Teaching Soil Mechanics (Civil Engineering) at University in the Years 2000+

二十一世纪大学土力学的教学（土木工程）

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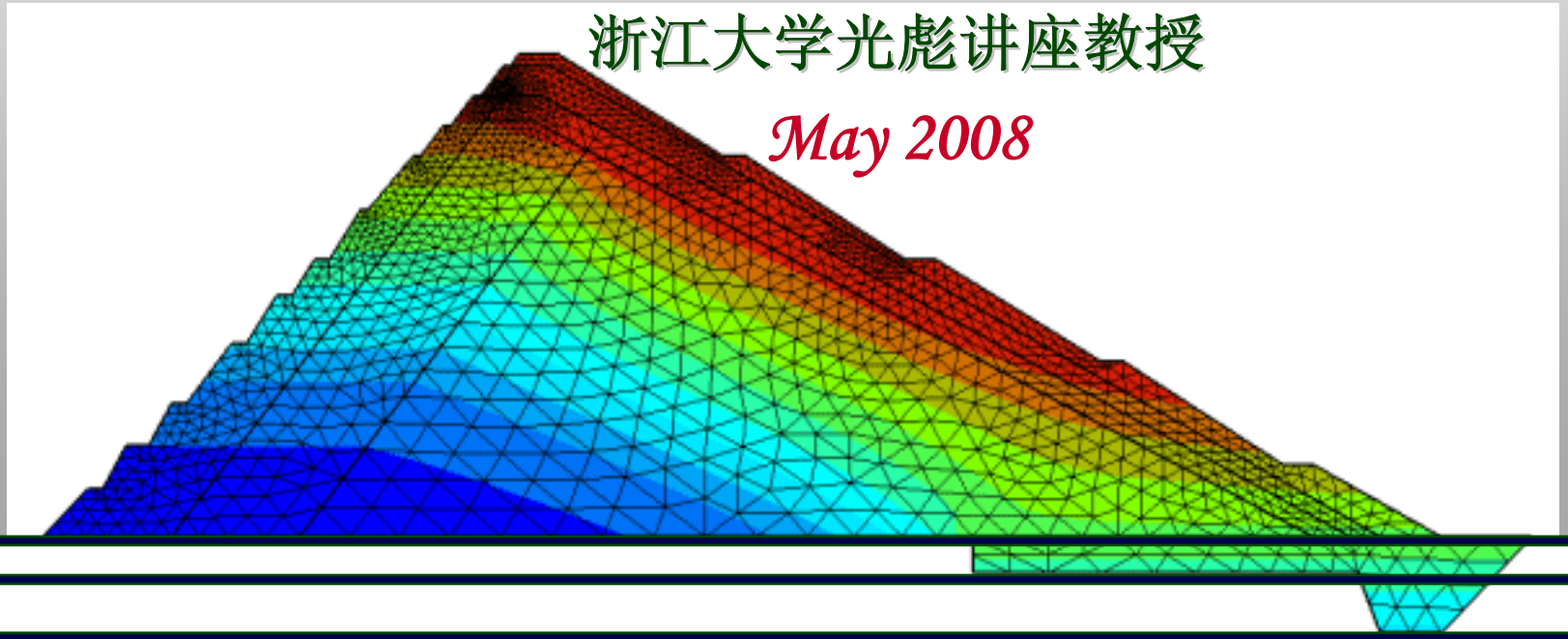


Common Complaints from Students about Soil Mechanics 学生们的抱怨

- ***Soil Mechanics* concepts are quite difficult to assimilate with the study of other materials**
  土力学的概念难以与其他材料学科融会贯通

Common Complaints after Graduation about Soil Mechanics 学生毕业后的抱怨

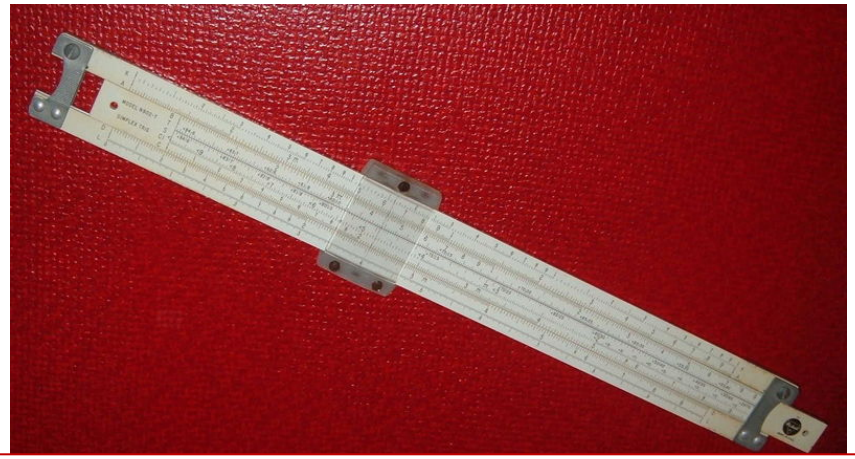
- ***Soil Mechanics* taught at university is quite removed from the practice of Geotechnical Engineering**
  大学里教授的土力学脱离工程实践

Soil Mechanics is a Young Science; Starting in the 1930s
土力学是一门年轻的学科，始于二十世纪三十年代

- ***Focus on*** 关注点:
  - ***Impact of the computer on how we practice Soil Mechanics***
    计算机对实践土力学的意义
  - ***Impact of the computer on how we teach Soil Mechanics***
    计算机对讲授土力学的意义

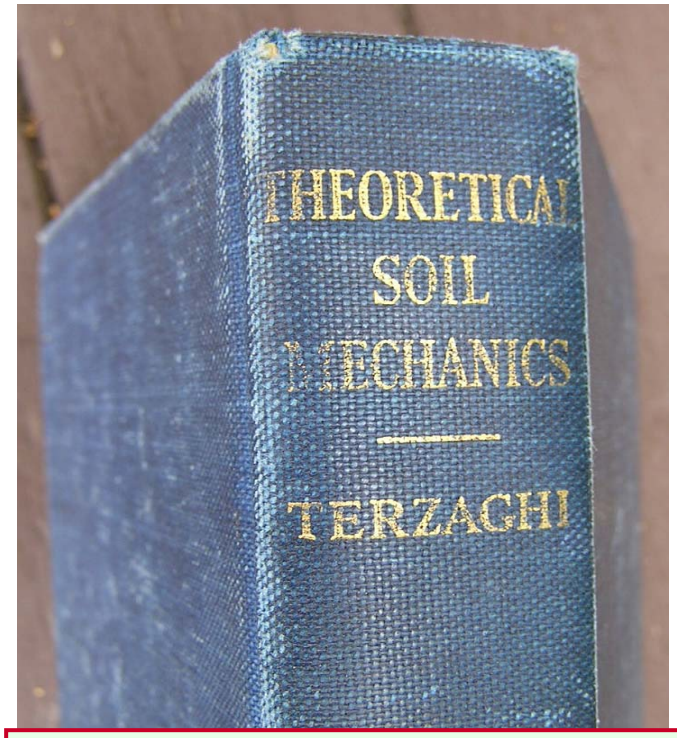
How did engineers perform calculations prior to the invention of the digital computer?
在电脑发明以前，工程师们如何进行计算？

Engineer in the 1970s
二十世纪七十年代的工程师



Slide Rule for multiplication, division, log & trig functions, etc.
计算尺: 用于乘法、除法、对数和三角运算等

Birth of Saturated Soil Mechanics
饱和土力学的诞生



- ***1943 Karl Terzaghi wrote "Theoretical Soil Mechanics"***
  1943年，太沙基写出《理论土力学》
- ***Saturated soil behavior is controlled by the effective stress variable, $(\sigma - u_w)$***
  有效应力$(\sigma - u_w)$决定饱和土的性质

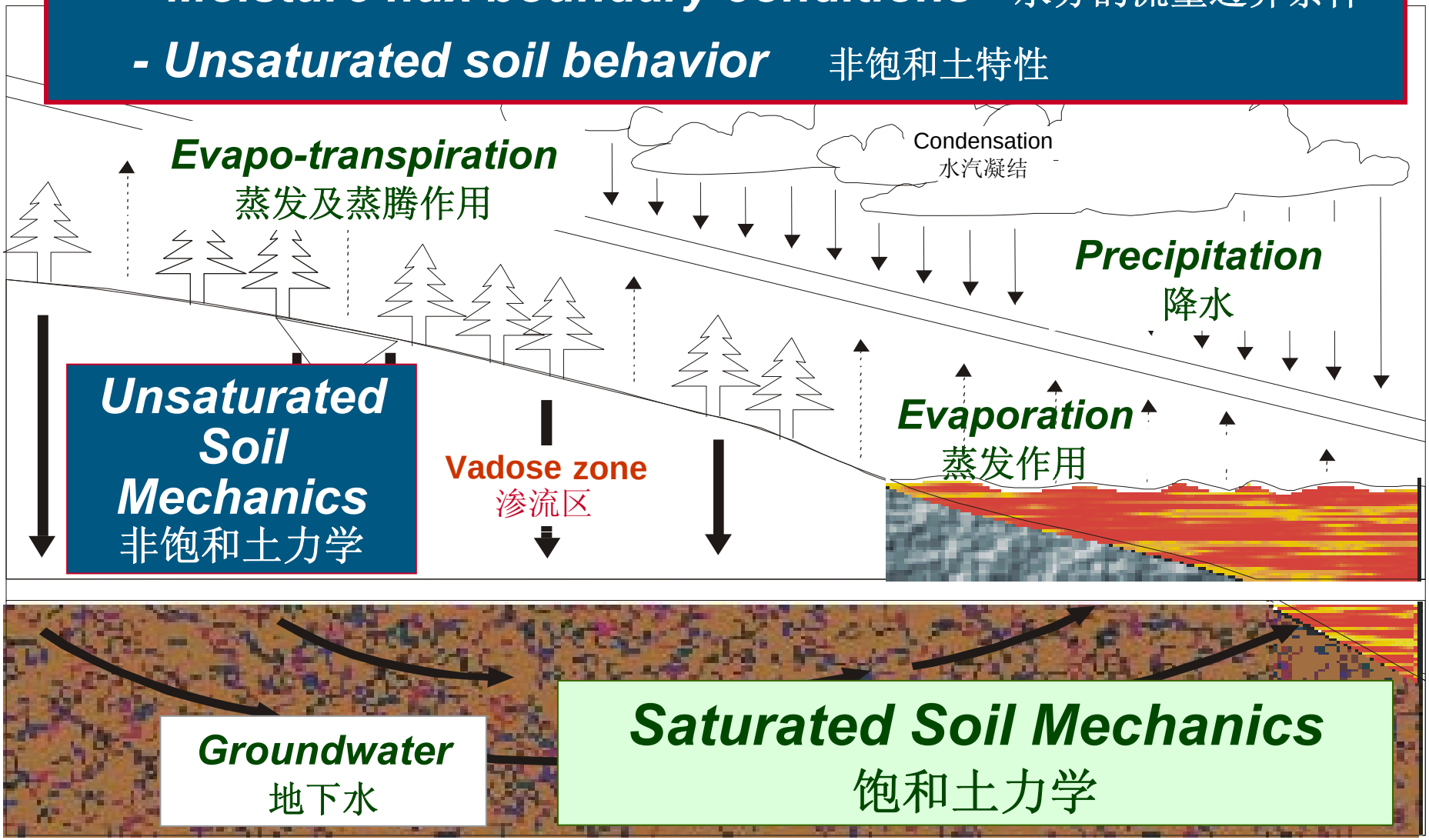
Attempt was to make Soil Mechanics a science with closed-form solutions for simplified representations of geotechnical problems

试图利用地质学问题中有闭合解的简单表达式使土力学成为一门科学

Classical Soil Mechanics developed without:

经典土力学的发展没有包括

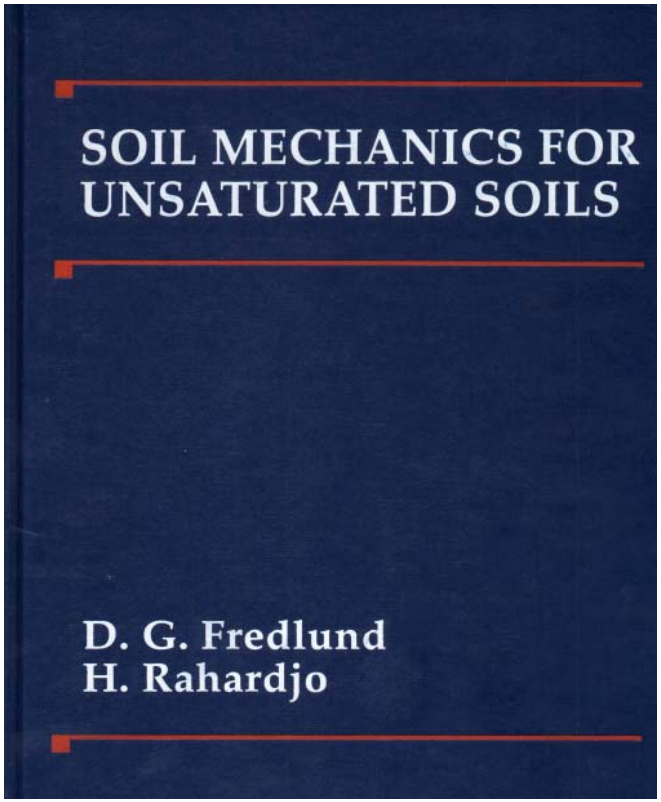
- ***Moisture flux boundary conditions*** 水分的流量边界条件
- ***Unsaturated soil behavior*** 非饱和土特性



