of drain design to hydraulic properties.
- Provide practitioner guidance in making decisions after preliminary analysis.
- Manual provides step-by-step tutorials on building a gw model.

Translational Failure

Assume a thin soil unit over impermeable material

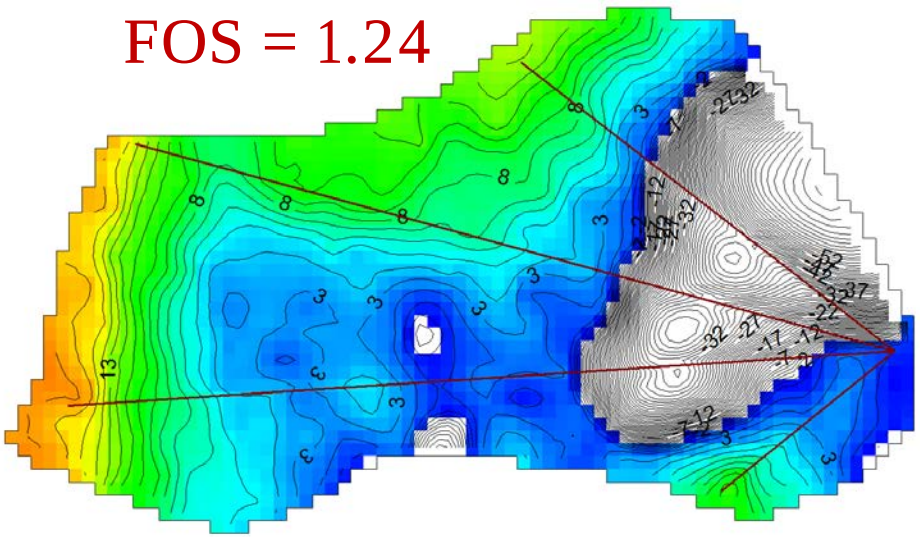




Silt, Sandy Silt, Clayey Sand or Till

(K_x = 0.1 ft/d)

Isotropic
FOS = 1.24



WT depth below land surface (ft)

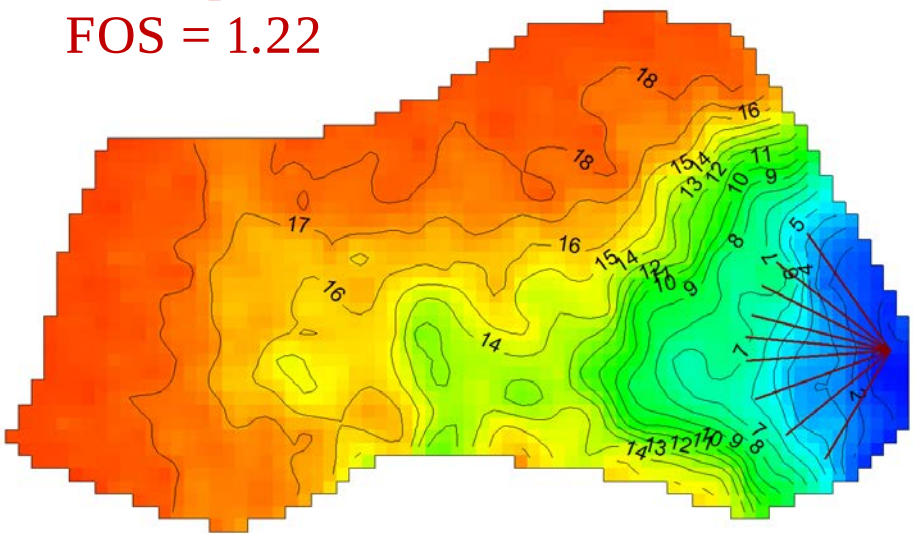
Numeric Model Results

- Higher storage (≥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. Kx/Kv = 10), though long drains of dense spacing are close (FOS = 1.15)

Silty Sands and Fine Sands

(K_x = 1 ft/d)

Isotropic
FOS = 1.22



WT depth below land surface (ft)

