A Regional Hydrologic Model of California's Central Valley

Land Subsidence Attributes for CVHM

Randy Hanson, Claudia Faunt, Ken Belitz, Michelle Sneed, and many others
California Water Science Center
U.S. Geological Survey

Water-Level Change and Subsidence

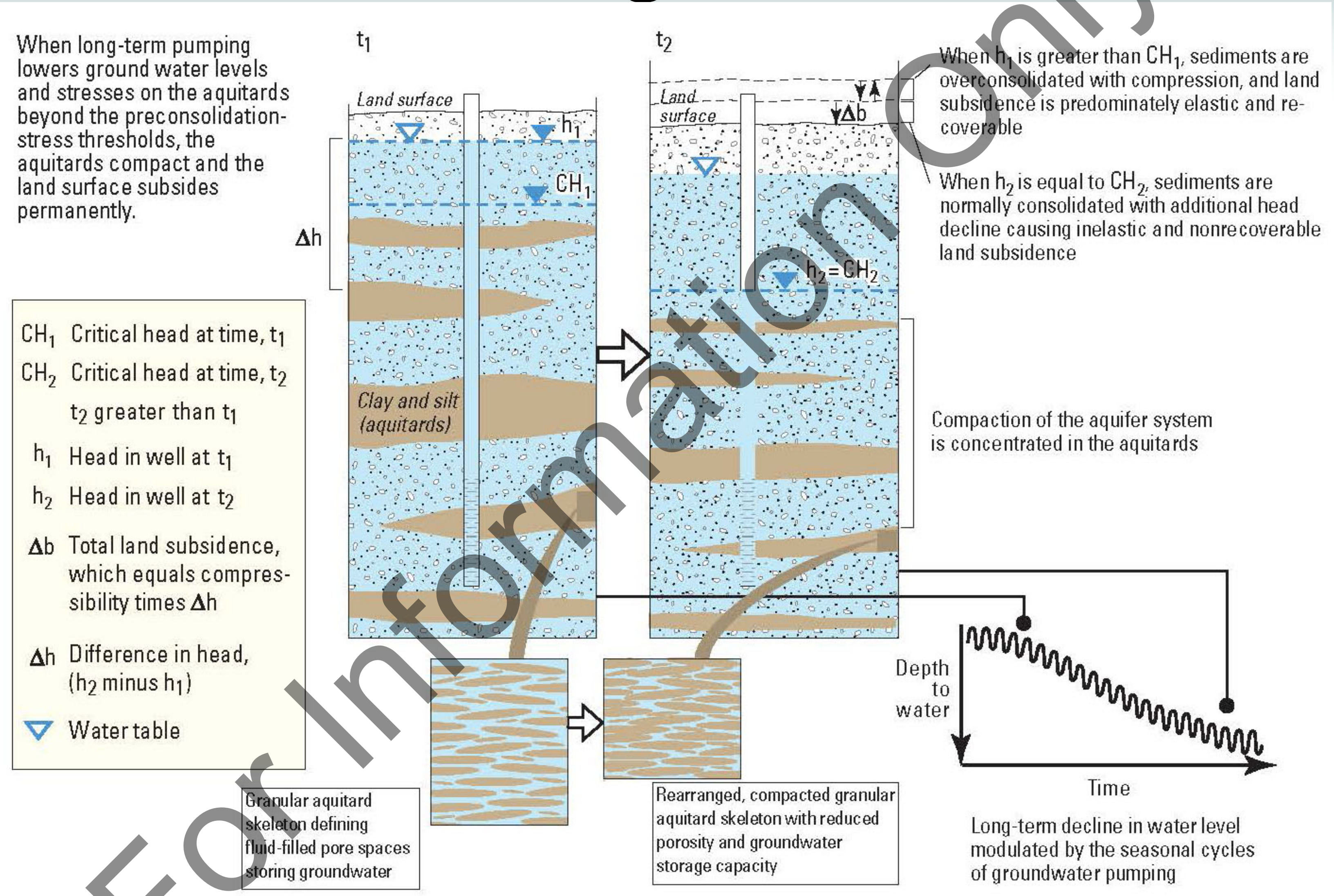
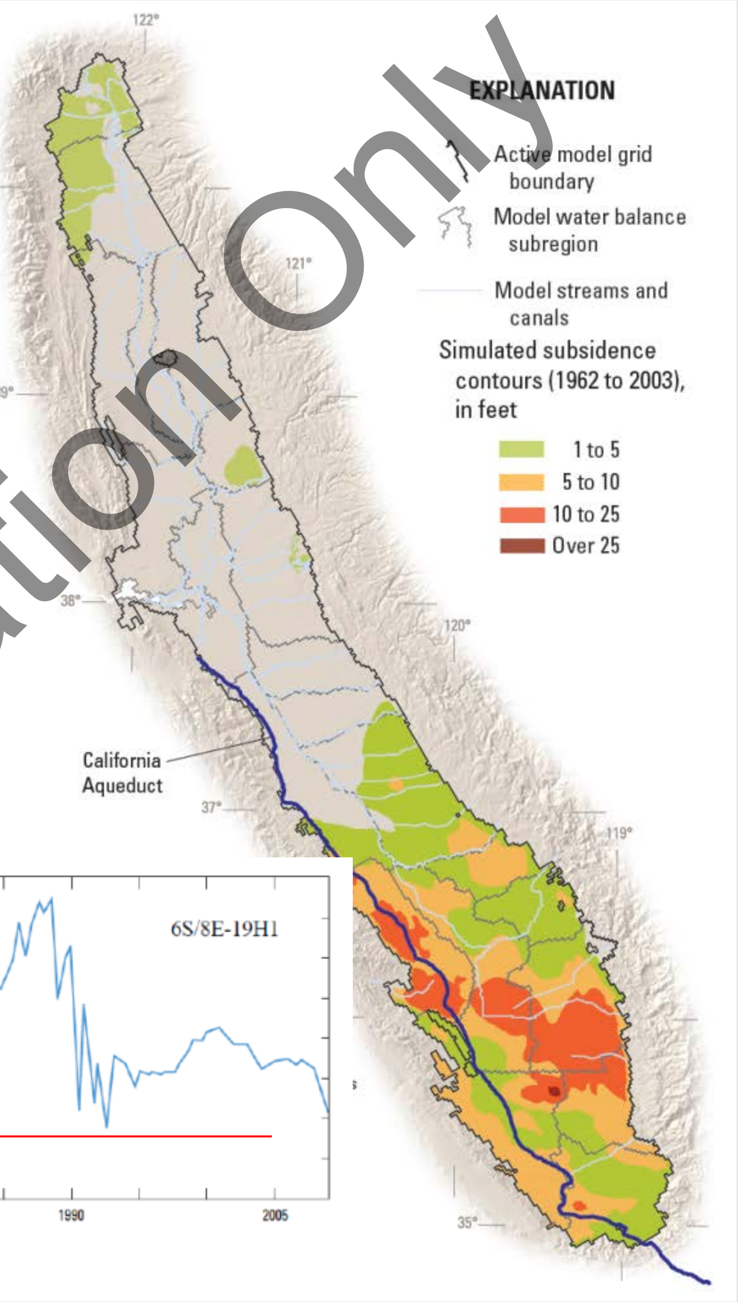
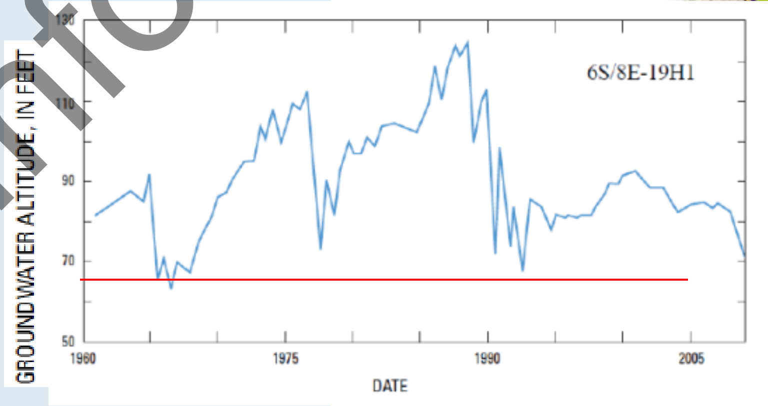