Evolution of Unsaturated Soil Mechanics
非饱和土力学的进展

- ***1970s Unsaturated Soil behavior is controlled by two stress variables; namely, net total stress, $(\sigma - u_a)$, and matric suction, $(u_a - u_w)$***

  二十世纪七十年代，非饱和土特性由两个应力参数决定，即：净总应力（$\sigma - u_a$）和基质吸力（$u_a - u_w$）



Attempt was to make Unsaturated Soil Mechanics a science through use of boundary-value representations of saturated-unsaturated soil problems

试图通过使用饱和—非饱和土问题的边界值表达式使非饱和土力学成为一门科学

Computers influence how a science is presented and practiced

Impact of Computers on Geotechnical Engineering
计算机对岩土工程的影响

- ***Field Logging* soil observations can be entered electronically in the field**

  现场记录　观测结果可以在现场进行电子输入

- ***Laboratory test* data can be entered into a database and calculations performed**

  室内实验　数据可以输入数据库进行计算

- ***Spreadsheets* (e.g., EXCEL) are used for simple calculations and simple problem solving**

  电子表格(如Excel)　可用于简单的计算和解决问题

- ***Word Processors* are used for writing reports**

  文字处理软件　可用于报告写作

Impact of Computers on Geotechnical Engineering
计算机对岩土工程的影响

- ***Graphics Software* is used to prepare plots and figures**
  图形处理软件　用于绘制图表
- ***Knowledge-based database* used to store and retrieve past experience and estimate soil properties** 知识库　用于查询实例，估测土性及土性函数
- ***Numerical modeling* software is used to solve a wide variety of Soil Mechanics problems** 数值模拟　可以解决很多土力学中的问题
- ***PowerPoint* and other software used to communicate with clients and agencies. Professors also use PowerPoint at University.** PowerPoint等　软件可用于技术交流和教学

All Software Packages should be Transparent
所有软件都必须是“透明”的

Objectives of a Soil Mechanics Course
土力学的课程目标

- ***Teach Soil Behavior and Problem Solving (e.g., seepage, shear strength, volume change)***

  讲授土的性状，解决土的问题(如：渗流，抗剪强度和体变)，包括

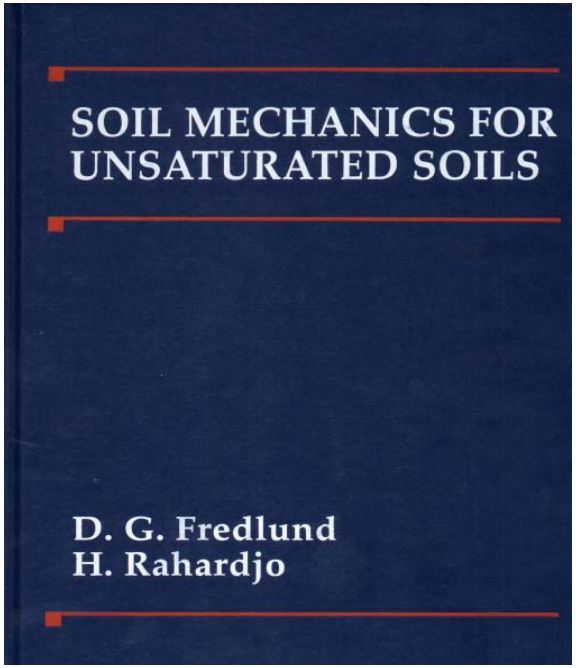
  - ***Theory associated with Constitutive behavior***

    与本构关系相关的理论
  - ***Measurement of the soil properties***

    土性测量
  - ***Estimation of the soil properties***

    土性预测
  - ***Application of theory in the form of a formulation of the practical engineering problem***

    应用理论解决实际问题



Geotechnical Engineering Practice is about Predicting the Future

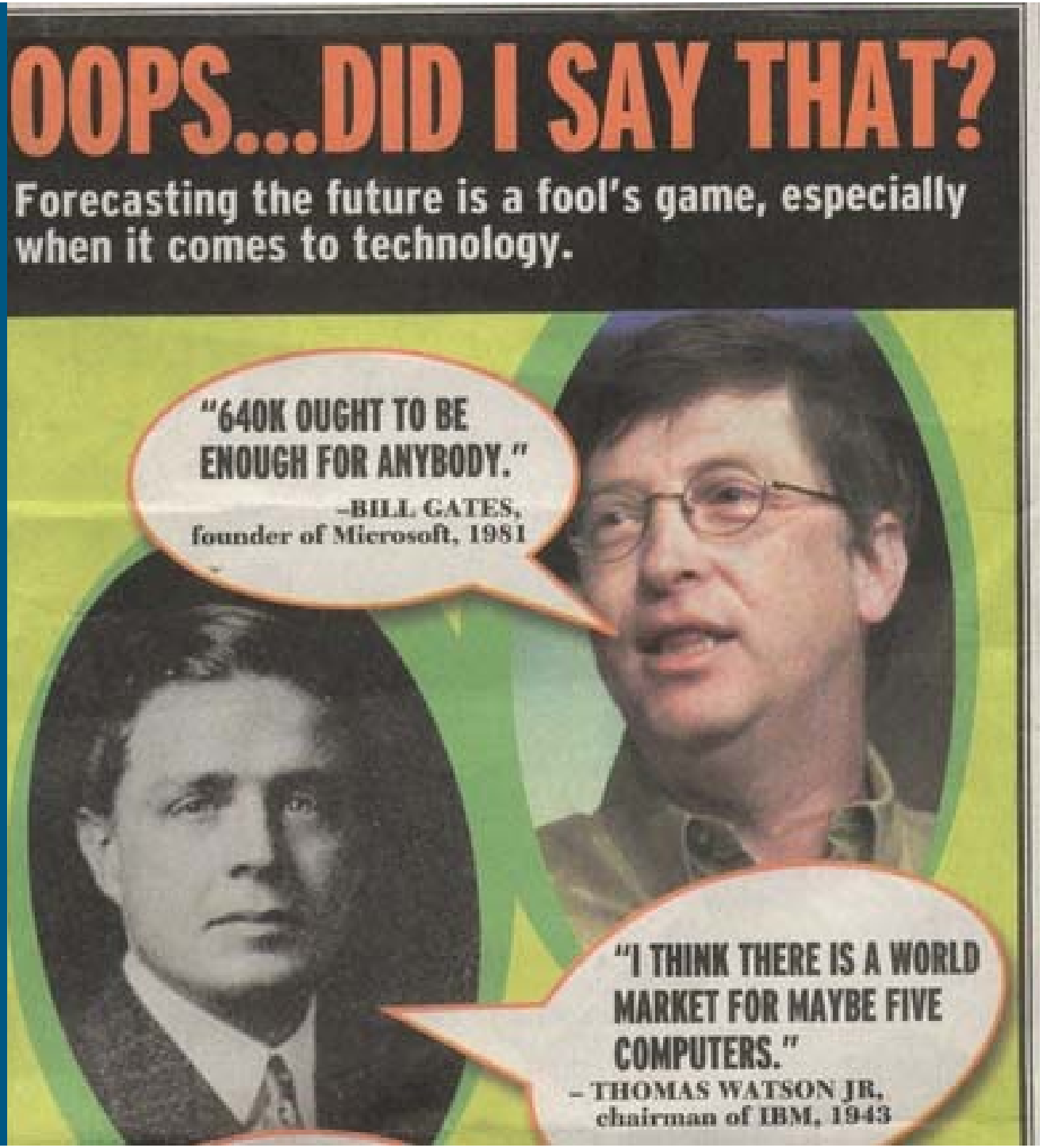
岩土工程就是做预测！

Predictions may be difficult for several reasons:

- ***The physics of the model may not be sufficiently rigorous***
  物理模型不够严格
- ***The input soil properties may not be sufficiently known or assessed***
  土性参数不够精确
- ***The initial conditions and boundary conditions may not be sufficiently defined***
  初始条件和边界条件不足于确定
- ***The computer results might not be properly interpreted***
  对电算结果不能给予准确的解释

It is extremely difficult to predict the future but if we do not attempt to do so, we will live without a "Vision for Survival"

尽管困难，
但若不做预测，
就无法“预见生机”

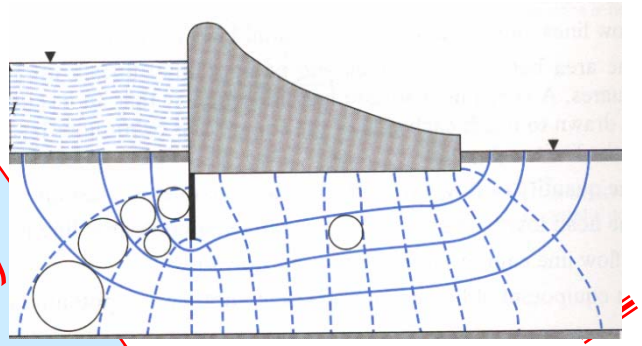


旧的模式：只要能挣钱，为什么要改变？

Focus of the Past

"If we're making money, why change?"

The Old Paradigm

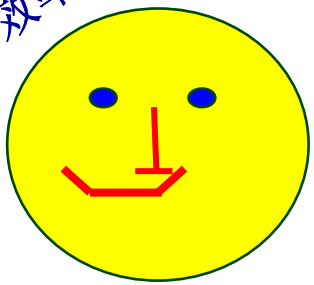


The New Paradigm

Focus of the Future

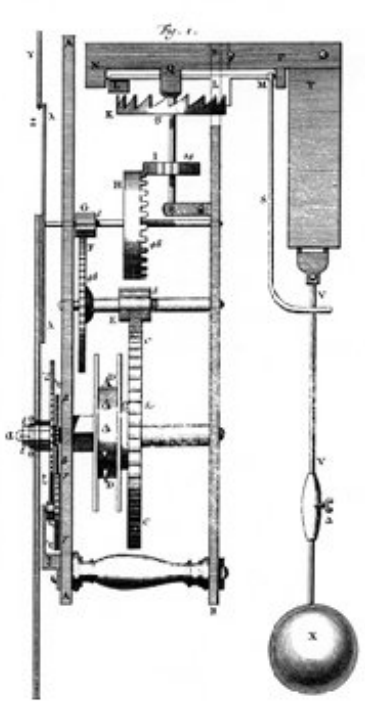
"Can our efficiency and effectiveness be improved?"

新的模式：提高效率和有效性！



What is a Paradigm Shift?
什么是“观念上的转变”？

Clock with Moving Parts
带钟摆的钟



The Paradigm Shift

Watch run with a Quartz Crystal
靠石英晶体走时的表

Discovered in1880 发现于1880年

Seiko made 1st watch in 1969
1969年日本精工(Seiko)公司制造
第一只石英表

History of Problem Solving in Soil Mechanics
土力学中解决问题的发展历史

- ***1930-1960 Era of closed-form solutions, graphical solutions and simple integration*** 解析解，图解法和简单积分法时代
- ***1960-1990 Era of development of digital computer hardware and computer solution software (as well as other software)*** 计算机软硬件的发展与数值解法时代
- ***1990-2000+ Era of a new generation of numerical modeling techniques and software capabilities with faster computers*** 新一代数值模拟技术及软件，采用更强大的计算机

Geotechnical Engineering Changes in the 21st Century
二十一世纪的岩土工程

- ***Saturated-Unsaturated Seepage analyses.***

  饱和－非饱和渗流分析

- ***Contaminant Transport analyses for geo-environmental engineering.***

  环境岩土工程中的污染物运移分析

- ***Stress-Deformation analysis for usage with:***

  应力－变形分析，结合：

  - ***Optimization Techniques (e.g. Dynamic Programming) for:*** 优化技术(如：动态规划)，应用于：
    - ***Slope stability analyses*** 边坡稳定分析
    - ***Lateral earth pressure analyses*** 侧向土压力分析
    - ***Bearing capacity analyses*** 承载力分析

Geotechnical Engineering Changes in the 21st Century
二十一世纪的岩土工程

- ***Implementation of Elasto-Plastic models*** 完善弹塑性模型
  - ***Combining stress-strain and a shear strength model*** 结合应力－应变关系和抗剪强度模型
- ***Geo-thermal analyses*** 地－热分析
  - ***Freeze-thaw analyses*** 冻融分析
  - ***Heat flow through saturated-unsaturated soil systems*** 饱和－非饱和土系统的热流
  - ***Soil-atmospheric models involving vapor flow*** 包括蒸气流的土壤－大气模型
- ***Solving Uncoupled analyses*** 非耦合分析
  - ***Importing pore-water pressures into slope stability analysis*** 将孔隙水压引入边坡稳定分析
  - ***Importing stresses into slope stability analyses*** 将应力引入边坡稳定分析

Geotechnical Engineering Changes in the 21st Century
二十一世纪的岩土工程

Coupled: 耦合分析

- ***Simultaneous solution of:*** 同时解决
  - ***Seepage and stress-deformation analysis for*** 渗流与应力－变形耦合分析，应用于：
    - ***Consolidation analysis*** 固结分析
    - ***Swelling clay analysis*** 粘土的膨胀变形分析
    - ***Collapsible soil analysis*** 土的湿陷性分析
  - ***Seepage and Heat flow analysis (Soil-Atmospheric model)*** 水的渗流与热流耦合分析(土壤－大气模型)
  - ***Seepage, thermal and stress analysis (Frost heave models)*** 水的渗流，热流和应力耦合分析(冻胀模型)