Numeric Model Results

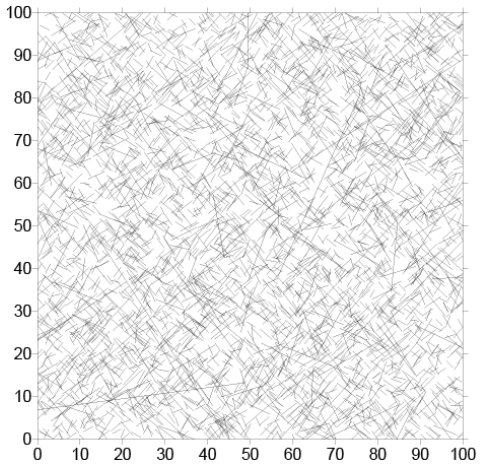
- Drains only necessary for low storage (1%) and isotropic to slightly anisotropic (VKA ≤ 2) conditions in this soil class.
- Short, slope toe drains of medium spacing are able to promote slope stability.
- Longer drains may be necessary for more anisotropic conditions (i.e. VKA = 5), but no drain array 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 ft/d).

Fractured Systems

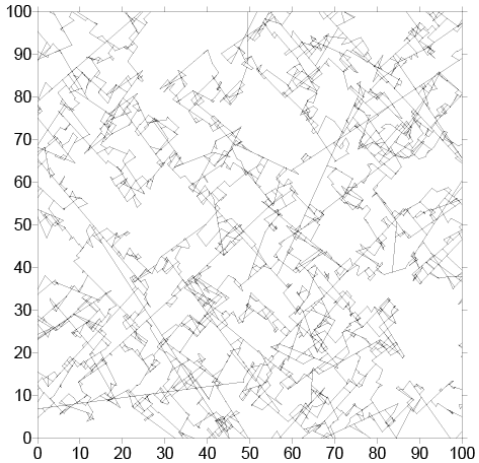
- Bedrock typically has little or no primary porosity and permeability, and networks of fractures serve as primary conduits for fluid flow.

- 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.

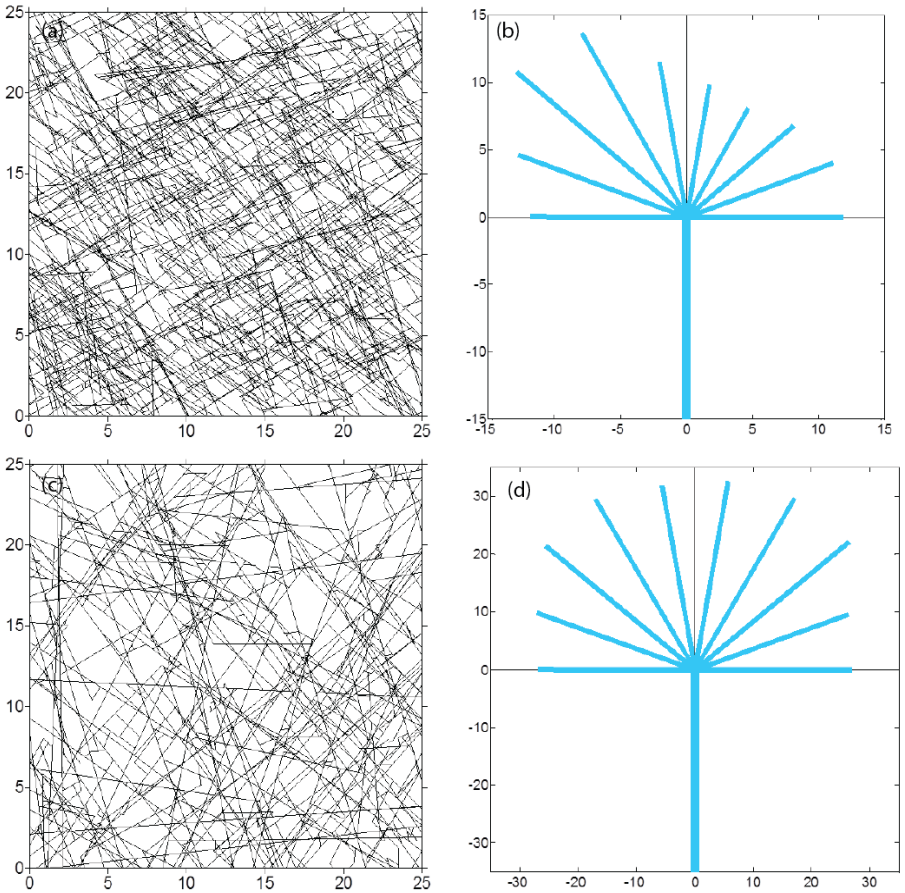


Fracture Network



Conductive Portion of Fracture Network

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.