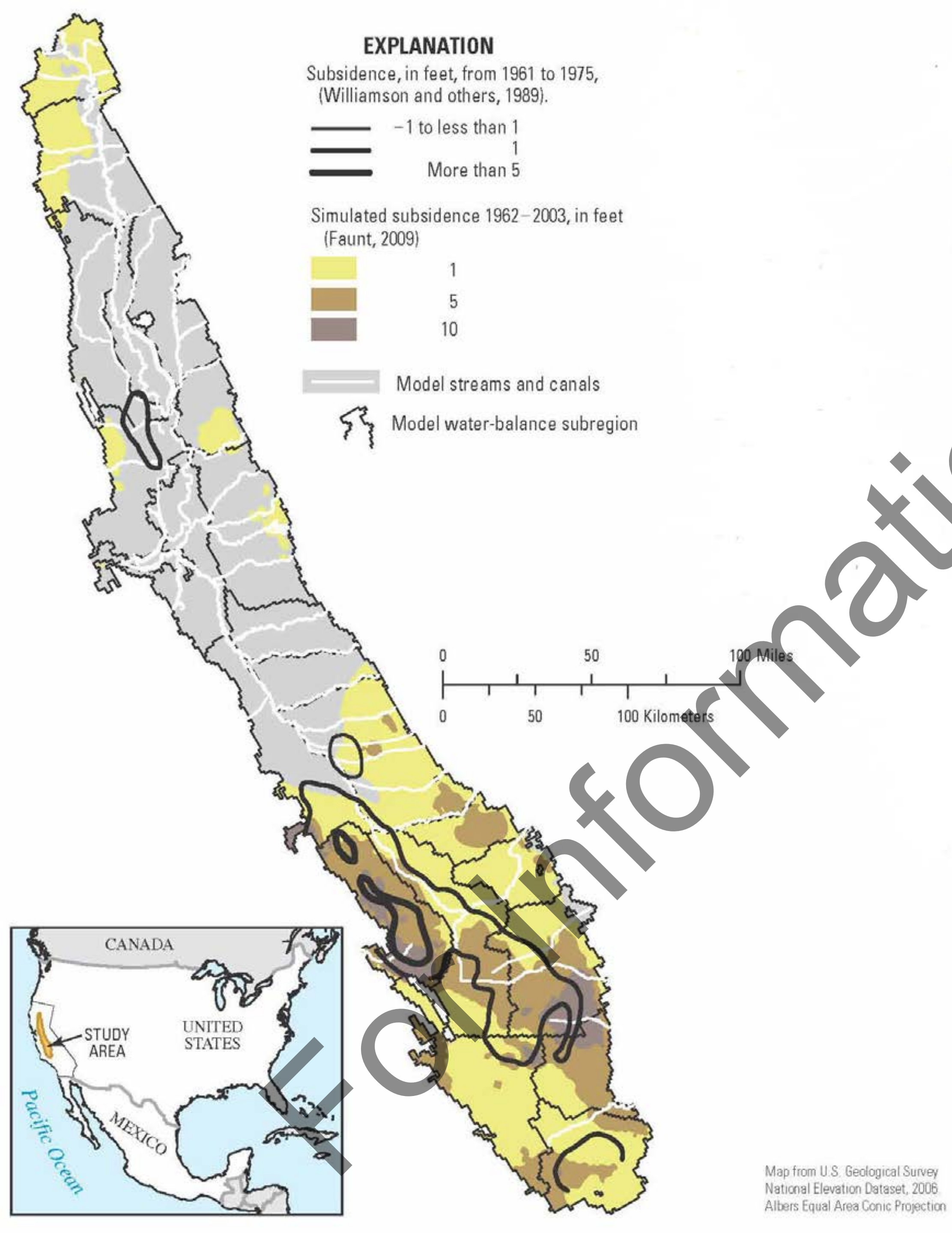
Figure B18. Relationship of water-level changes and critical heads to subsidence and inelastic compaction.

Subsidence:

- In1960s, groundwater pumping caused water levels to decline
- Water-level declines cause compaction of fine-grained deposits, which results in subsidence
- Surface-water deliveries since the late 1960s have reduced the dependence on groundwater
- Water levels are again reaching their historic lows and subsidence may be renewed
- Management constraint