The Problem We Face in Teaching Soil Mechanics
土力学教学中遇到的问题

- ***Concepts and Principles* of Soil Mechanics were defined in the 1930's and still form the context for most Soil Mechanics books**

  概念和原理是二十世纪三十年代确立的，仍然被当今大多数土力学教材所遵循

- ***Consequently, a large gap exists between geotechnical engineering practice and what is taught in Soil Mechanics at universities***

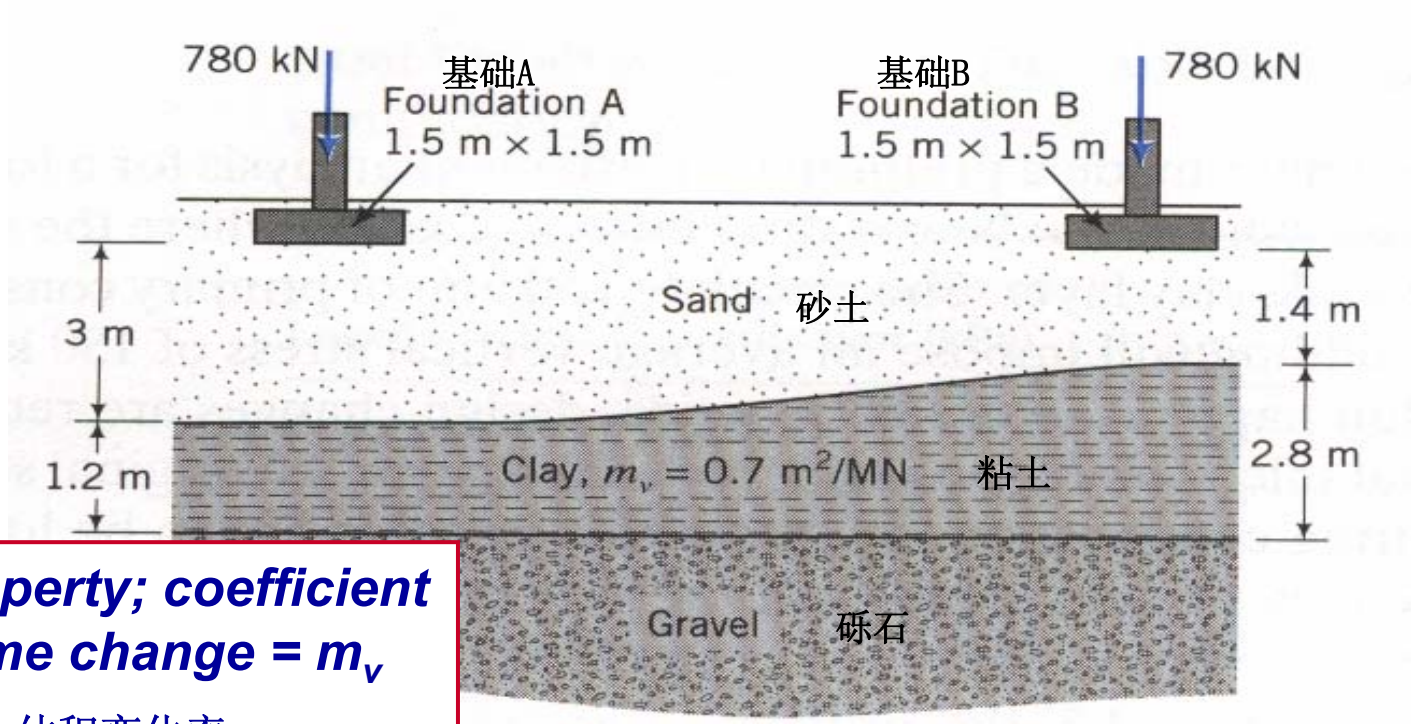
  导致了授课内容与工程实践的脱节

Historical Categorization of Classic Soil Mechanics Problems
经典土力学问题的归类

- ***Volume Change* of soft compressible clays**

  软土的体变

  - ***Settlement Analyses*** 沉降分析



Soil property; coefficient of volume change = m_v

土的性质：体积变化率 = m_v

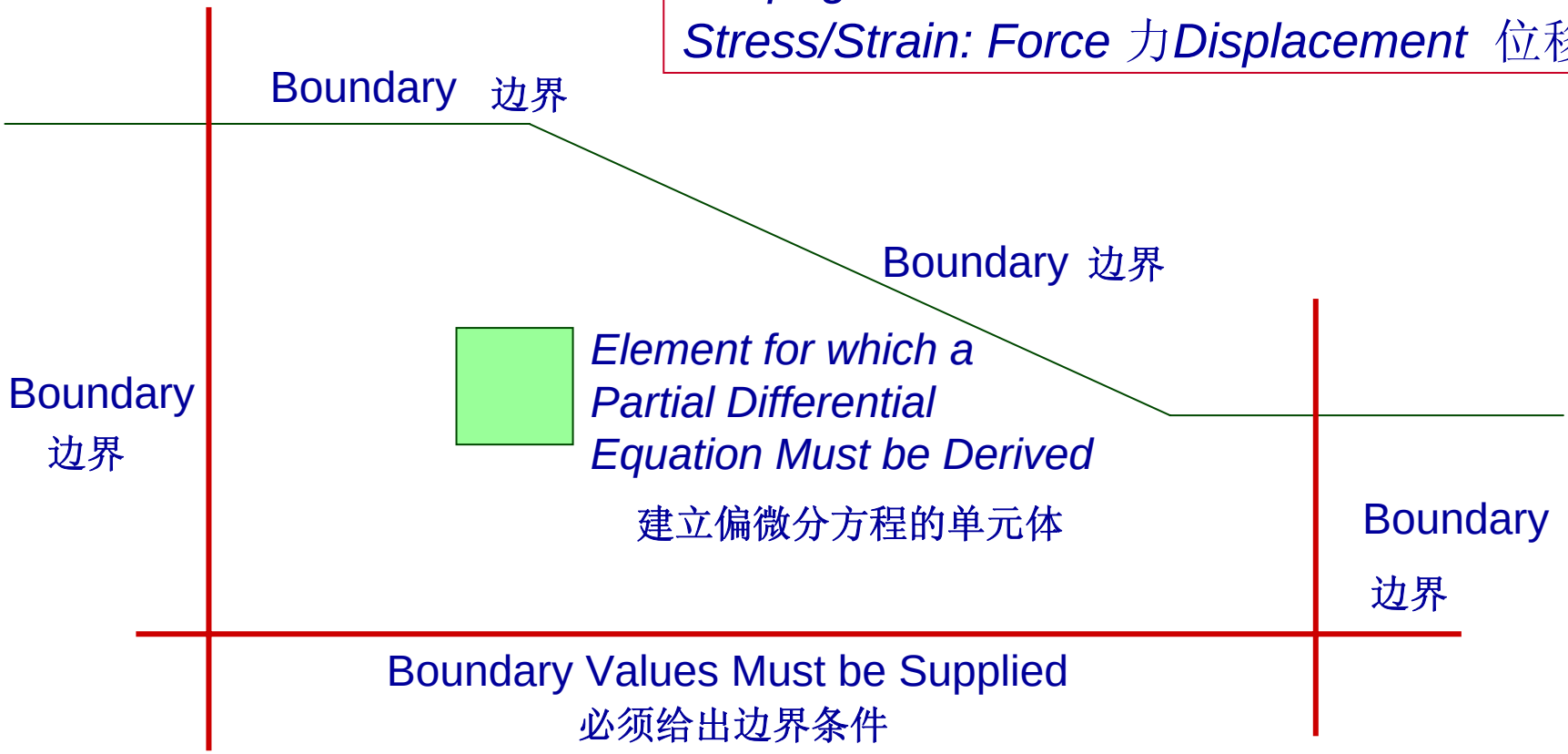
Soil Mechanics Partial Differential Equations, PDEs
土力学中的偏微分方程

- ***All classic areas of soil mechanics can be viewed in terms of the solution of a Partial Differential Equation*** 所有经典的土力学领域都可以看作求解偏微分方程
- ***Water flow through porous soils (Saturated or Unsaturated)*** 多孔介质的渗流(饱和或非饱和土)
- ***Stress analysis for slope stability, bearing capacity and earth pressure***
  应力分析，应用于边坡稳定，承载力和土压力问题
- ***Stress-Deformation volume change and distortion***
  应力—变形问题：体积变化和形变
  - ***Incremental elasticity*** 增量弹性模型
  - ***Elasto-plastic models*** 弹塑性模型

Boundary Value Context for Geotechnical Engineering Problems
岩土工程中的边值问题

Boundary Conditions

Seepage: Flux 流量 *Head* （水）头
Stress/Strain: Force 力*Displacement* 位移



Consider Flow Through Porous Media as an Example of Teaching from a PDE Base

举例：如何以偏微分方程为基础，教授多孔介质的渗流

- ***Start with picking an REV and defining what is meant by a "field"***

  选取*REV (Representative Elementary Volume),*即表征单元体积，确定分析的“范围”

- ***Derive the Partial Differential Equation, PDE***
  列出偏微分方程

- ***Explain the meaning of the PDE and the Soil Properties*** 解释偏微分方程和土性的物理意义

- ***Solve & Interpret the Computer Results*** 分析电算的结果

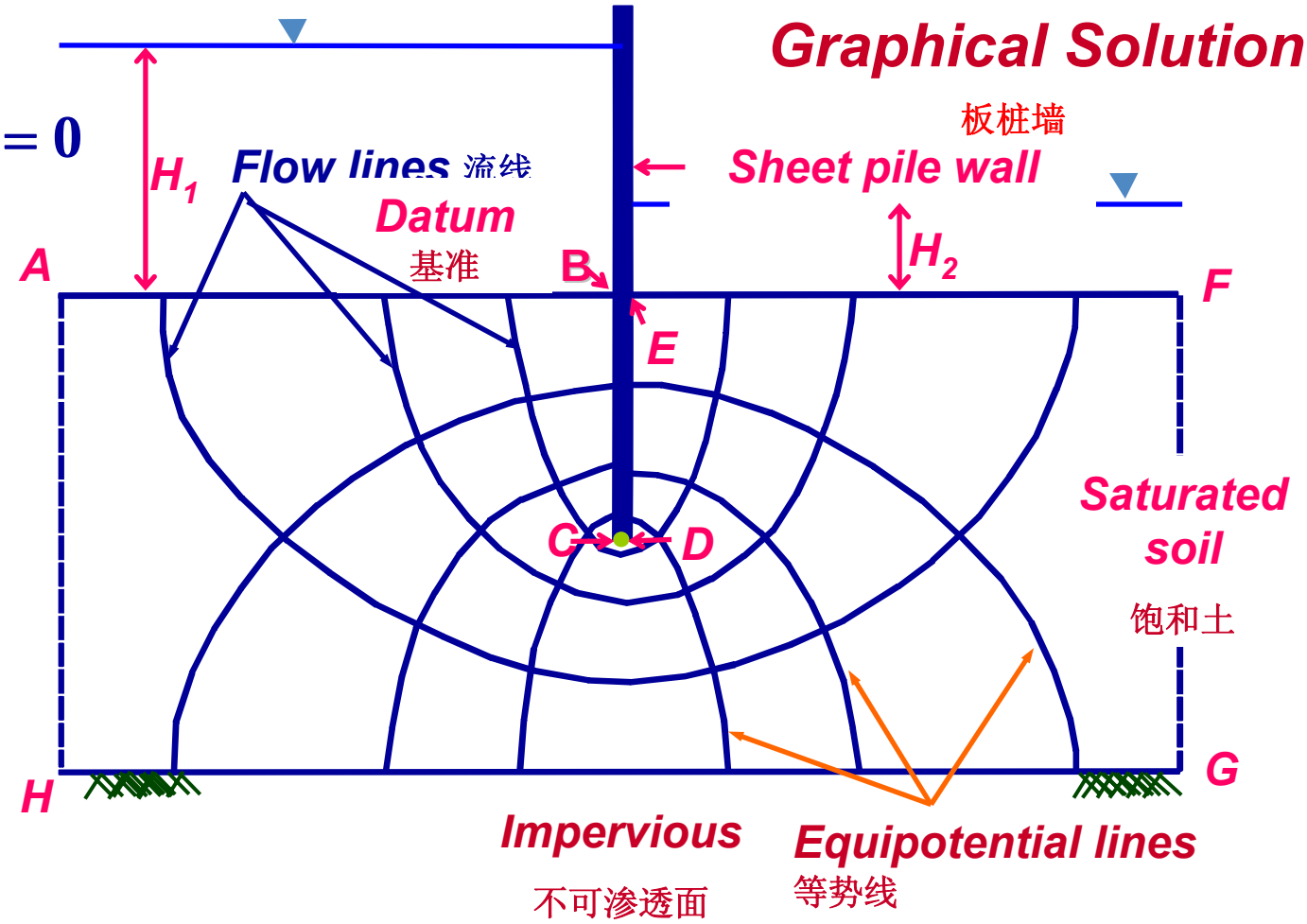
Steady State Seepage Flownets 稳态渗流：流网

- **Homogeneous, Isotropic, Saturated soil**
- 单一的饱和土

Old Paradigm 旧的模式

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} = 0$$

Graphical Solution 图解



Partial Differential Equation for Saturated-Unsaturated Water Flow Analysis
用偏微分方程进行饱和—非饱和渗流分析

Head variable to be solved
未知量：水头

$$k_x^w \frac{\partial^2 h}{\partial x^2} + \frac{\partial k_x^w}{\partial x}\frac{\partial h}{\partial x} + k_y^w \frac{\partial^2 h}{\partial y^2} + \frac{\partial k_y^w}{\partial y}\frac{\partial h}{\partial y} = -m_2^w \gamma_w \frac{\partial h}{\partial t}$$