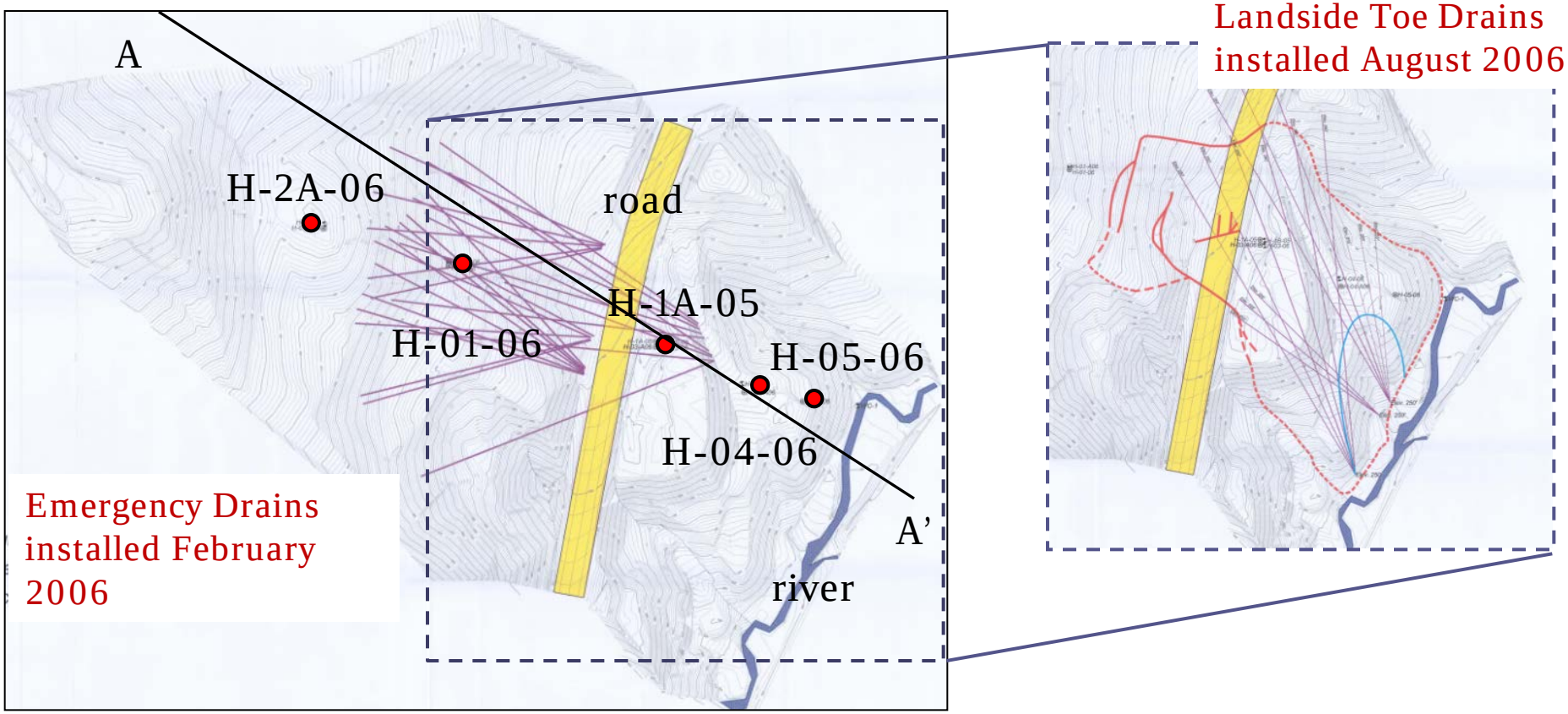
Drainage networks based on site-specific fracture data where drain laterals vary in length according average distance to conductive fractures.