Historical and Recent Subsidence

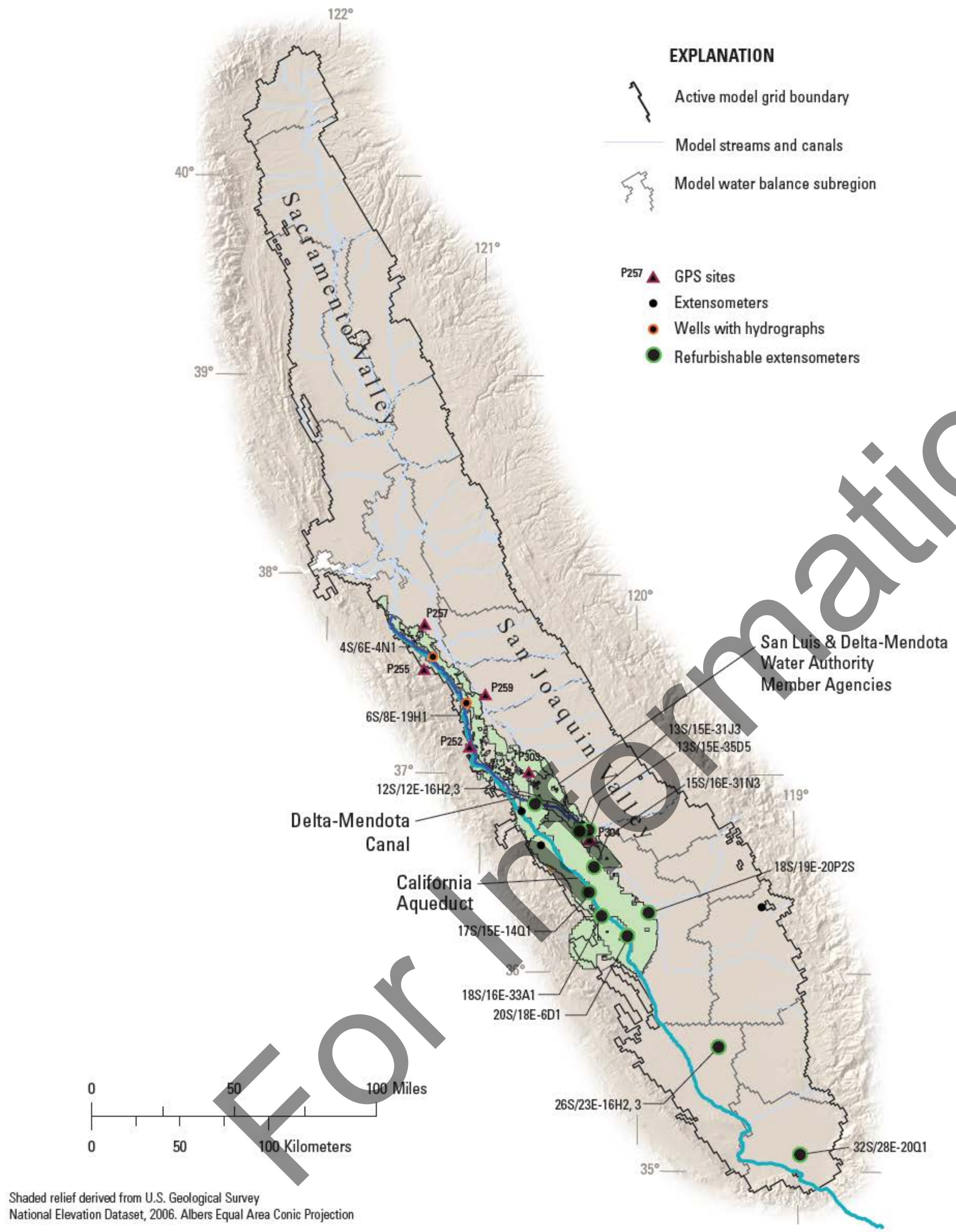
Recent more extensive

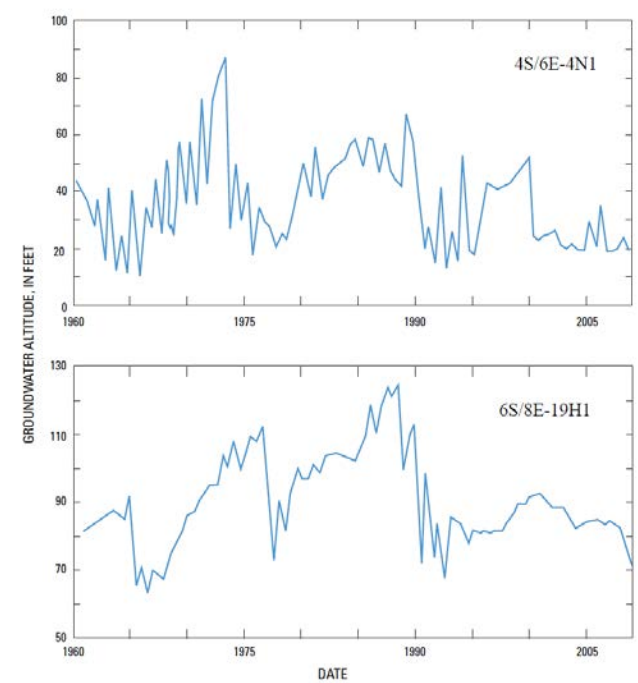
Both cut across existing canals

Canals may be affected by land subsidence and differential land subsidence

Additional pumpage to supplement reductions in surface-water deliveries may additionally affect land subsidence near Delta-Mendota and California Aqueduct

Location of historical extensometers used to measure subsidence, extensometers that can possibly be refurbished, continuous GPS sites, and selected wells in the San Joaquin Valley.





Parameters needed for Quantitative Subsidence Assessments

- Preconsolidation Head (Stress)
- Vertical Hydraulic Conductivity
- Specific Storage (compressibility)

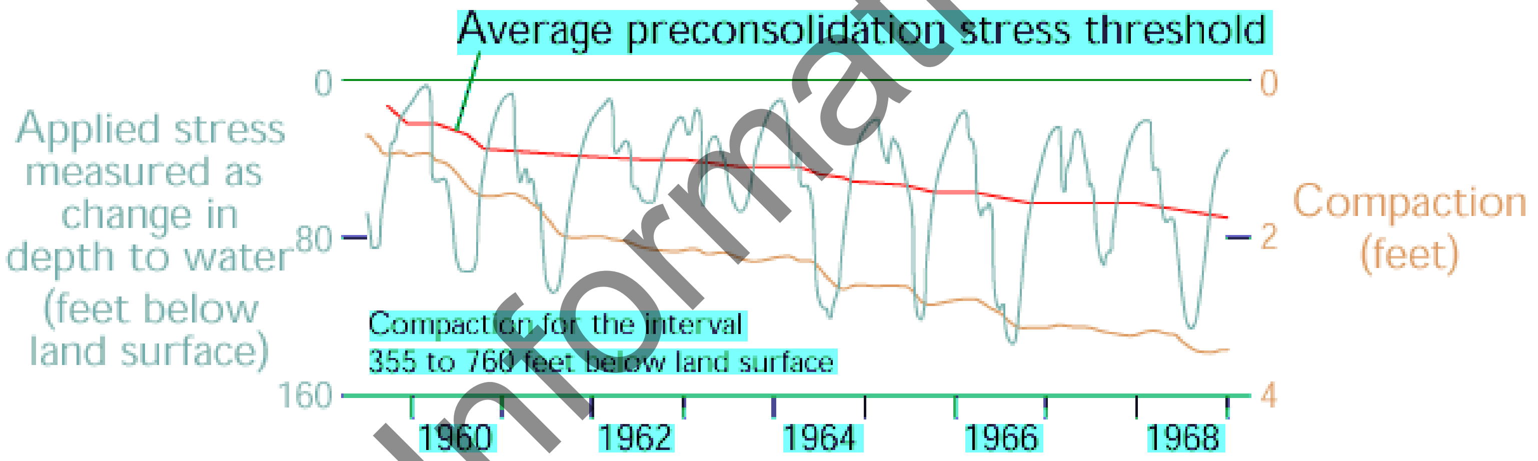
Preconsolidation Stress

- Estimate preconsolidation stress using
  - Head/subsidence history
  - Consolidation tests

Preconsolidation stress:

estimated from ground-water level and borehole extensometer data

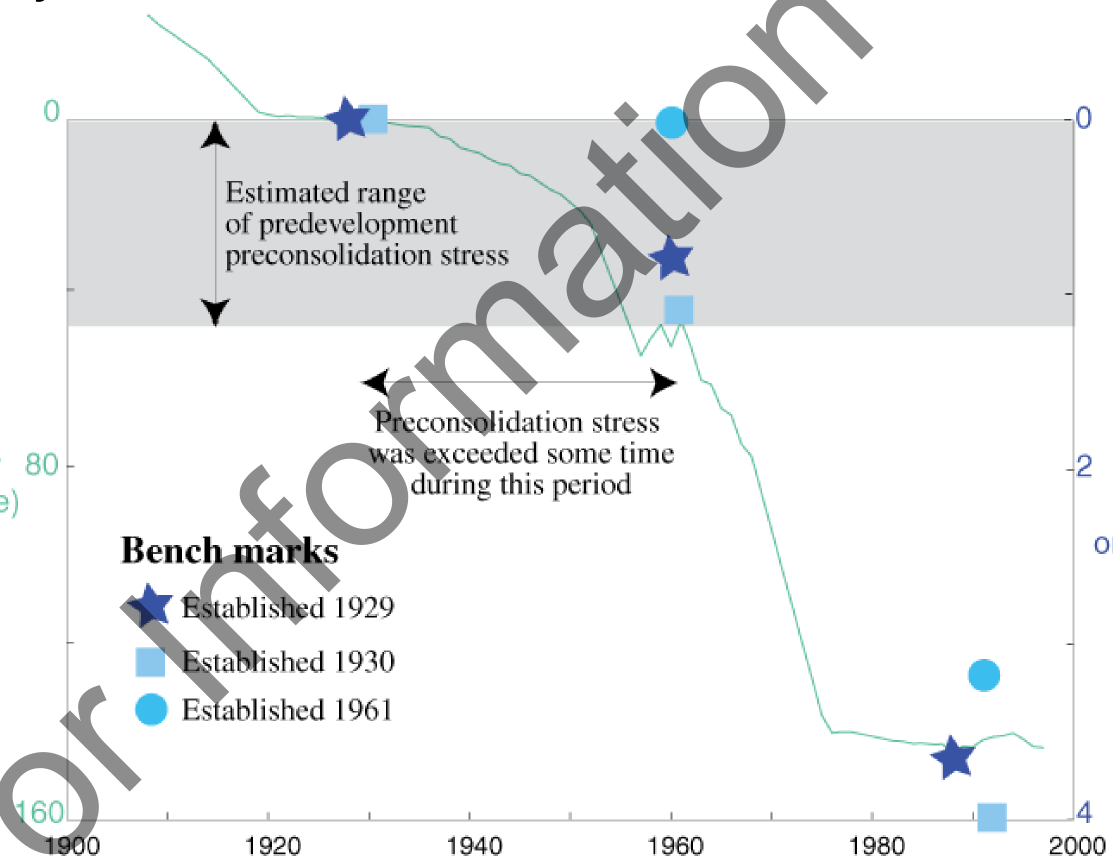
Pixley, California



Preconsolidation stress:

estimated from ground-water level and spirit leveling data

Antelope Valley, California



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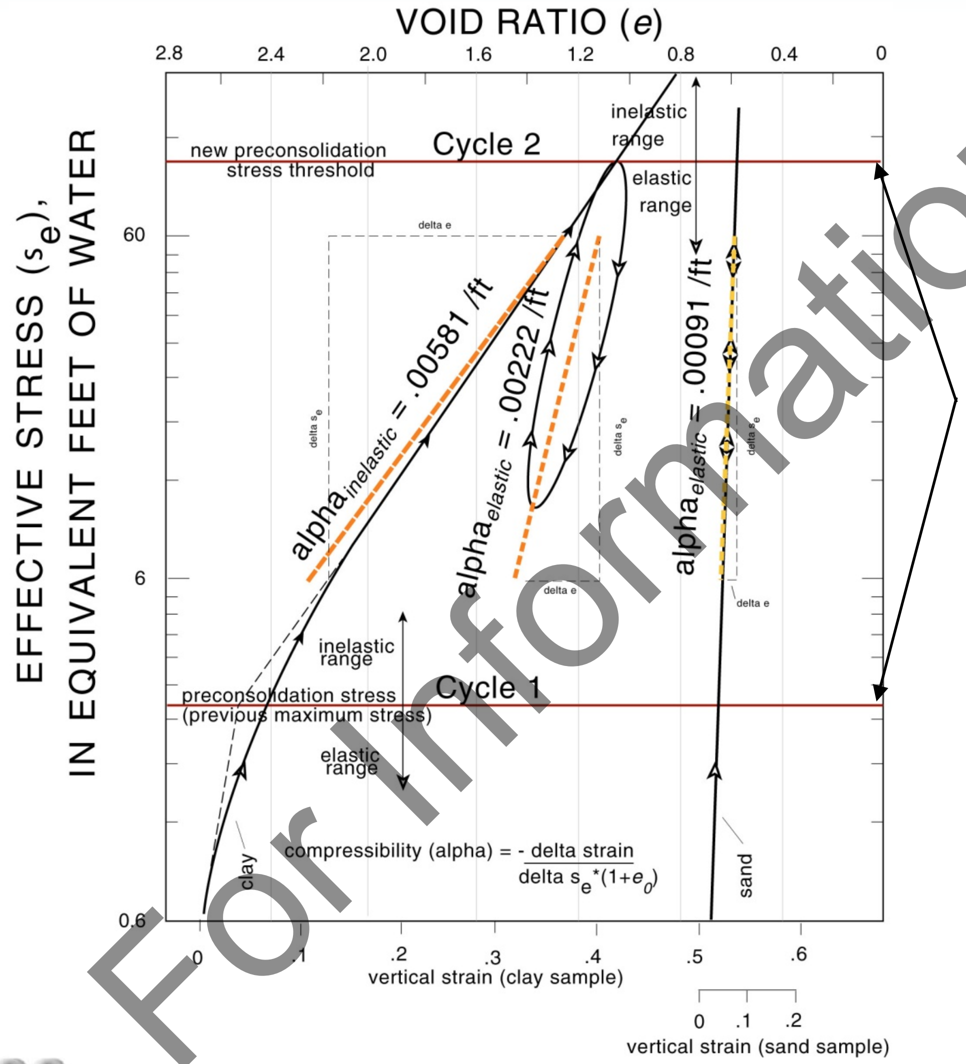
Preconsolidation stress:

1-D vertical, drained consolidation tests of clay and sand



Preconsolidation stress thresholds

Parameters needed for Quantitative Subsidence Assessments

- Preconsolidation Head (Stress)
- Vertical Hydraulic Conductivity
- Specific Storage (compressibility)

Vertical Hydraulic Conductivity

- Literature
  - Neuzil, C.E., 1994, How permeable are clays and shales?, WRR v. 30, no. 2
- Lab tests
  - Stand alone
    - ASTM D5084-03 Standard Test Methods for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter
  - Part of consolidation tests

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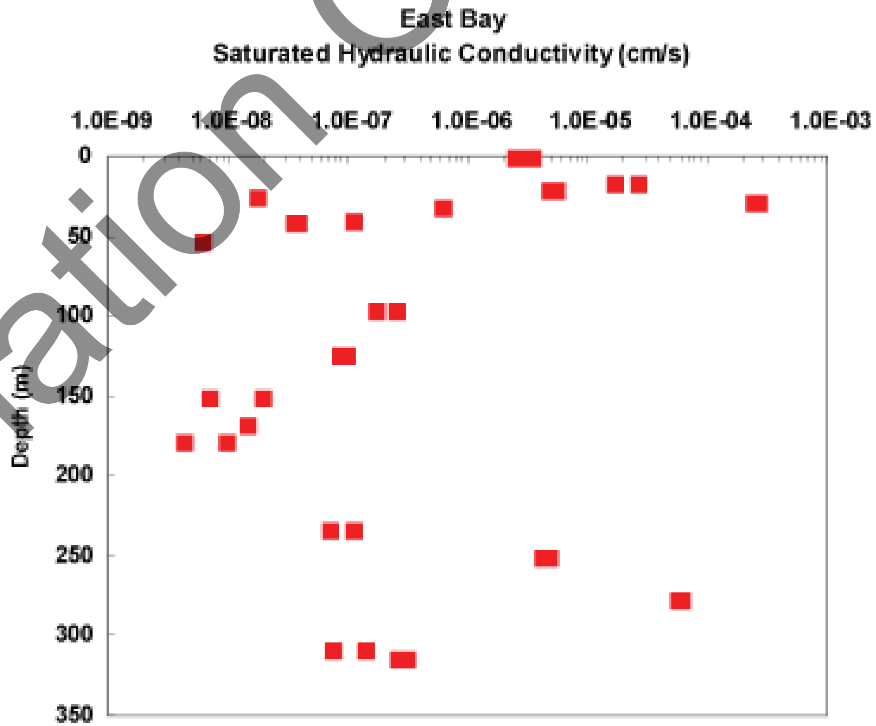
Vertical Hydraulic Conductivity: Stand Alone



- Generally decreasing K_v with depth

Vertical Hydraulic Conductivity: Consolidation Tests

- Consolidometer as a variable-head permeameter at different loads

$$K_v = c_v(\gamma_w)(e_o - e)/\Delta p(1+e_o)$$

- c_v is coefficient of consolidation
- γ_w is specific weight of water
- e_o and e are void ratios at the start and end of load increment, respectively
- Δp is the load increment

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Typical Ranges of Hydraulic Conductivity

Unconsolidated Aquifer Systems	Hydraulic Conductivity, md^{-1}	
Aquifer-system component	K_v	K
Aquitards	10^{-6} – 10^{-3}	10^{-6} – 10^{-3}
Aquifers	10^{-4} – 10^{5}	10^{-2} – 10^{5}

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Parameters needed for Quantitative Subsidence Assessments

- Preconsolidation Head (Stress)
- Vertical Hydraulic Conductivity
- Specific Storage (compressibility)

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Specific Storage (Compressibility)

- Aquitard
  - Skeletal inelastic (S'_{skv})
  - Skeletal elastic (S'_{ske})
- Aquifer
  - Skeletal elastic (S_{ske})
- Aquifer system
  - Skeletal elastic (S^*_{ske})
  - Skeletal inelastic (S^*_{skv})

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Specific Storage Data Sources

- Literature
  - Elastic (S^*_{ske}) and inelastic (S'_{skv}) values tend to fall in a narrow range
- Aquifer tests
  - Focus on coarse-grained units (S_{se})
- Stress/strain analyses (Riley, 1969)
  - Extensometer/head time series (S^*_{ske} & S^*_{skv})
    - Focus on coarse-grained & quickly equilibrating (thin) fine-grained units
  - Consolidation tests (S_{skv})
    - Tend to focus on fine-grained units, but can be used for coarse-grained units

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Typical Ranges of Specific Storage