Water coefficient of permeability (function of soil suction)
渗透系数（为吸力的函数）

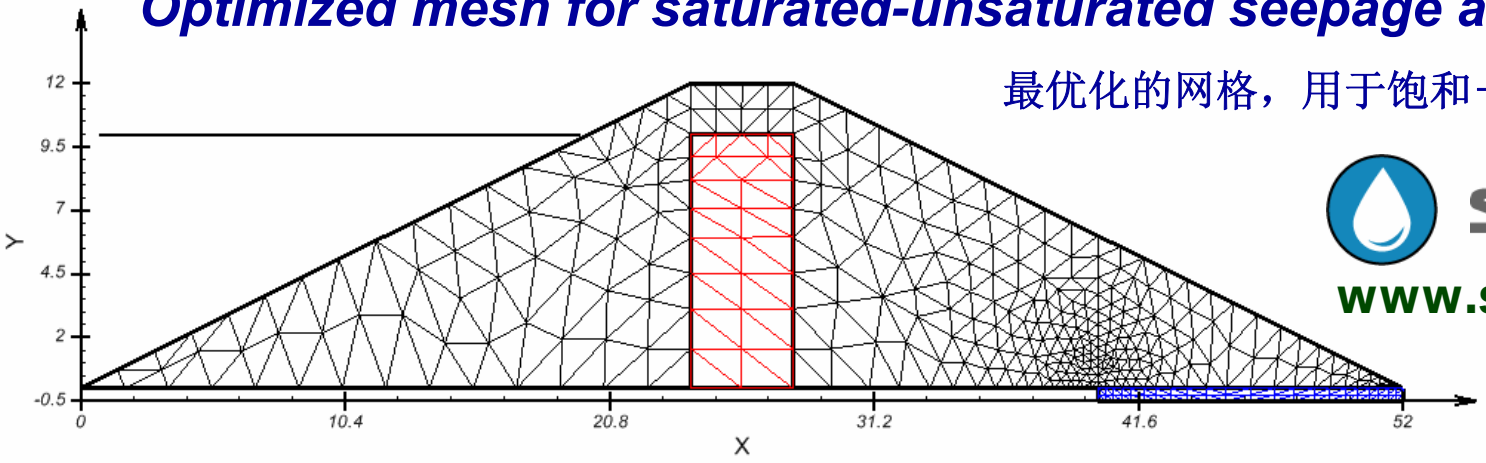
Water storage (function of soil suction)
持水量（为吸力的函数）

Time
时间

Two-dimensional seepage analysis through an earthfill dam with a clay core.
通过带粘土心墙的土坝的二维渗流分析

Optimized mesh for saturated-unsaturated seepage analysis

最优化的网格，用于饱和－非饱和渗流分析

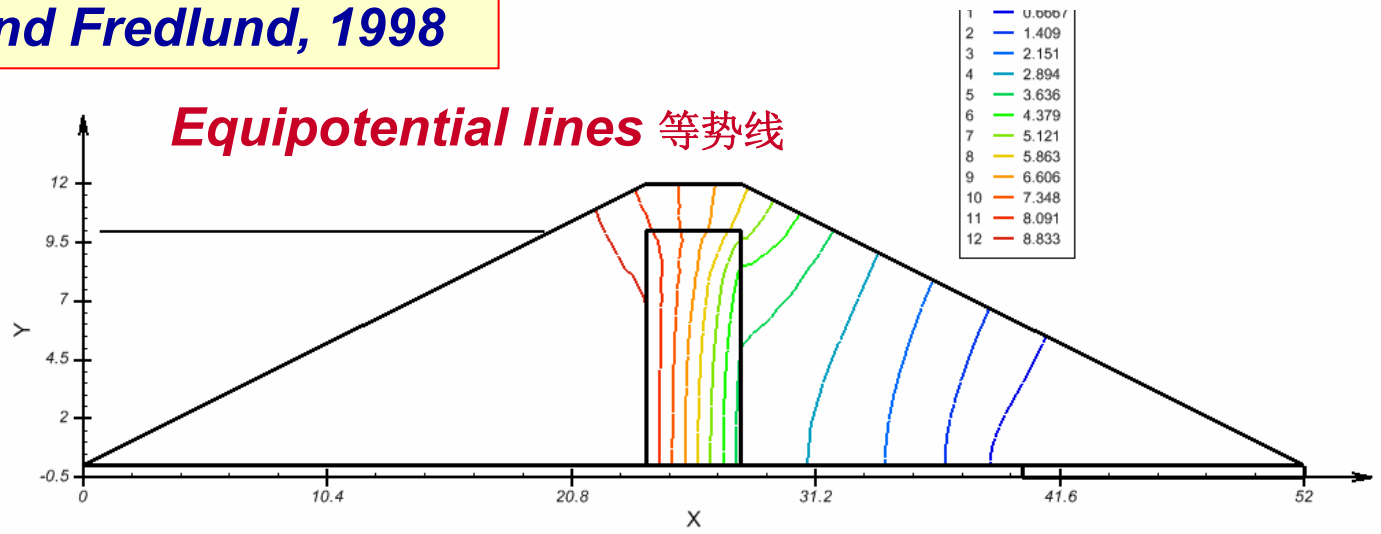


SVFLUX

www.soilvision.com

Thieu and Fredlund, 1998

Equipotential lines 等势线



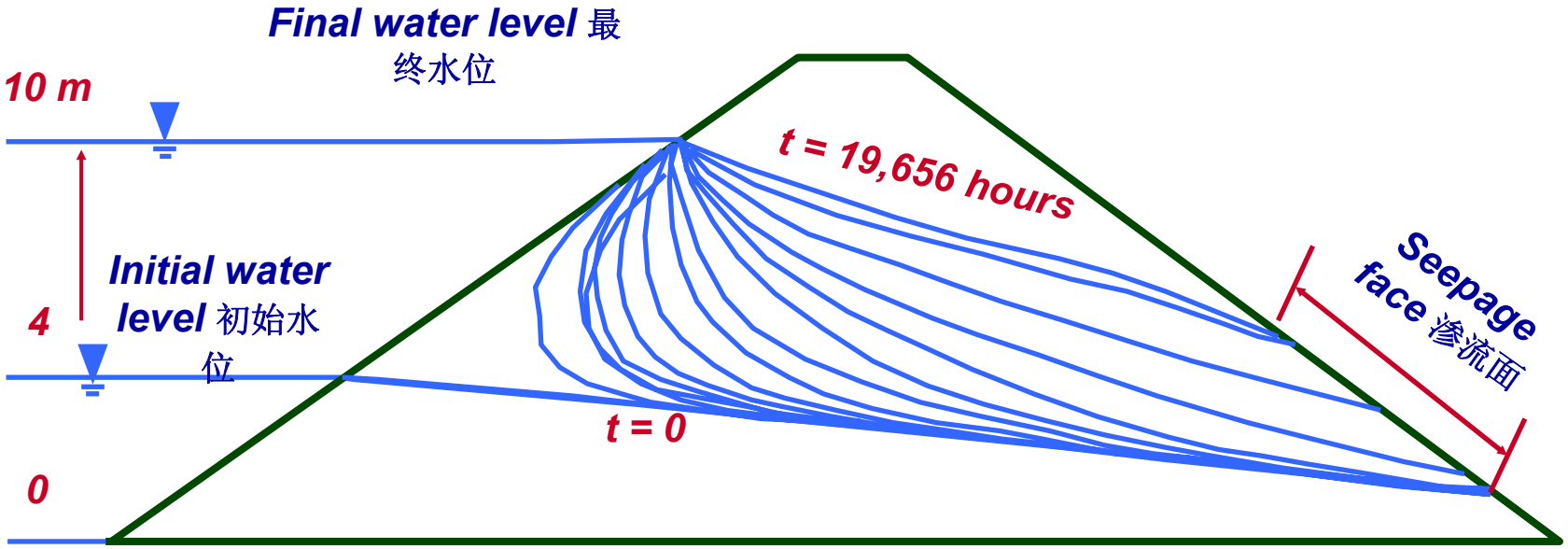
Transient Seepage Analysis Saturated-Unsaturated Soil Systems
饱和—非饱和瞬态渗流分析