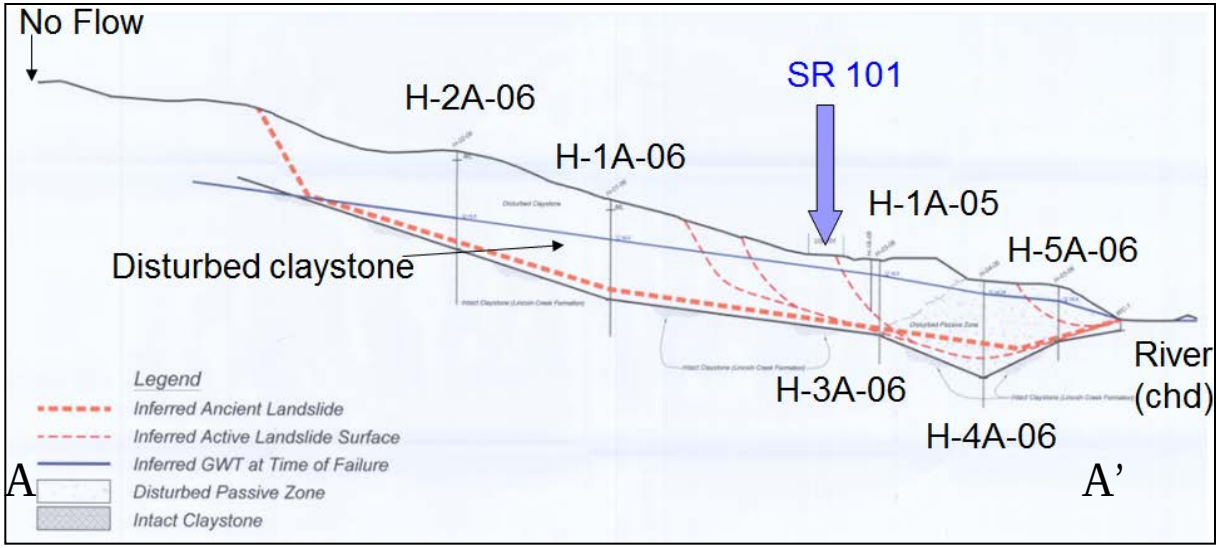
Demonstration Site

MP 69.8

Located in Western Washington

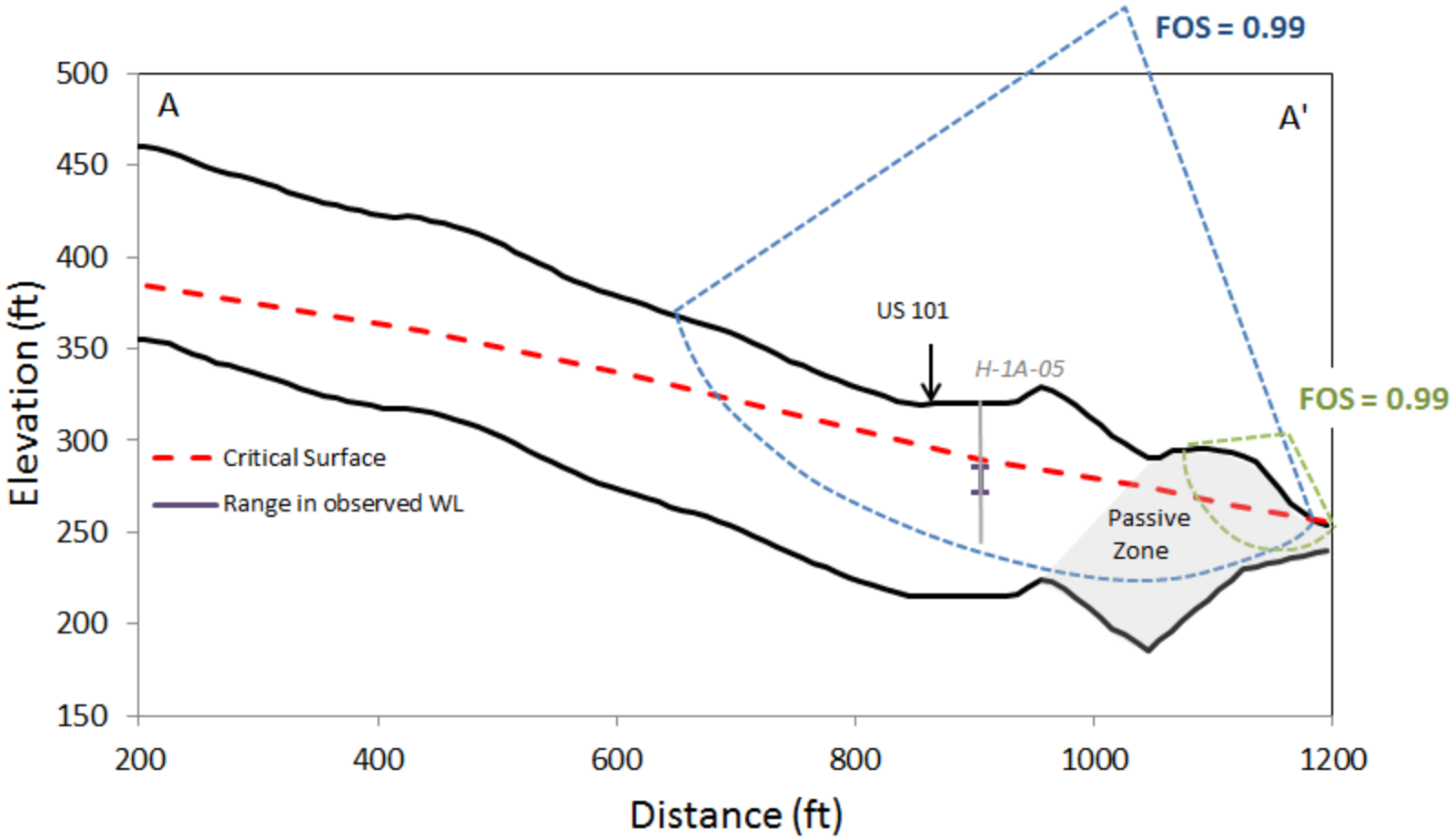
Rotational Failure


A
H-2A-06
road
H-1A-05
H-01-06
H-05-06
H-04-06
A'
river
Emergency Drains installed February 2006
Landside Toe Drains installed August 2006


No Flow
SR 101
H-2A-06
H-1A-06
H-1A-05
H-5A-06
Disturbed claystone
River (chd)