Unconsolidated Aquifer Systems	Skeletal Specific Storage, m^{-1}	
Aquifer-system component	S_{ske}	S_{skv}
Aquitards	5×10^{-6} – 5×10^{-5}	10^{-5} – 3×10^{-4}
Aquifers*	10^{-6} – 10^{-5}	—

Specific Storage: Aquifer Tests

- Average S_{se} for coarse-grained sediment
  - Not just the skeletal component, but also includes the storage attributed to the compressibility of water
- Constrained to screened interval

Specific Storage: Stress/Strain Analyses (Field Measurements)

- S^*_{ke} (aquifer system)
- S'_{kv} (thin aquitards)
- Concurrent measurements of:
  - Stress: water level measurements
  - Strain: borehole extensometer measurements

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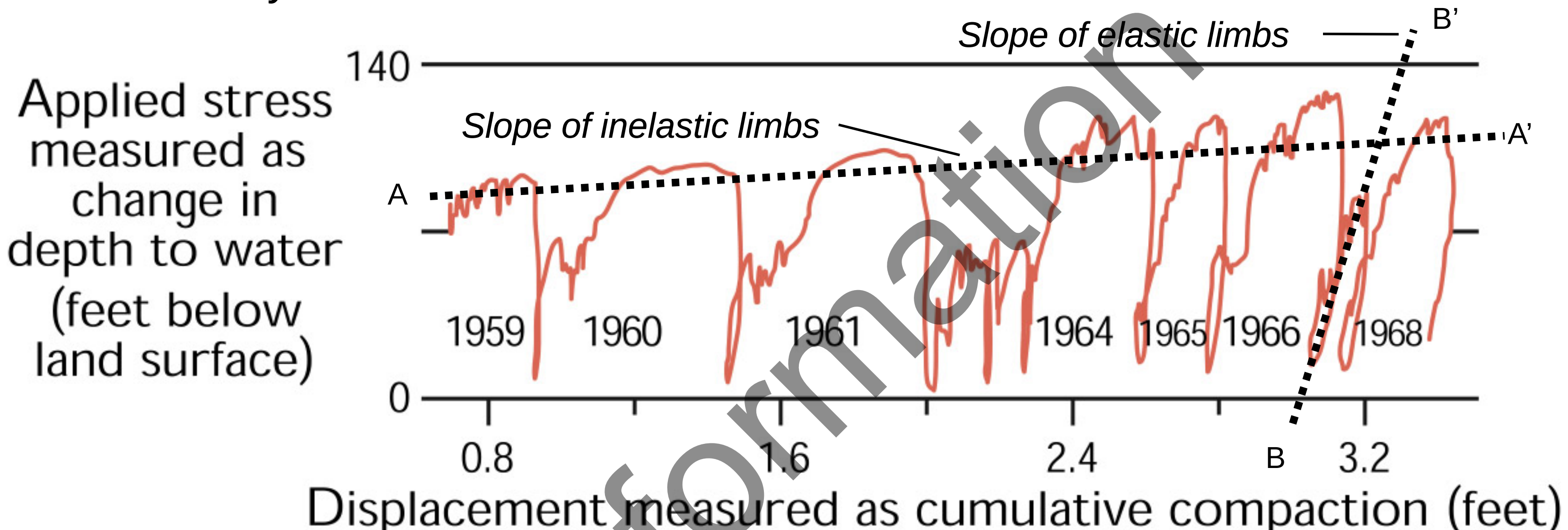
In-situ determination of skeletal storage values from stress-strain observations

Pixley, California



Inelastic (A – A')

$S^*_k = 5.7 \times 10^{-2}$

$S^*_{sk} = (S^*_k)/405\ m = 4.6 \times 10^{-4}\ m^{-1}$

! Inverse slopes !

Elastic (B – B')

$S^*_{ke} = 1.1 \times 10^{-3}$

$S^*_{ske} = (S^*_{ke})/405\ m = 9.3 \times 10^{-6}\ m^{-1}$

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Riley, 1969

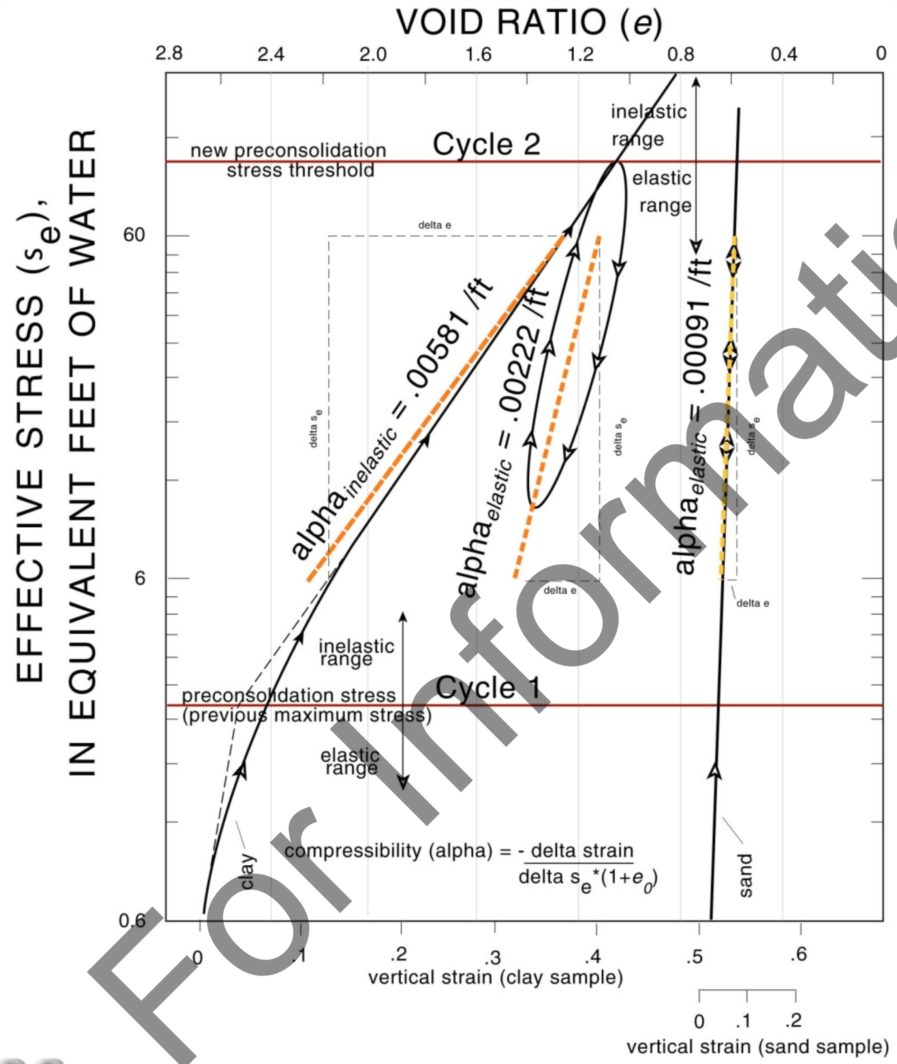
Specific Storage: Stress/Strain Analyses (Lab Measurements)

1-D Consolidation Measurements of Core

- $S^\wedge_{skv}$ and $S^\wedge_{ske}$ (^ denotes ‘sample’)

Specific Storage (compressibility):