- ***Changing zero pressure isobar with time***

  零等压线随时间变化

- ***Total elapsed time, transient is 19,658 h***

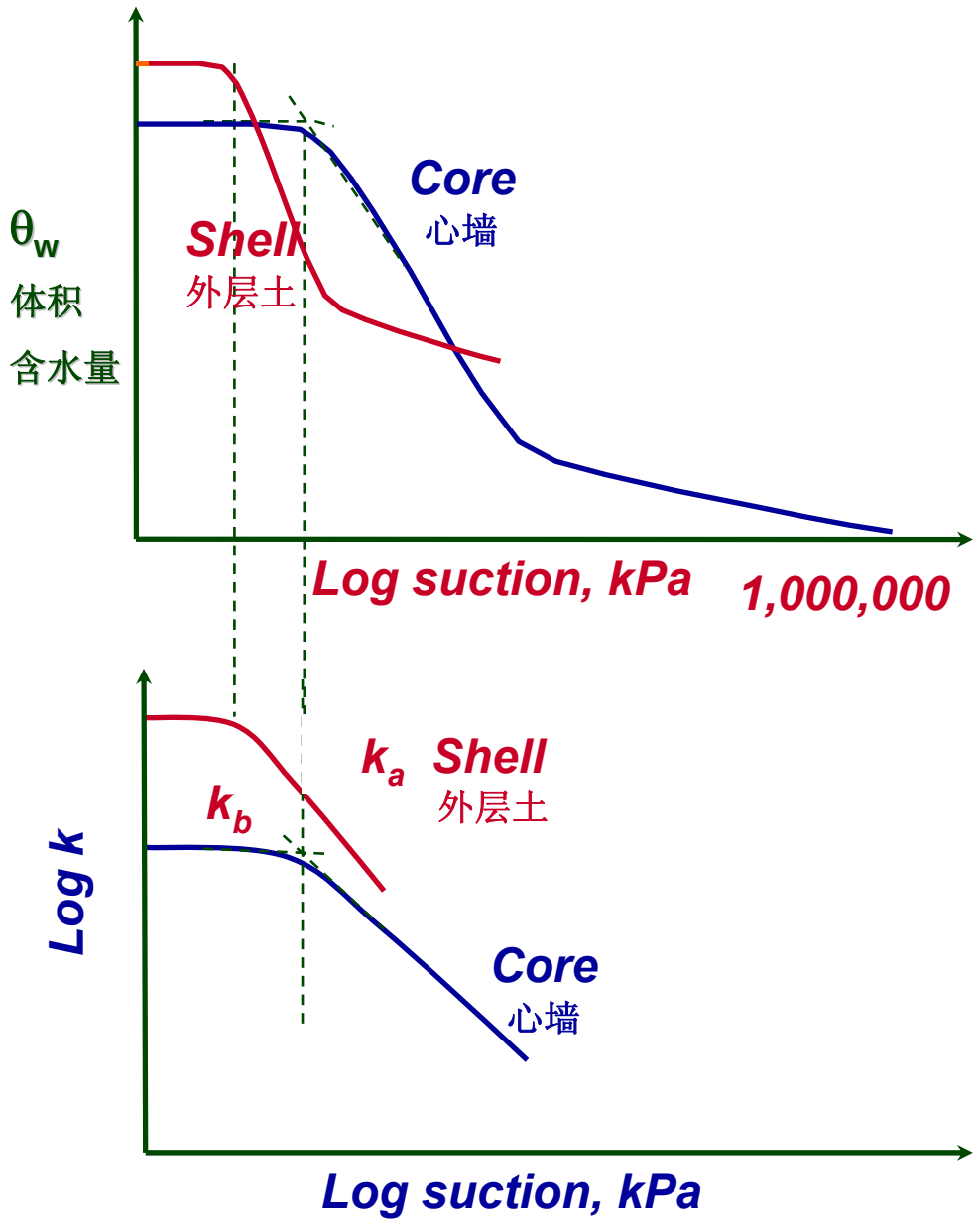
  总历时为19, 658小时



Introduction to Unsaturated Soils
非饱和土介绍

Permeability Function indirectly determined from the SWCC

渗透性函数常通过SWCC,
即土水特征曲线间接确定



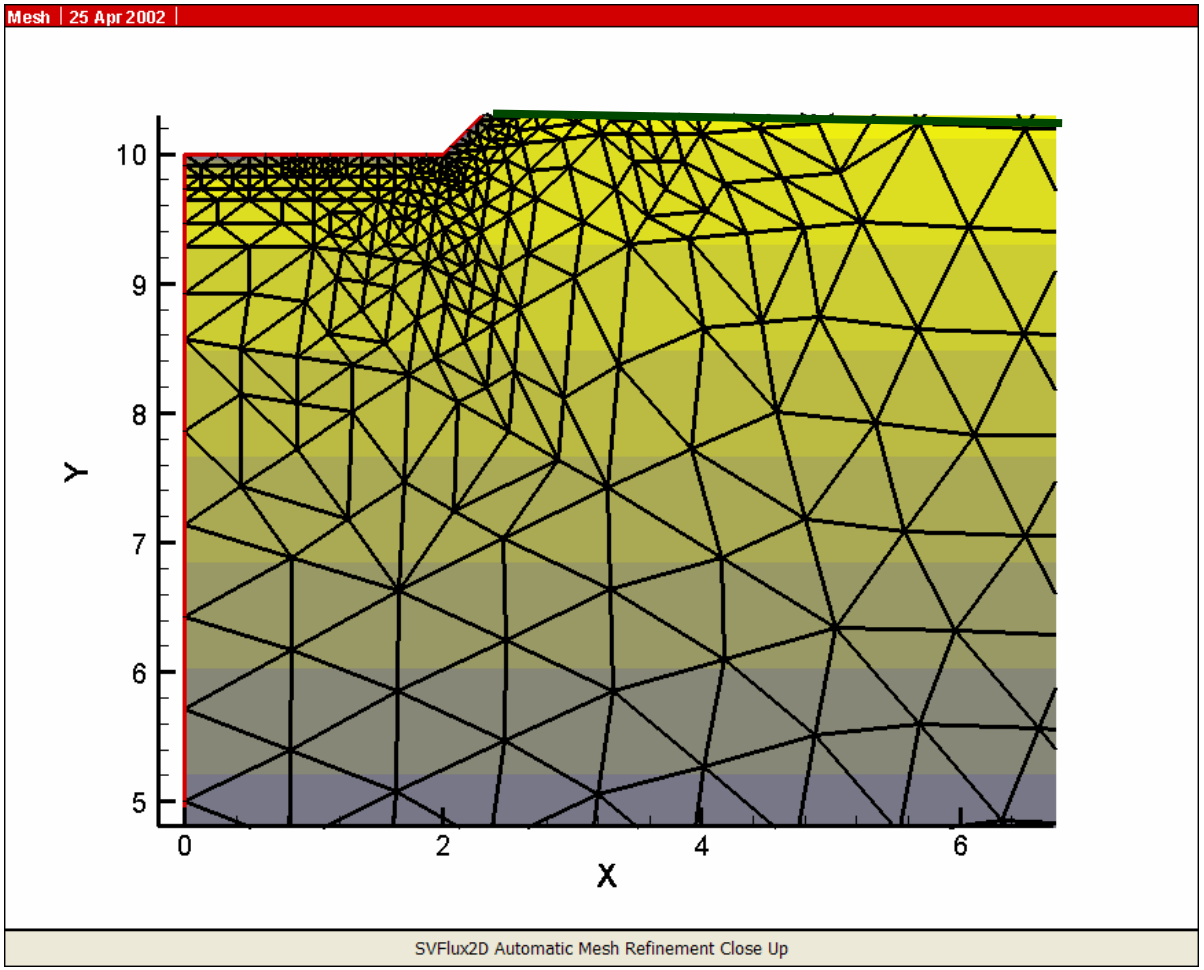
Relationship of the SWCC to the Permeability Function

SWCC与渗透性函数的关系

Convergence of Nonlinear Partial Differential Equations
非线性偏微分方程的收敛

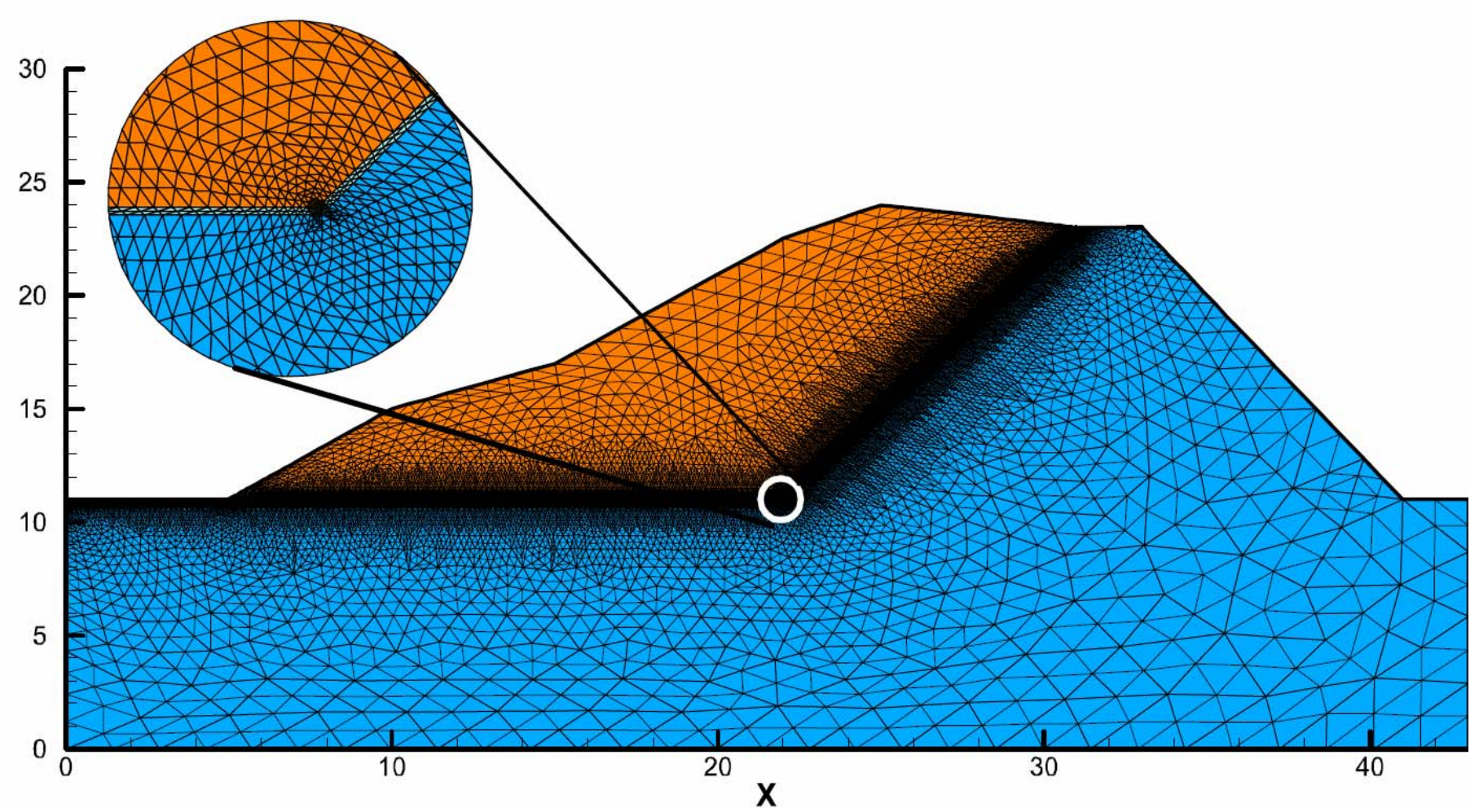
- ***Convergence is the single most pressing problem facing modelers*** 收敛是模拟软件面临的最迫切的问题
- ***Most successful solutions have involved Adaptive Grid Refinement methods, AGR (Oden, 1989; Yeh, 2000)*** 大多数成功的解法采用了自适应网格细化技术，即**AGR**
- ***Mesh is dynamically upgraded during the solution based on error estimates***
  基于误差估测，网格可在求解过程中动态地升级

Contaminant Transport with Automatic Mesh Refinement
网格自动细化在污染物扩散中应用



Retainment Dyke with an Internal Geomembrane

中间含土工膜的堤坝的网格细化

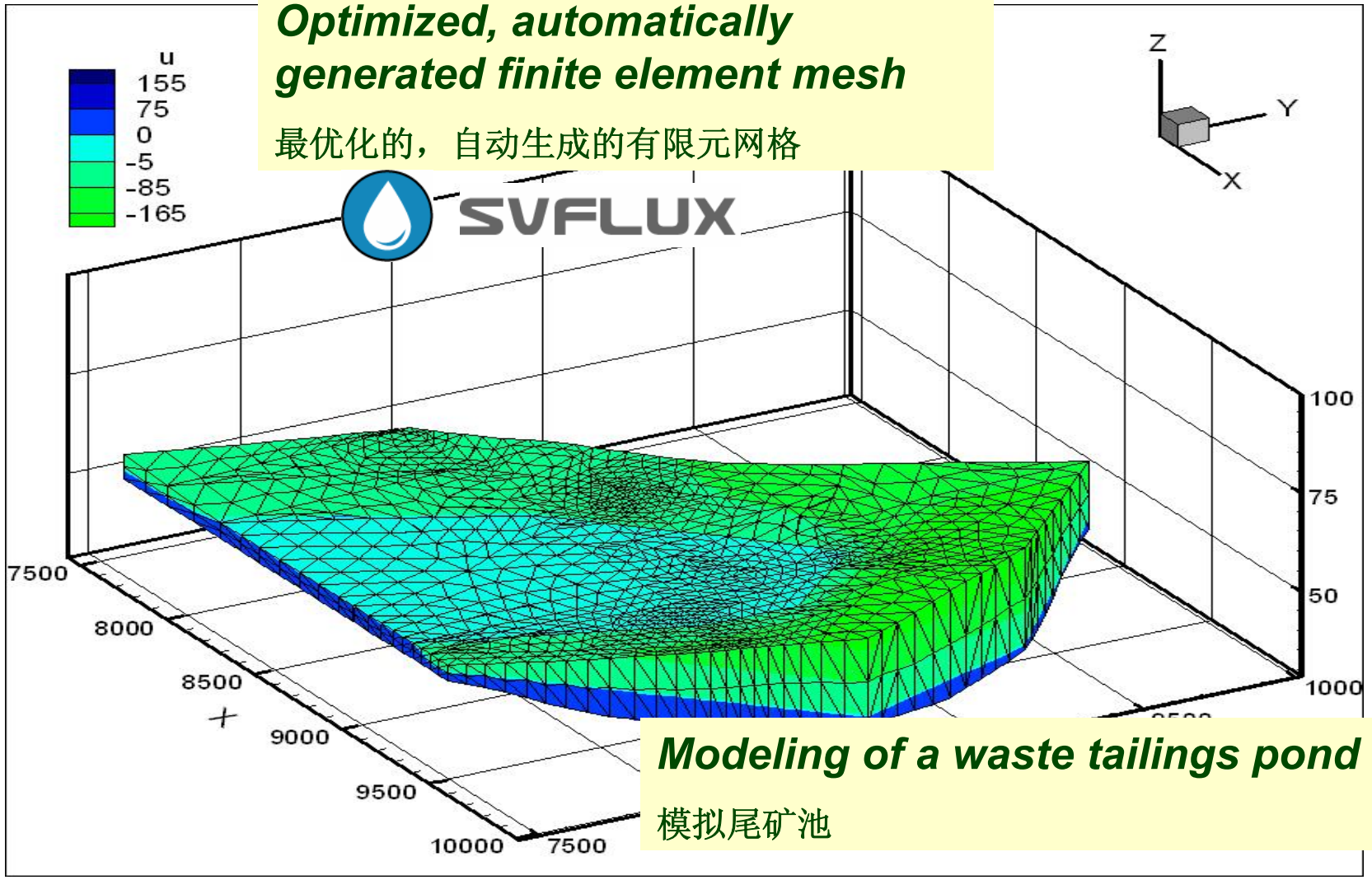


Problem illustrating the solution of a 3-dimensional, saturated-unsaturated seepage PDE