H-3A-06
H-4A-06
A
A'
Legend
Inferred Ancient Landslide
Inferred Active Landslide Surface
Inferred GWT at Time of Failure
Disturbed Passive Zone
Intact Claystone

Geotechnical Analysis

(Bishop Simplified Method)



Numeric Modeling Approach

Steady State
Calibrate K to match observed WL

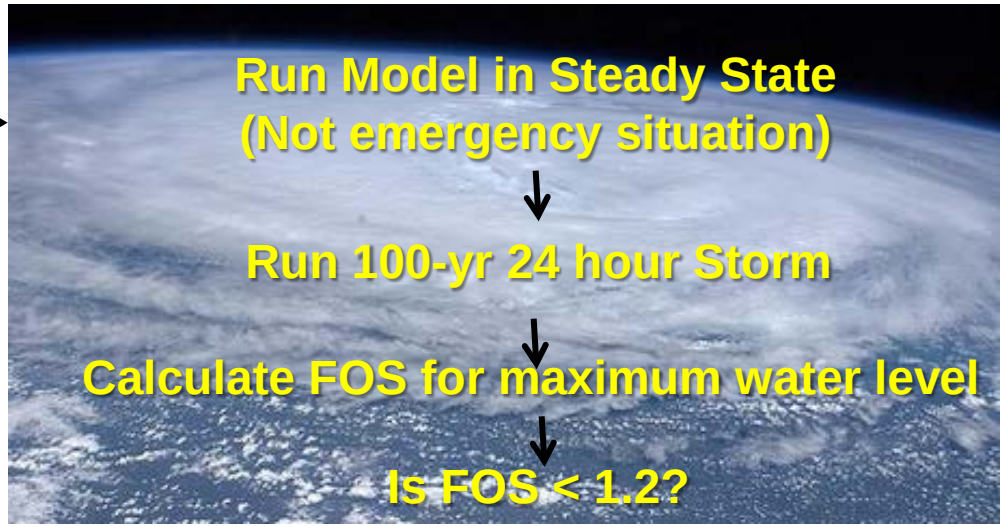
Transient (pre-drains)
Calibrate Storage Terms to match WL