1-D vertical, drained consolidation tests of clay and sand



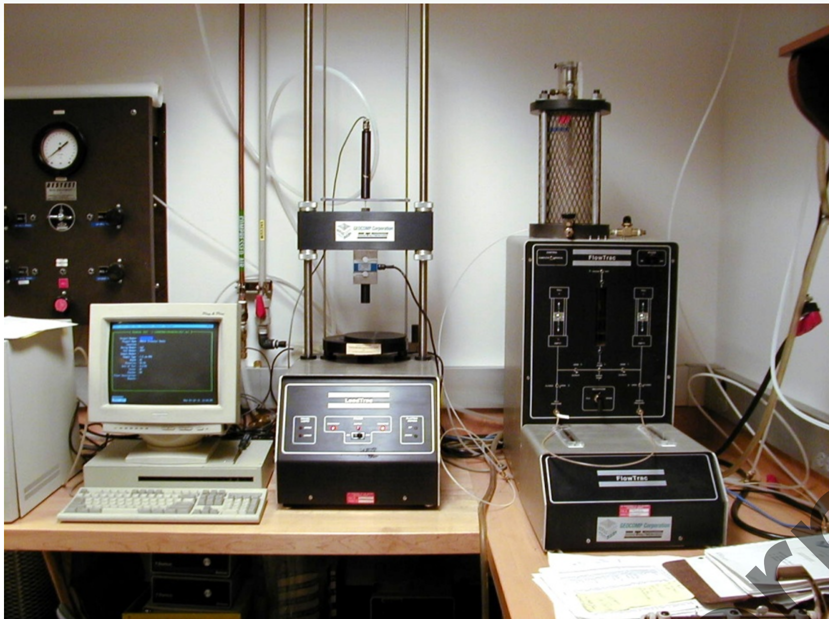
α (compressibilities: elastic and inelastic) computed from slope of strain-stress relations

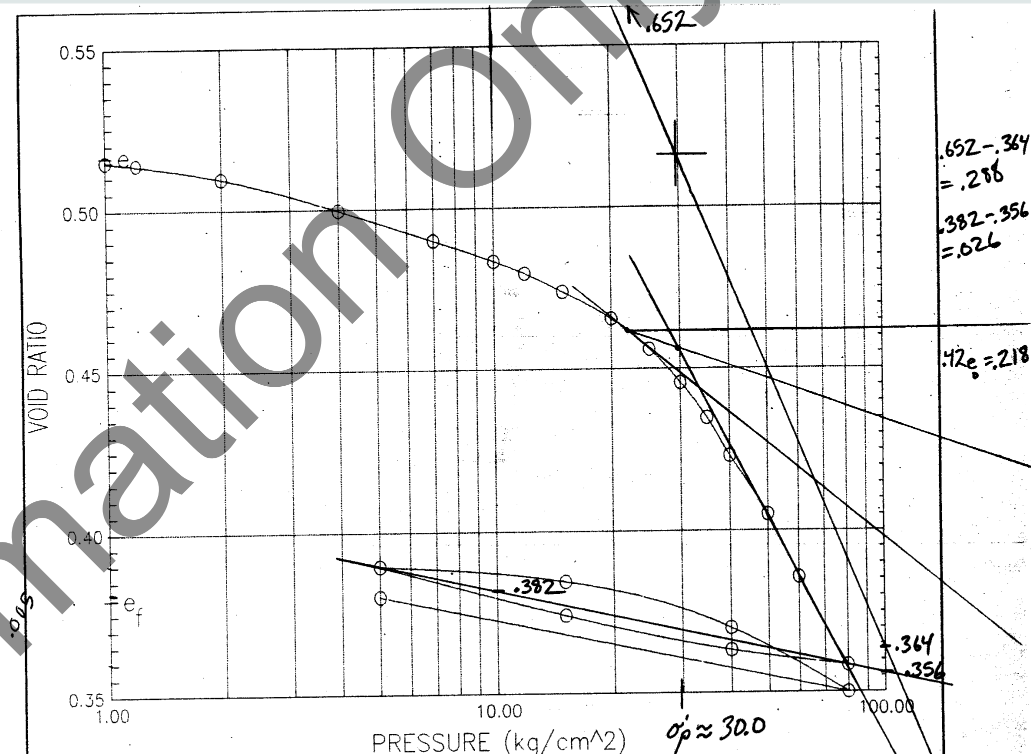
$$S^\wedge_{skv} = K^\wedge_v / C^\wedge_v$$

C_v = coefficient of consolidation

Example Output for A 1-D Step Consolidation Test

Santa Clara valley -- Guadalupe Multiple-Well Monitoring Site Core No. 114 (175—176.5 meters depth)





			BEFORE TEST	AFTER TEST
OVERBURDEN PRESSURE (kg/cm^2)	---	WATER CONTENT (%)	20.0	15.6
PRECONSOL. PRESSURE (kg/cm^2)	---	DRY DENSITY (gm/cm^3)	1.75	1.92
COMPRESSION INDEX	---	SATURATION (%)	102.66	108.57
TYPE SPECIMEN	2.5 Lexan	VOID RATIO	0.52	0.38
DIA. (cm) 5.100	HT. (cm) 2.920	BACK PRESSURE (kg/cm^2)	---	---
CLASSIFICATION	very stiff, mottled, greenish gray silty clay			
LL --- PL ---	PI ---	PROJECT GUAD High Stress Tests		
GS 2.650	D_{10} ---	icon177.asc		
REMARKS	$C_c = 0.29$	BORING NO. GUAD	SAMPLE NO. Core 114	
	$C_R = 0.03$	DEPTH 574-579 ft	DATE 11/14/02	
		U S Geological Survey CONSOLIDATION TEST REPORT		

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Summary of Core Properties

$C_c = 0.29$ $C_r = 0.03$

$P' = 30$ kg/cm^2

$e_o = .52$

$S_{skv} = 4.2 \times 10^{-4}$ m^{-1}

$S_{ske} = 4.3 \times 10^{-5}$ m^{-1}

Ratio $S_{skv}/S_{ske} = 10$

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Use of Well and Consolidation tests

Aquifer Properties for Flow Model

(1) Slug Tests from Wells ➔ Horizontal Hydraulic Conductivity

(2) Core Hydraulic Tests ➔ Porosity & Vertical Conductivity (aquifers and confining beds)

Subsidence Properties for Flow Model

(1) Consolidation Tests ➔ Elastic and Inelastic Specific Storage (Compressibility) & Vertical Conductivity (Fine grained layers/Corcoran)

(2) Critical Head ➔ Transition from Elastic to Inelastic (Permanent) Subsidence

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Ranges of relevant mechanical and fluid-flow properties

Unconsolidated Aquifer Systems	Skeletal Specific Storage, m^{-1}		Hydraulic Conductivity, md^{-1}		Time Constant, yrs
Aquifer-system component	S_{ske}	S_{skv}	K_v	K	τ
Aquitards	5×10^{-6} – 5×10^{-5}	10^{-5} – 3×10^{-4}	10^{-6} – 10^{-3}	10^{-6} – 10^{-3}	0 - 1350
Aquifers	10^{-6} – 10^{-5}	—	10^{-4} – 10^{5}	10^{-2} – 10^{5}	—

Specific storage of water ≈ 1.38×10^{-6} m^{-1} (n = 0.32)

Parameters needed for Simulation of Subsidence

- Critical Head ➔Preconsolidation Head (Stress) (Specified in the SUB Pkg)
- Vertical Hydraulic Conductivity (Specified in the LPF Pkg Instantaneous Compaction & or delayed Compaction)
- Elastic & Inelastic Storage ➔ Compressibility (Specified in the SUB Pkg)

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Alternatives for Simulation of Subsidence