举例：解决三维饱和－非饱和渗流偏微分方程

Optimized, automatically generated finite element mesh

最优化的，自动生成的有限元网格

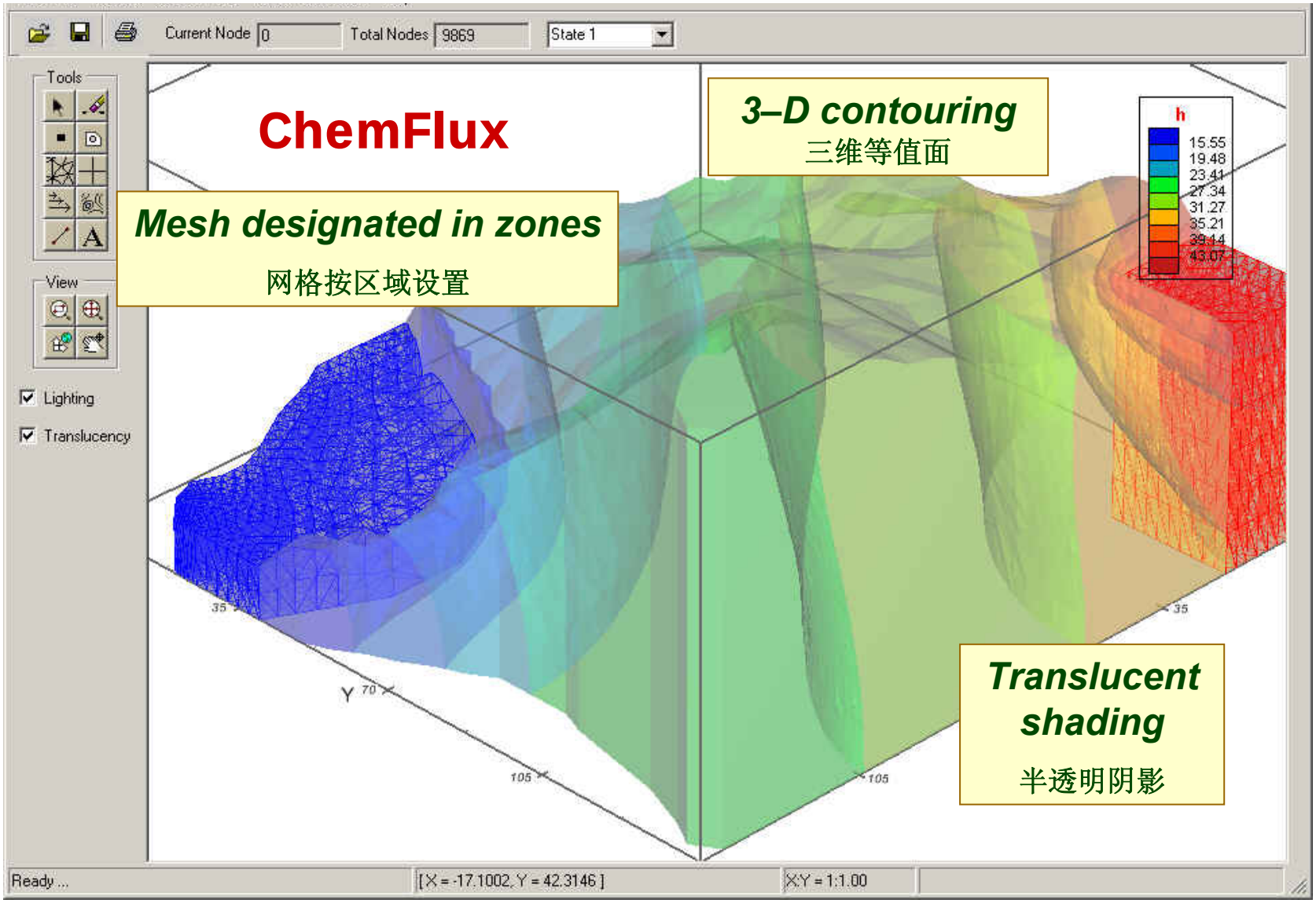


Modeling of a waste tailings pond

模拟尾矿池

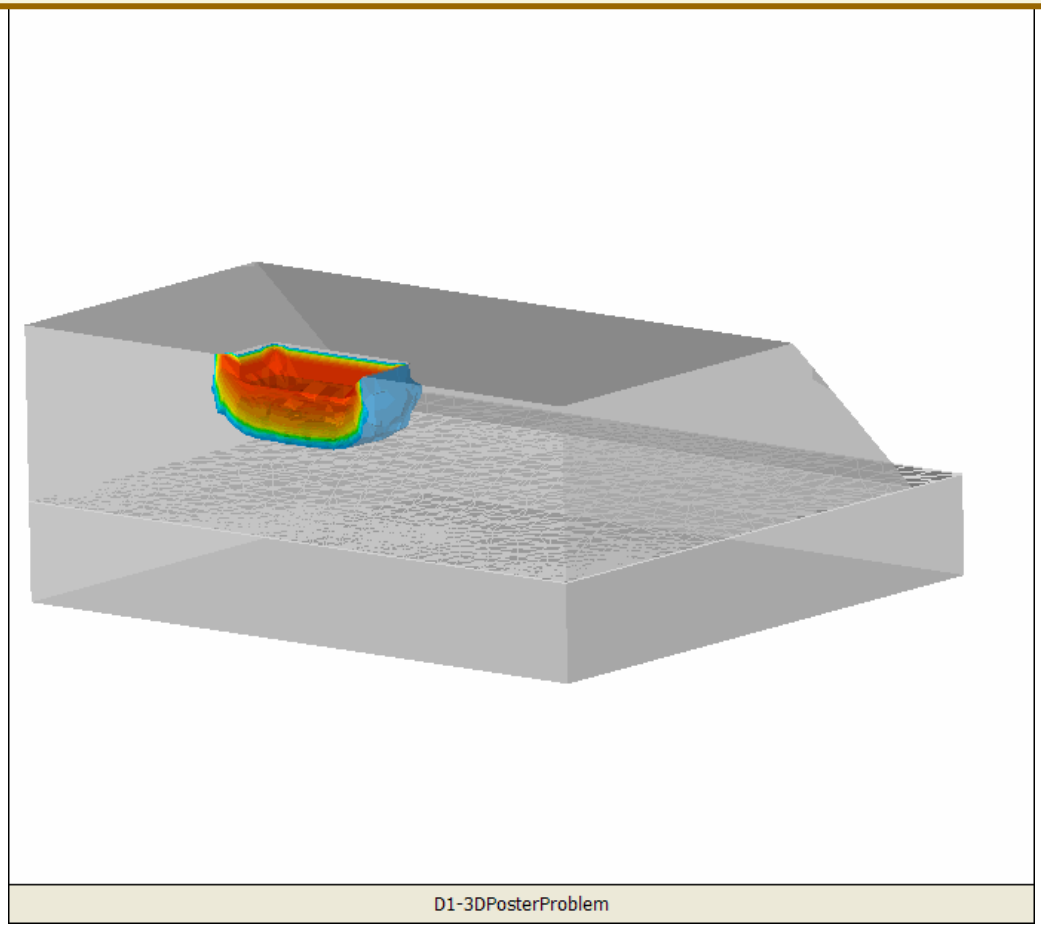
Typical Subjects Covered in a Conventional Soil Mechanics Book (*Soil Mechanics & Foundations by M. Budhu*) 常规的土力学书中涵盖的典型问题

- *Definition of Head and Darcy's Law* 定义水头和达西定律
- *Estimation of the Saturated Permeability* 估测饱和渗透系数
- *Measurement of Coefficient of Permeability* 测量渗透系数
- *Flow Parallel and Perpendicular to Soil Layers* 平行和垂直于土层方向的渗流
- *Criteria for Sketching Flow Nets* 绘制流网的原则
- *Flow Nets for Isotropic Soils* 各向同性土的流网绘制
- *Flow Through Anisotropic Soils* 各向异性土中的渗流
- *Flow Rates* 渗流速率
- *Hydraulic Gradients* 水力梯度
- *Critical Hydraulic Gradients* 临界水力梯度
- *Uplift Forces* 浮托力
- *Flow Through Earth Dams* 土坝的渗流


Current Node 0
Total Nodes 9869
State 1
Tools
View
Lighting
Translucency
ChemFlux
3–D contouring
三维等值面
Mesh designated in zones
网格按区域设置
h
15.55
19.48
23.41
27.34
31.27
35.21
39.14
43.07
Translucent shading
半透明阴影
35
70
105
Y
Ready ...
[X = -17.1002, Y = 42.3146]
X:Y = 1:1.00

▶ *ChemFlux - 3D finite element analysis of a contaminant transport problem (animated)*

污染物运移问题的三维有限元分析（动画模拟）



Thermal Analysis for Saturated-Unsaturated Soil Systems
饱和—非饱和系统的热分析

- ***Heat flow* partial differential equations are similar to water flow except for the Latent heat associated with:**

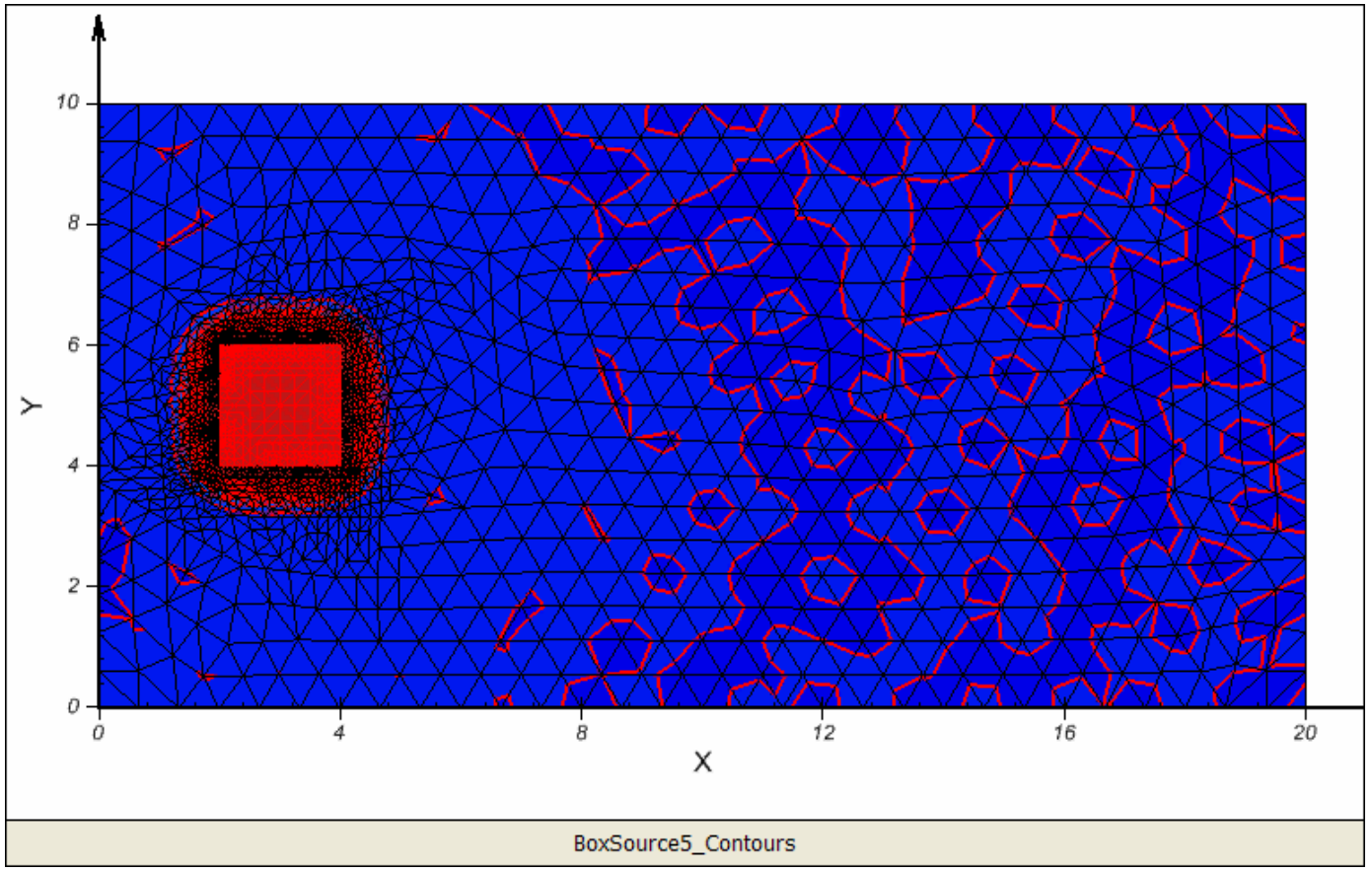
  热流偏微分方程与水流相似，除了以下两种相态变化：

  - ***freezing and thawing*** 冻融
  - ***vaporization*** 蒸发

- ***Thermal soil properties* are a function of the soil-water characteristic curve , SWCC** 土的热性质是土水特征曲线，即SWCC的函数

▶ *SVHeat - 2D finite element analysis of a problem with extremely steep thermal gradients*

热梯度极其陡的条件下的二维有限元分析



Partial Differential Equation for Saturated-Unsaturated Stress-Deformation Analysis
饱和－非饱和土应力－变形分析的偏微分方程

$$\frac{\partial}{\partial x}\left[D_{11}\frac{\partial u}{\partial x}+D_{12}\frac{\partial v}{\partial y}\right]+\frac{\partial}{\partial y}\left[D_{44}\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)\right]=0$$

X –

$$\frac{\partial}{\partial x}\left[D_{44}\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)\right]+\frac{\partial}{\partial y}\left[D_{12}\frac{\partial u}{\partial x}+D_{11}\frac{\partial v}{\partial y}\right]+\gamma_t=0$$

Y –

D_{11}, D_{12}, D_{44} = Combination of E and μ which are function of soil suction and net total stresses

结合E和μ，二者是吸力和净正应力的函数

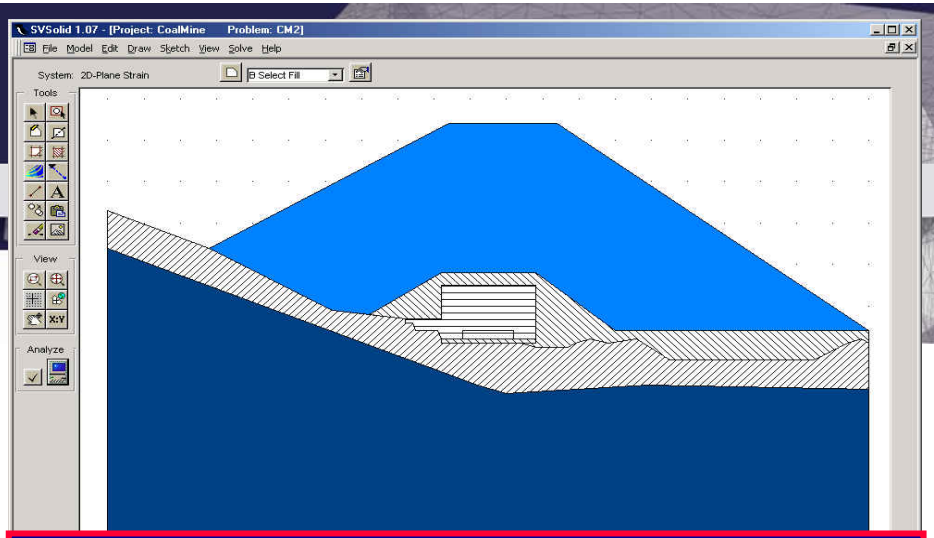
Stress-deformation analyses have a degrees of freedom in each of the Cartesian coordinate directions

应力－变形分析在每个笛卡儿坐标下都有一个自由度

SoilVision Systems Ltd.