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

OR

Transient (post-drains)
Hypothetical/No Drains

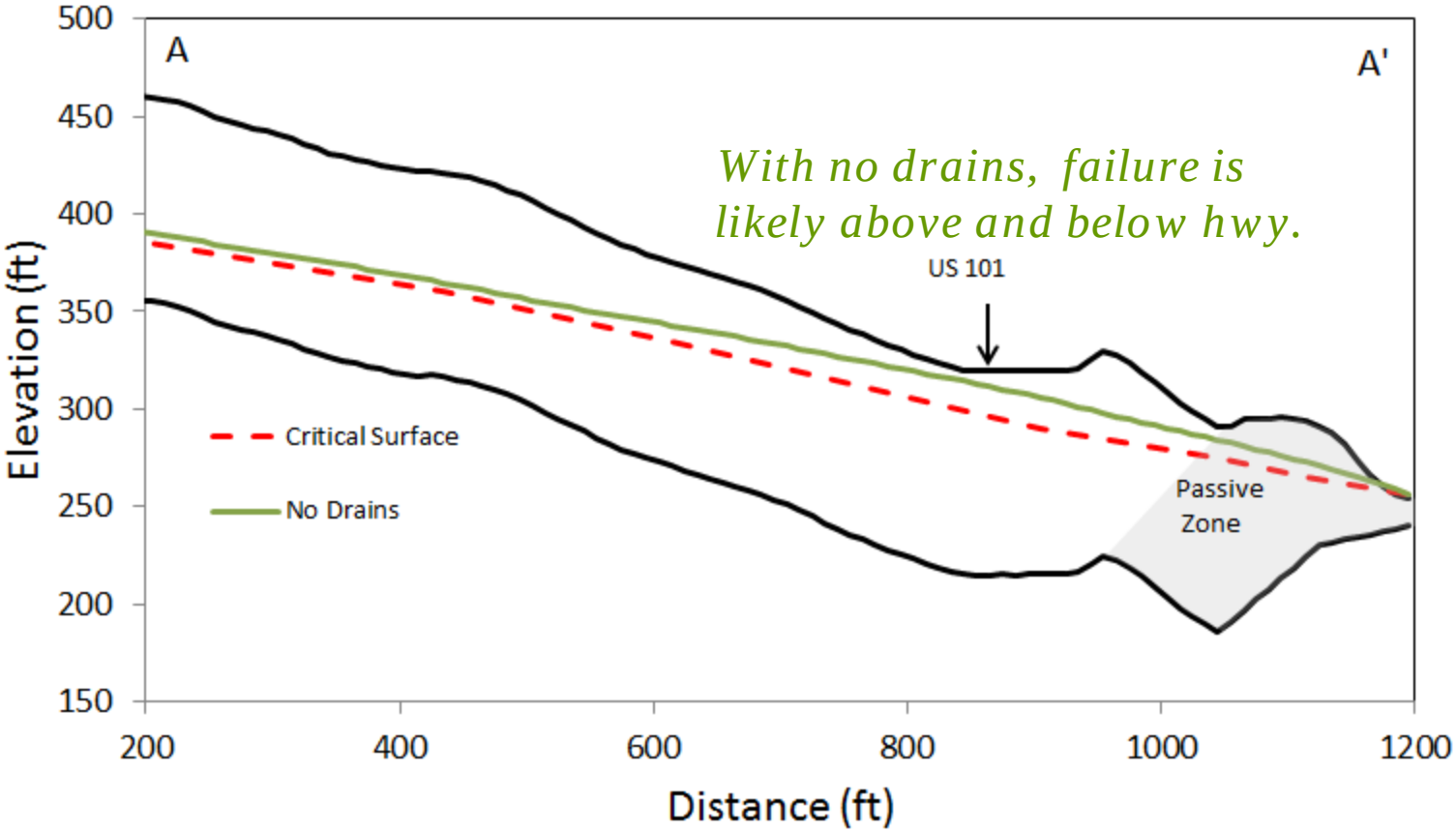
Design Storm



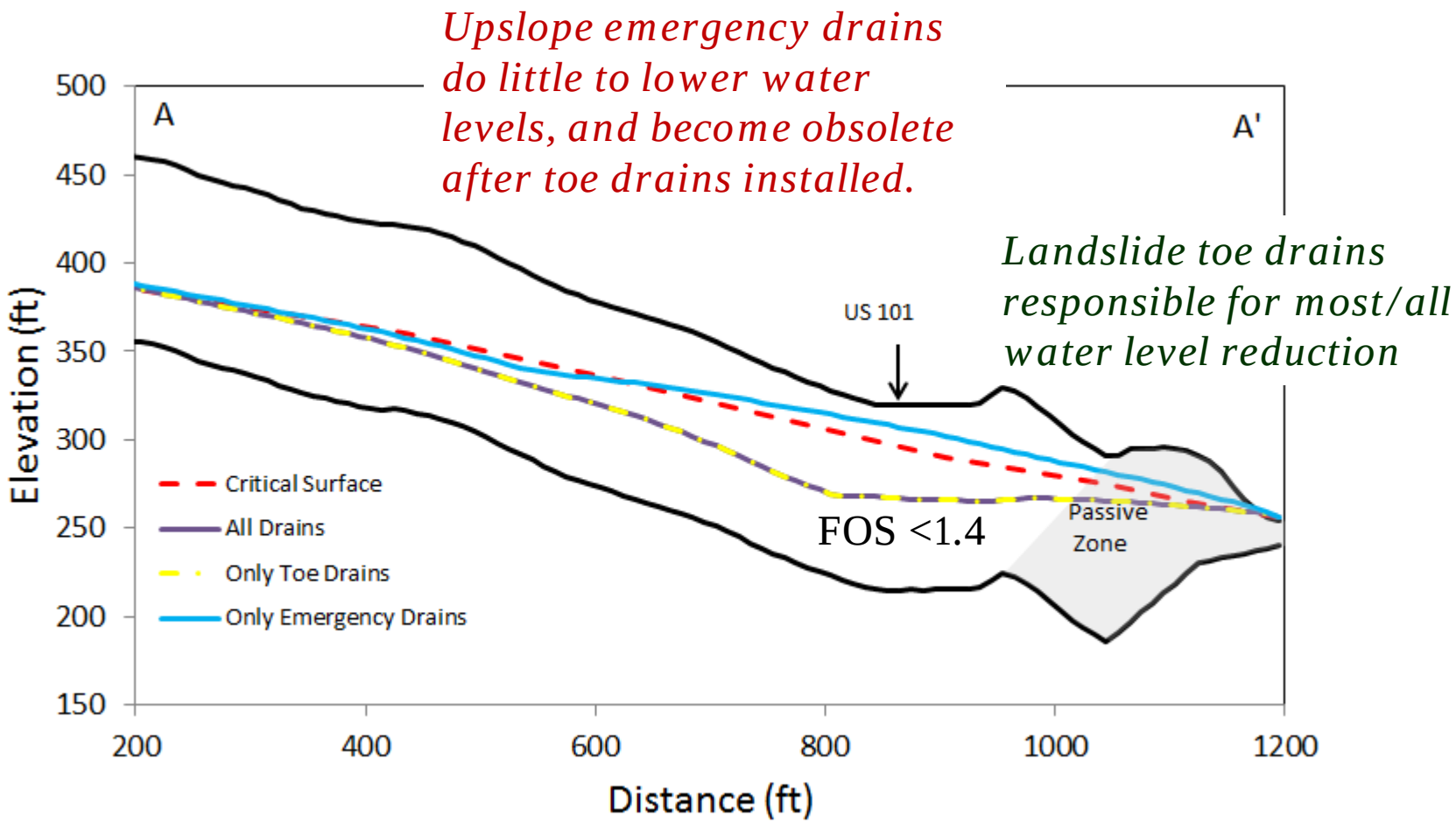
No

Modeled Peak Water Level

100-yr, 24-hr Design Storm



How well do modeled drains work during a design storm?



Concluding Remarks

- Every drainage problem is unique, and expert opinion can not 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.