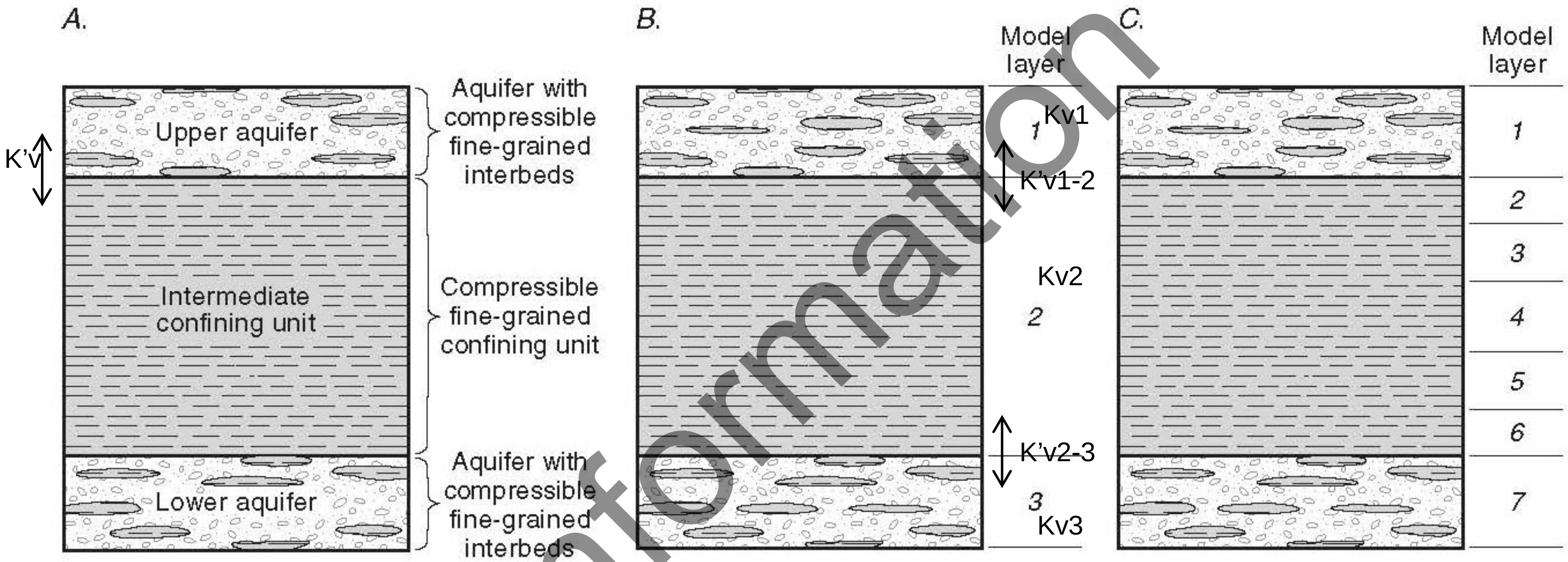

Figure 5. Compressible beds in an aquifer system and two approaches to representing the confining unit in the MODFLOW simulation of aquifer-system compaction using the SUB Package. *A*, Vertical section of an aquifer system with compressible sediments within and adjacent to aquifers. *B*, Use of one model layer to simulate flow and storage changes in the confining unit. *C*, Use of five model layers to simulate flow and storage changes in the confining unit.

SUB Pkg ➔ MODFLOW-2000 Ground-Water Model—User Guide to the Subsidence and Aquifer-System Compaction (SUB) Package
By Jörn Hoffmann, S.A. Leake, D.L. Galloway, and Alica M. Wilson USGS OFR03-233

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Critical Head for CVHM

- Initial Values Derived from 2-layer RASA-1 Model (Williamson et al., 1988)
- Values extrapolated between additional layers based on starting head and top of layer and previous 1961 heads (minimum ➔ whichever were lower)
- Generally Critical Heads represent conditions of overconsolidation
- Range of Critical heads (meters above mean sea level):

Layer Number	Minimum	Maximum	Mean
1	-6.4	191.8	36.9
2	-6.8	191.5	39.6
3	-18.4	265.2	44.8
4	-104.2	220.8	41.5
5	-185.1	220.8	36.7
6	-269.9	209.5	36.1
7	-254	197.	35.6
8	-253.2	184.5	35.1
9	-262.9	175.6	35.3
10	-169.1	171.8	37.2

Elastic Storage for CVHM

- Initial Values of Specific Storage derived from earlier Subsidence work see summary in table C8, p157 in USGS Prof. Paper 1766) Generally typical elastic compressibility of alluvial material
- Sske – elastic

Coarse-grained = 1.4 - 1.0×10^{-6} per ft;
Fine-grained = 2.0×10^{-6} to 7.5×10^{-6} per ft;
Fine-grained = 4.5×10^{-6} per ft

Values extrapolated to each model cell based on product of Sske and texture data aggregate thickness within each cell for each layer.

- Range of Ske values (dimensionless):

Layer Number	Minimum	Maximum	Mean
1	3.8e-5	6.54e-4	2.8e-4
2	2.9e-5	4.5e-4	3.2e-4
3	2.9e-5	2.8e-3	6.1e-4
4	1.0e-5	1.8e-2	3.2e-4
5	1.0e-5	2.2e-2	3.2e-4
6	3.04e-4	8.37e-4	6.7e-4
7	4.13e-4	1.1e-3	8.4e-4
8	5.09e-4	1.3e-3	9.9e-4
9	5.8e-4	1.4e-3	1.19e-3
10	6.5e-4	1.7e-3	1.27e-3

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Fine-grained Aggregate Thickness for CVHM

- Texture Model of CVHM (Faunt et al., 2009)
- Values extrapolated between additional layers based on textural model data for each layer.
- Range of aggregate thickness of fine-grained deposits (meters above mean sea level):

Layer Number	Minimum	Maximum	Mean
1	1.57	43.4	17.
2	1.35	30.5	19.4
3	0.73	186.	36.8
4	.0001	15.3	2.5
5	.00015	38.1	2.6
6	9.2	55.6	40.7
7	14.2	69.7	51.0
8	18.2	85.1	59.9
9	20.1	93.9	69.
10	21.7	110.9	76.1

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Parameters needed to identify or estimate for basin-scale subsidence models

(1) SUB Package for MODFLOW— "no-delay" beds

- Critical head
- Elastic storage factor- $Sske \times b_{total}$
- Inelastic storage factor- $Sskv \times b_{total}$

(2) SUB Package for MODFLOW— "delay" beds

- Critical head
- Representative thickness of interbeds- b_{avg}
- Vertical hydraulic conductivity of interbeds, K'_v
- Elastic skeletal specific storage- $Sske$
- Inelastic skeletal specific storage- $Sskv$

Aquifer-system storage coefficients:

elastic and inelastic coefficients

(subscript ‘e’ denotes elastic property, subscript ‘v’ denotes ‘virgin’ or inelastic property)

$$S^* = \begin{cases} S_e^* = S'_{ke} + S_{ke} + S^*_w & \sigma_e < \sigma_{e(max)} \\ S_v^* \approx S'_{kv} & \sigma_e > \sigma_{e(max)} \end{cases}$$

For compacting aquifer systems, because $S_{kv} \sim 0$, and $S'_{kv} >> S^*_w$ the inelastic storage coefficient of the aquifer system is approximately equal to the interbed inelastic skeletal storage coefficient, $S^*_v \approx S'_{kv}$.

CONSTRUCTION OF LAYER FLOW PROPERTIES

(Horizontal Hydraulic Conductivity (HK), Vertical Hydraulic Conductivity (VK), Specific Storage (SS))

Cell-by-Cell Fraction of Coarse-Grained Sediment Arrays for each Layer from Hydrogeologic Framework Model (HFM)

Cell-by-Cell Layer Elevation Arrays for each Layer from HFM

Multiplier Package

Construction of Basic Model-Layer Hydraulic Properties

Definition of Global Scalar Values for HK, VK, & SS Ex. Kc, Kf for HK for each layer or subregions within layers

Cell-by-Cell Calculation of HK, VK, & SS for Coarse & Fine-grained Fractions for each Layer

Cell-by-Cell Calculation of Arithmetic sum for HK & SS, Power Mean for VK for each Layer

Zone Definition Files ➔ Defines arrays that represent cell-by-cell parameter definition of each zone in each layer (Indicator arrays)

Parameter Definition File ➔ Defines Parameter Value Multiplier

Layer Property Flow Package ➔ Construction of Cell-by-Cell Hydraulic Properties Used by MF2K5

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CONSTRUCTION OF HYDRAULIC PROPERTIES for LPF and SUB package for Regional Hydrologic Models

(1) LPF Package ➔ Horizontal Hydraulic Conductivity (HK), Vertical Hydraulic Conductivity (VK), Aquifer Specific Storage (SS))

(2) SUB Package ➔ Elastic and Inelastic Storage

(3) Hydraulic properties computed internally in MODFLOW using the Multiplier Package (Not currently available for SUB Package ➔ Computed externally a priori)