Innovative database and finite element solutions

SVSolid



Behavior - Set By Soil Region

土性在“区域”中定义

Hooke's Law 胡克定律

Linear Elastic 线弹性

Non-linear Elastic 非线性弹性

Anisotropic Linear Elastic

各向异性线弹性

Hyperbolic 双曲线形应力应变曲线

Mohr-Coulomb Failure Criteria
摩尔－库仑破坏准则

Effective or total stress parameters

有效应力或总应力参量

Drained or undrained analysis

排水或不排水的情况

Skempton A and B parameters to calculate pore-water pressure

斯肯普顿A, B值，用以计算孔隙水压

Body loads applied for any particular soil region

特定区域所受的体积载荷

Analysis Types 分析形式

2-D Plane Strain 二维平面应变

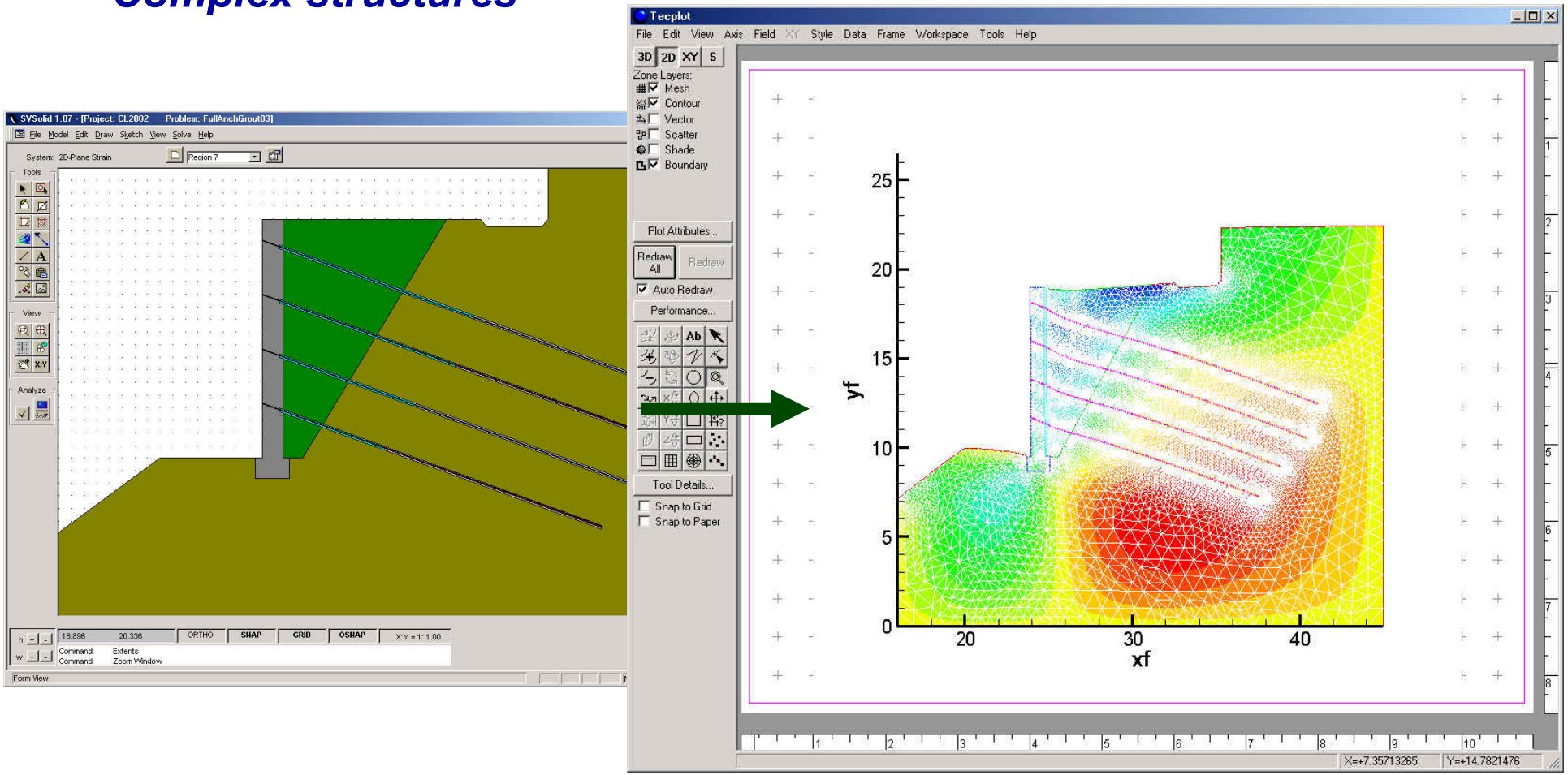
Axisymmetric 轴对称

3-D 三维

SVSolid

Representation of extremely fine features 显示细致入微

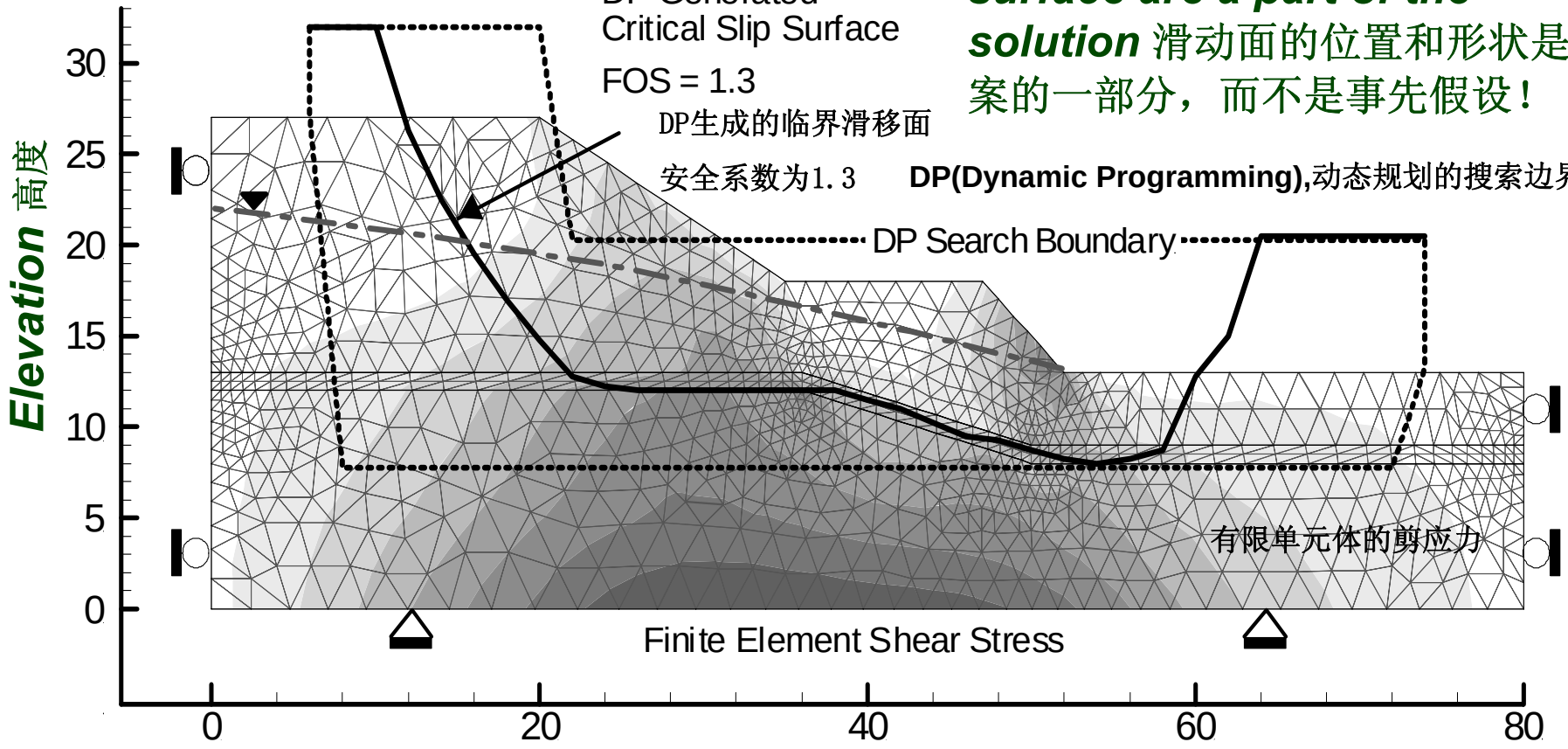
Complex structures



Stress analysis can be combined with the Dynamic Programming to compute the factor of safety
应力分析结合动态规划，计算安全系数

SVDynamic

Shape and location of the slip surface are a part of the solution 滑动面的位置和形状是答案的一部分，而不是事先假设！



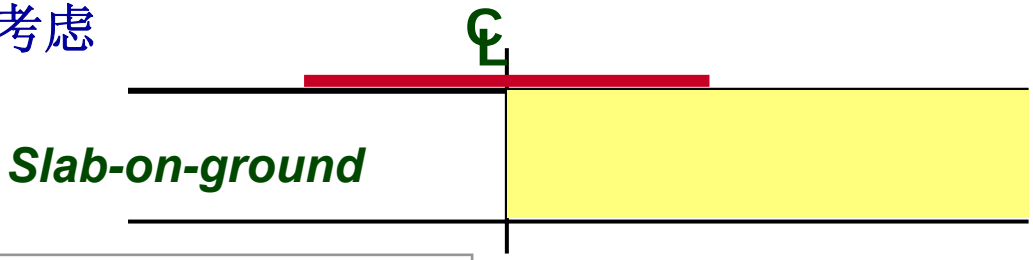
Pham and Fredlund, 2002

Prediction of Heave or Collapse of a Soil
预测土的隆胀与湿陷

Must consider effects of: 需要考虑

-Nonlinearity 非线性

-Coupling 耦合作用



Coupled 耦合

Uncoupled 非耦合

Pseudo-coupled 准耦合

Saturated-Unsaturated Seepage Model

饱和－非饱和渗流模型

Computes changes in suction

计算基质吸力的变化

Saturated-Unsaturated Stress-Deformation Model

饱和－非饱和应力－变形模型

Computes deformations

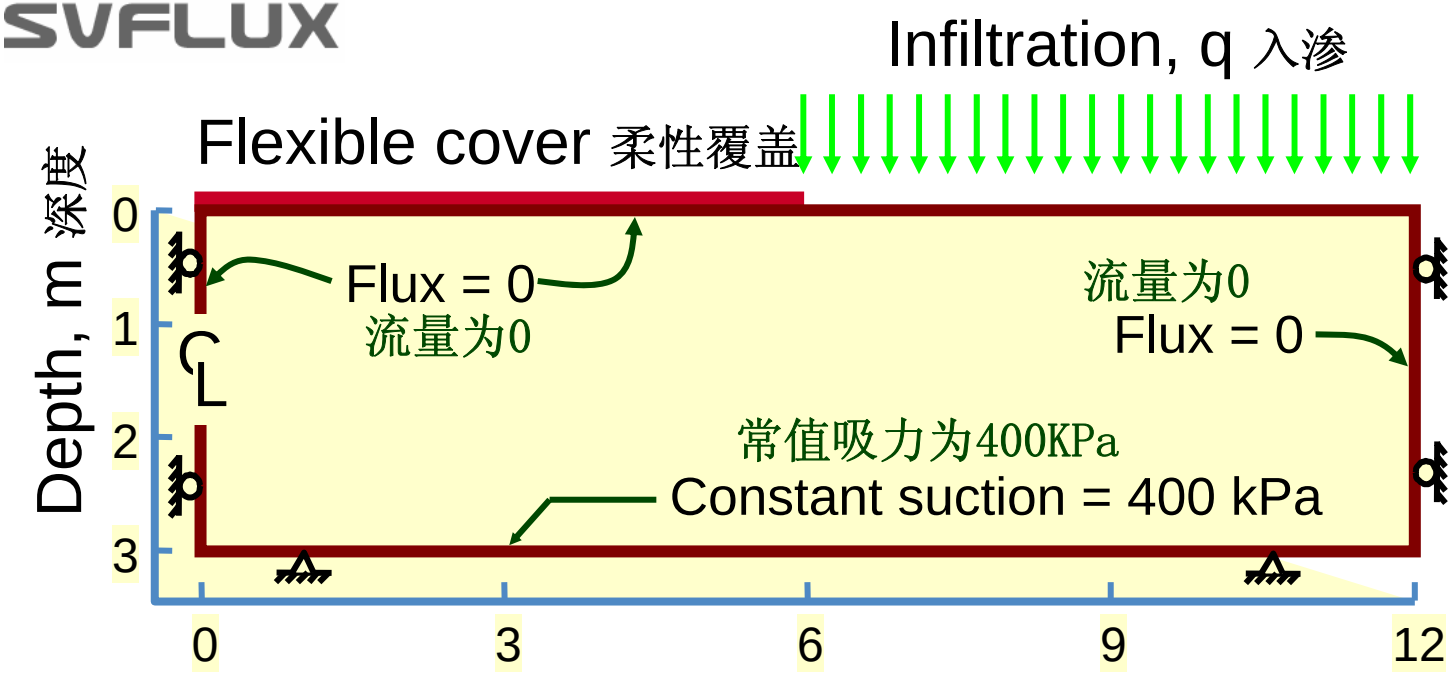
计算变形

Consider Edge Lift for a Flexible Impervious Cover
考虑不透水柔性覆盖层的边界上抬

Boundary conditions and initial conditions must be specified both seepage and stress-deformation

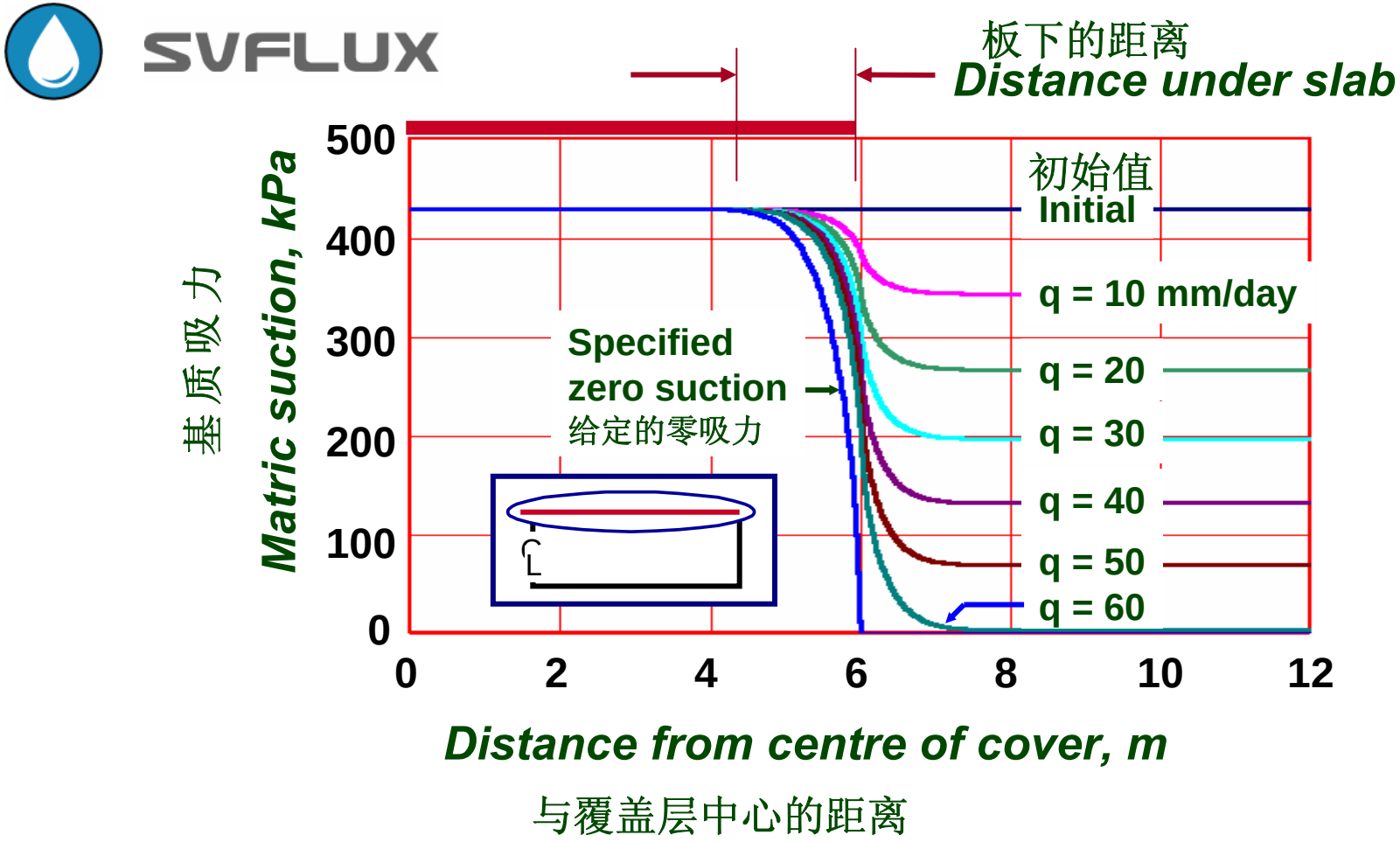
进行渗流和应力－变形分析，必须给出边值和初值条件

SVFLUX

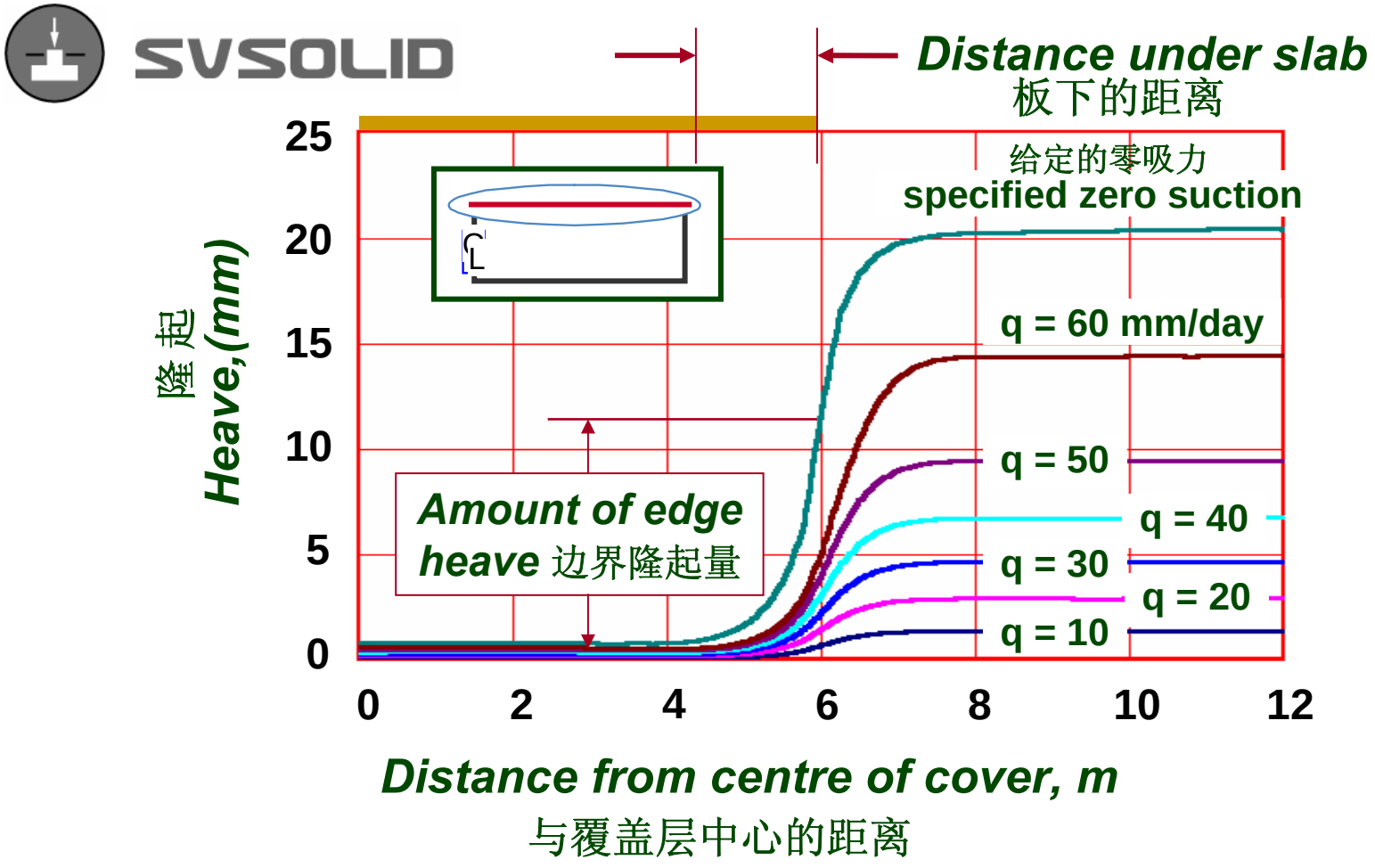


Matric Suction at Ground Surface after One Day of Infiltration for Various Infiltration Rates

不同入渗速率下，一天后地表的基质吸力



Vertical Displacements at Ground Surface after One Day of Infiltration
入渗一天后，地表的竖向位移



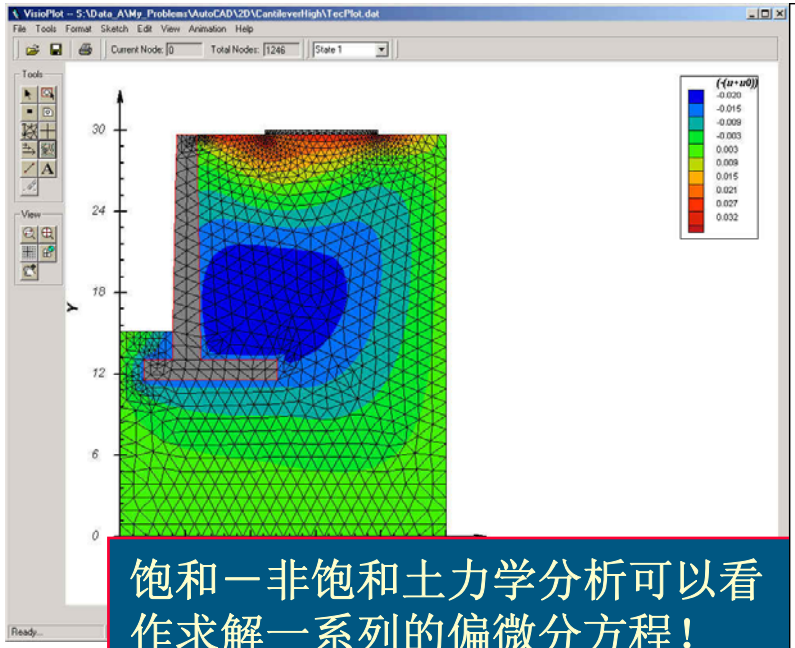
Observations on Teaching Soil Mechanics from a PDE Basis

基于偏微分方程，讲授土力学的一些观察心得

- ***Saturated-unsaturated soil systems can be described in terms of a variety of nonlinear partial differential equations*** 饱和－非饱和土系统可以通过一系列非线性偏微分方程描述
- ***Unsaturated soil property functions can be related to the soil-water characteristic curve***

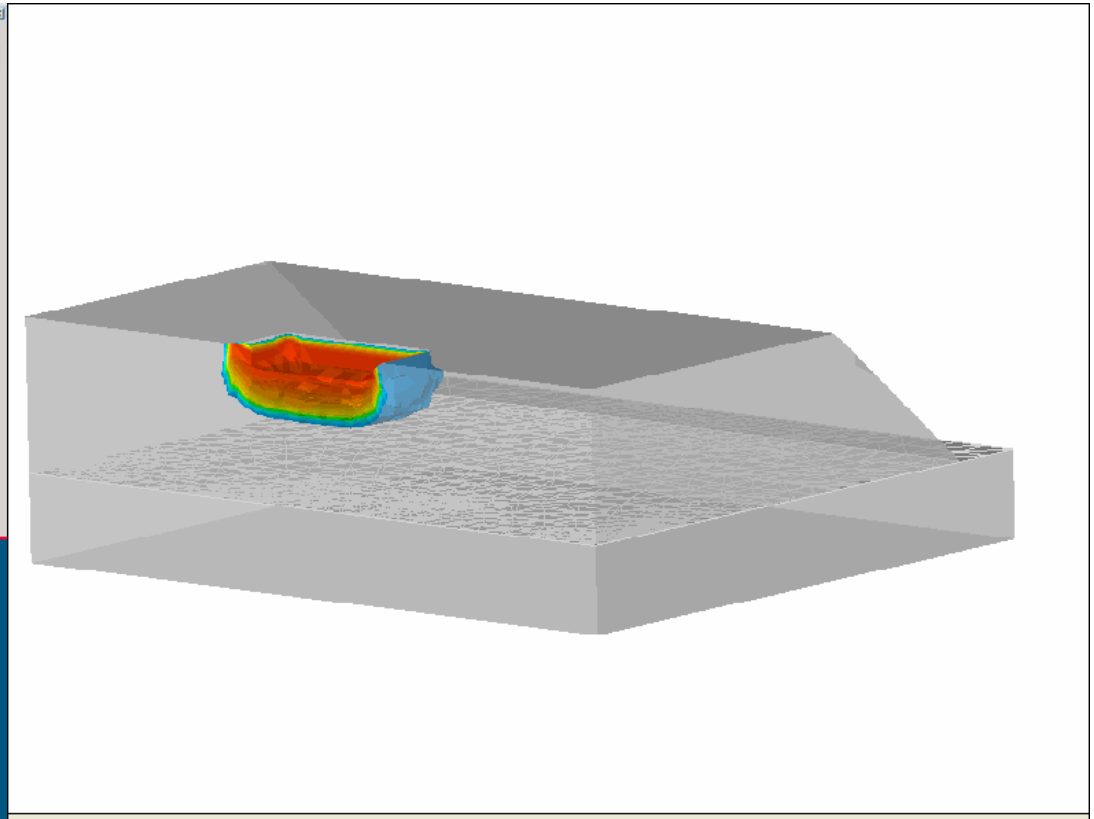
  非饱和土的土性参数可与其土水特征曲线相联系
- ***Partial differential equations are derivable for:***

  偏微分方程可以这样得到
  - ***one, two and three-dimensional problems*** 一维，二维和三维问题
  - ***water flow*** 水的流动
  - ***Stress-deformation analysis*** 应力－变形分析
  - ***contaminant transport*** 污染物运移
  - ***thermal analysis involving evaporation or freeze-thaw***
    包含蒸发或冻融的热分析
  - ***vapor flow and air flow*** 蒸汽流和空气流



饱和－非饱和土力学分析可以看作求解一系列的偏微分方程！

Conclusion:



D1-3DPosterProblem

Geotechnical engineering analyses for Saturated-Unsaturated Soil Mechanics can indeed be viewed as the Solution of a Series of Partial Differential Equations

Delwyn G. Fredlund