(4) Also Define LAYER ZONE ARRAYS In Zone Package & Parameters in PVAL

TRANSMISSION HYDRAULIC PROPERTIES (Based on Texture estimates of Alluvial Aquifer Systems)

Aquifer/Aquitard Horizontal Conductivity (HK) ➔ Weighted Arithmetic Mean

HK ➔ $K_h = (K_{coarse} * F_{coarse}) + (K_{fine} * F_{fine})$

F_{coarse} is fraction of coarse-grained sediment per model cell relative to thickness

F_{fine} is fraction of fine-grained sediment per model cell $(1–F_{coarse})$ relative to thickness

Aquifer /Aquitard Vertical Hydraulic Conductivity (VK) ➔ Power Mean

VK ➔ $K_v = [(K^{p}_{coarse} * F_{coarse}) + (K^{p}_{fine} * F_{fine})]^{1/p}$

F_{coarse} is fraction of coarse-grained sediment per model cell,

F_{fine} is fraction of fine-grained sediment per model cell $(1–F_{coarse})$

P is power 0=geometric mean (decreased anisotropy)

-1=harmonic mean (increased anisotropy) (ex -.8)

OR for Compressible Fine-Grained Layers ➔ Stress-Dependent Vertical Hydraulic Conductivity

VK ➔ $K_v = c_v(\gamma_w)(e_o-e)/\Delta p(1+e_o)$

- c_v is coefficient of consolidation
- γ_w is specific weight of water
- e_o and e are void ratios at the start and end of load increment, respectively
- Δp is the load increment

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CONSTRUCTION OF HYDRAULIC PROPERTIES for LPF and SUB package for Regional Hydrologic Models (Continued)

LPF Package ➔ Aquifer Specific Storage (SS) ➔ Also Define LAYER ZONE ARRAYS In Zone Package & Parameters in PVAL

SUB Package ➔ Elastic and Inelastic Storage

LPF Aquifer Specific Storage (SS) ➔ Weighted Arithmetic Mean for LPF of Compressibility of Water or Specific Yield (Computed with Multiplier Package)

SS ➔ $S_s = S_{sw} + S_y$/(Total Thickness for each uppermost cell in a model layer)

S_y= Specific Yield

S_{sw}= Specific Storage from Compressibility of Water $(Phi_{coarse} * F_{coarse} + Phi_{fine} * F_{fine}) * B_w$

Phi_{coarse} = Porosity of coarse-grained sediment

Phi_{fine} = Porosity of fine-grained sediment

B_w = Compressibility of water

SUB Fine-Grained Elastic Storage (S'_{ke}) ➔ Weighted Arithmetic Mean for SUB Package

$S'_{ke} = (S'_{skeCoarse} + S'_{skeFine})$ * Vertical Thickness of each model cell

$S'_{skeCoarse}$= Texture & Porosity weighted Skeletal Elastic Specific Storage of Coarse-grained sediment
$= (1 - Phi_{coarse}) * F_{coarse} * (S'_{skec})$

$S'_{skeFine}$= Texture & Porosity weighted Skeletal Elastic Specific Storage of Fine-grained sediment
$= (1 - Phi_{fine}) * F_{fine} * (S'_{skef})$

S'_{skec} = Skeletal Specific Storage of Coarse-grained sediment (estimated from Aquifer Tests)

S'_{skef} = Skeletal Specific Storage of Fine-grained sediment (estimated from extensometer or consolidation tests)

$S'_{kv} = (S'_{skvFine})$ * Vertical Thickness of each model cell

$S'_{skvFine}$= Texture &Porosity weighted Skeletal Inelastic Specific Storage of Fine-grained sediment
$= (1 - Phi_{fine}) * F_{fine} * (S'_{skvf})$

S'_{skvf} = Skeletal Inelastic Specific Storage of Fine-grained sediment (estimated from extensometer or consolidation tests)

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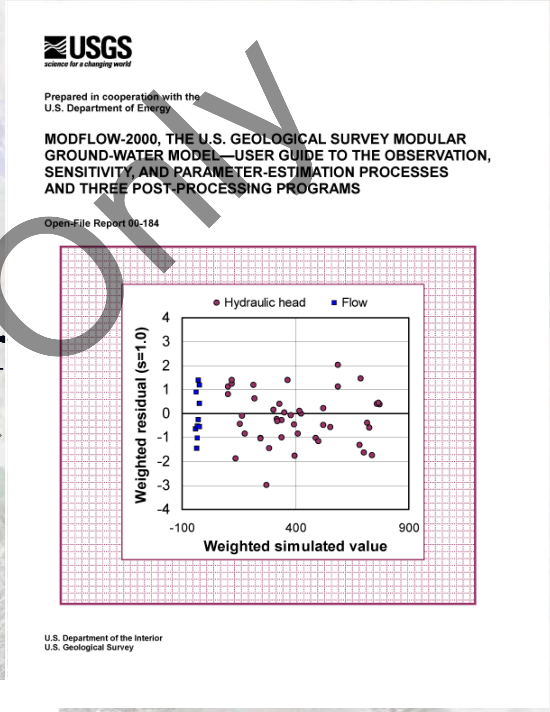
Model Simulations: Parameter Estimation

- Subsidence Observations needed for subsidence models to constrain parameter estimation
  - Accuracy
  - Importance
- Geohydrologic Framework allows Parameter Estimation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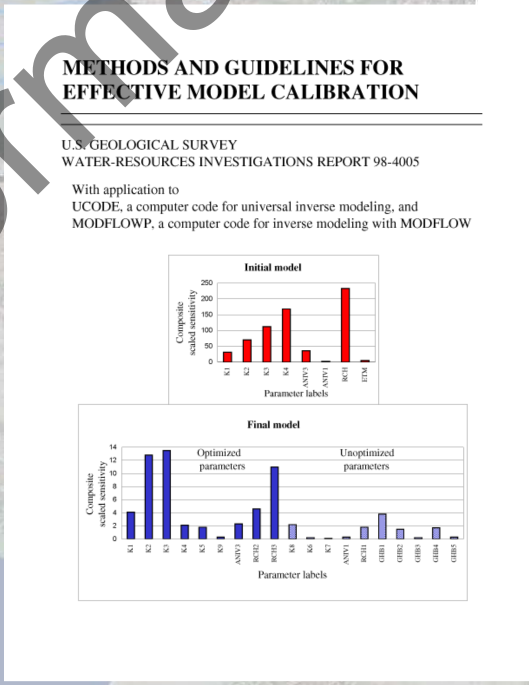
Prepared in cooperation with the
U.S. Department of Energy

MODFLOW-2000, THE U.S. GEOLOGICAL SURVEY MODULAR GROUND-WATER MODEL—USER GUIDE TO THE OBSERVATION, SENSITIVITY, AND PARAMETER-ESTIMATION PROCESSES AND THREE POST-PROCESSING PROGRAMS

Open-File Report 00-184

U.S. Department of the Interior
U.S. Geological Survey


METHODS AND GUIDELINES FOR EFFECTIVE MODEL CALIBRATION

U.S. GEOLOGICAL SURVEY
WATER-RESOURCES INVESTIGATIONS REPORT 98-4005

With application to
UCODE, a computer code for universal inverse modeling, and
MODFLOWP, a computer code for inverse modeling with MODFLOW

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Subsidence Model Construction

Conceptual Model

↕

**ID Subsidence Processes & Properties
Management Factors**

↕

Geologic Framework Model ↔ Hydrologic Model

↕

Regionalize Properties & Parameters

↕

Simulation, Analysis, & Comparison of Measured and Simulated Data

↕

**Hydrologic Flow Analysis
(Conjunctive Use)**

MODFLOW provides Multiple Approaches to Simulation of Land Subsidence

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Recent MODFLOW Developments ➔ More Complete Hydrologic Models ➔ More Realistic Simulations ➔ Better Analysis of Resources within the entire Hydrologic Cycle of Regional Aquifer Systems

Thank You

Questions?

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USGS Models ➔
http://water.usgs.gov/software/ground_water.html

California's Central Val