THE OBSERVATIONAL METHOD: CASE HISTORY AND MODELS

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ABSTRACT The observational method was used to design and construct an embankment over a deposit of soft sludge. The first part of the paper describes the case history of the project. The second part describes the use of analytical models as part of the observational method. The finite element method and one-dimensional consolidation solution were used as prediction models. Bayesian updating was used to revise the material properties with observed performance. Advantages and limitations of updating are presented.

SUMMARY AND CONCLUSIONS

This case history demonstrates a successful application of Terzaghi's observational method. Observed performance of a test embankment was used to verify design assumptions and formulate construction control. Exercise of judgment based on experience and a conservative approach successfully avoided failure where there were weak zones in the subsoil. Updating with analytical models showed that the models gave results consistent with sound geotechnical practice and could be used as part of the observational method. Where there were multiple sources of error, sensitivity analysis was used to identify the input properties with high sensitivities and further investigation provided improved estimates of these variables.

Bayesian updating with the FEM model provided updated material properties that gave improved predictions of the embankment performance. The presence of undetected weak materials, always an important issue in geotechnical engineering, was reflected in the uncertainty about the updated properties. This, in turn, was reflected in the uncertainty about the updated performance. Also, the models could be used to identify the problem when departures from expected performance occur and evaluate their seriousness.

Updating coefficient of consolidation c_r with the radial consolidation model and measured pore pressures was used to evaluate the in-situ c_r. The c_r updated with the observed consolidation rate during the first stage of construction of the I-670 embankment gave good prediction of the consolidation rate during the subsequent stage. However, the c_r updated with the observed data from the test embankment did not give good prediction of the consolidation rate for the I-670 embankment because the observed data from the limited area of the test embankment did not represent the condition along the I-670 embankment.
Comparison with other case histories showed that the in-situ c_r is strongly dependent on the continuity of the pervious layers within the flow domain; the ratio of the in-situ c_r to the laboratory c_r decreases as the pervious layers become thinner and less continuous.

In both examples, spatial variations in material properties were reflected in differences in observed performances. It is appropriate to remember Terzaghi's (1936) statement, "A natural soil is never homogeneous. Its properties change from point to point, while our knowledge of these properties is limited to those few spots at which the samples have been collected."

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The Observational Method: Case History and Models

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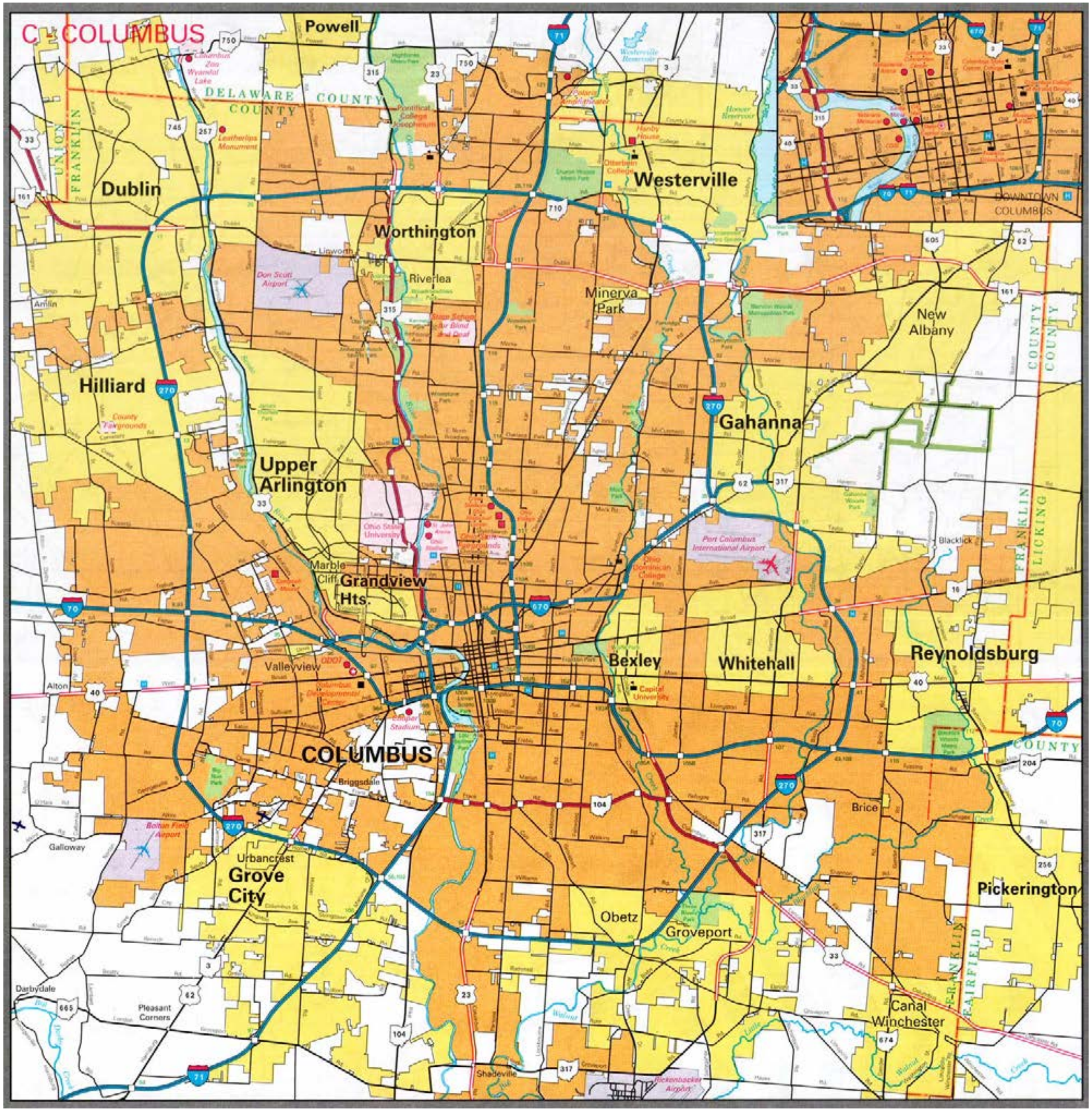
The observational method

Base the design on whatever information can be secured. Make a detailed inventory of all the differences between reality and assumptions, various quantities that can be measured in the field... On the basis of such measurements, gradually close the gaps in knowledge and, if necessary, modify the design during construction.

(Terzaghi, 1961)

Site Location



Outline

1. Design and Construction, I-270, Columbus, OH.
   Sludge has low strength. Proposed design is staged construction of a reinforced embankment and PVD for drainage.

2. “Observational Method”. A test embankment was built to verify strength gain.
   Observed performance was used as guide in construction control of I-270 embankment.

3. Models of Observational Method.
   Models are used to evaluate observed performance of test embankment and obtain revised material properties
   Revised properties are used to predict embankment performance, and revise design if necessary.
   Simple Models.

4. Summary and Conclusions.

1. Design and Construction

1.1. Site Conditions

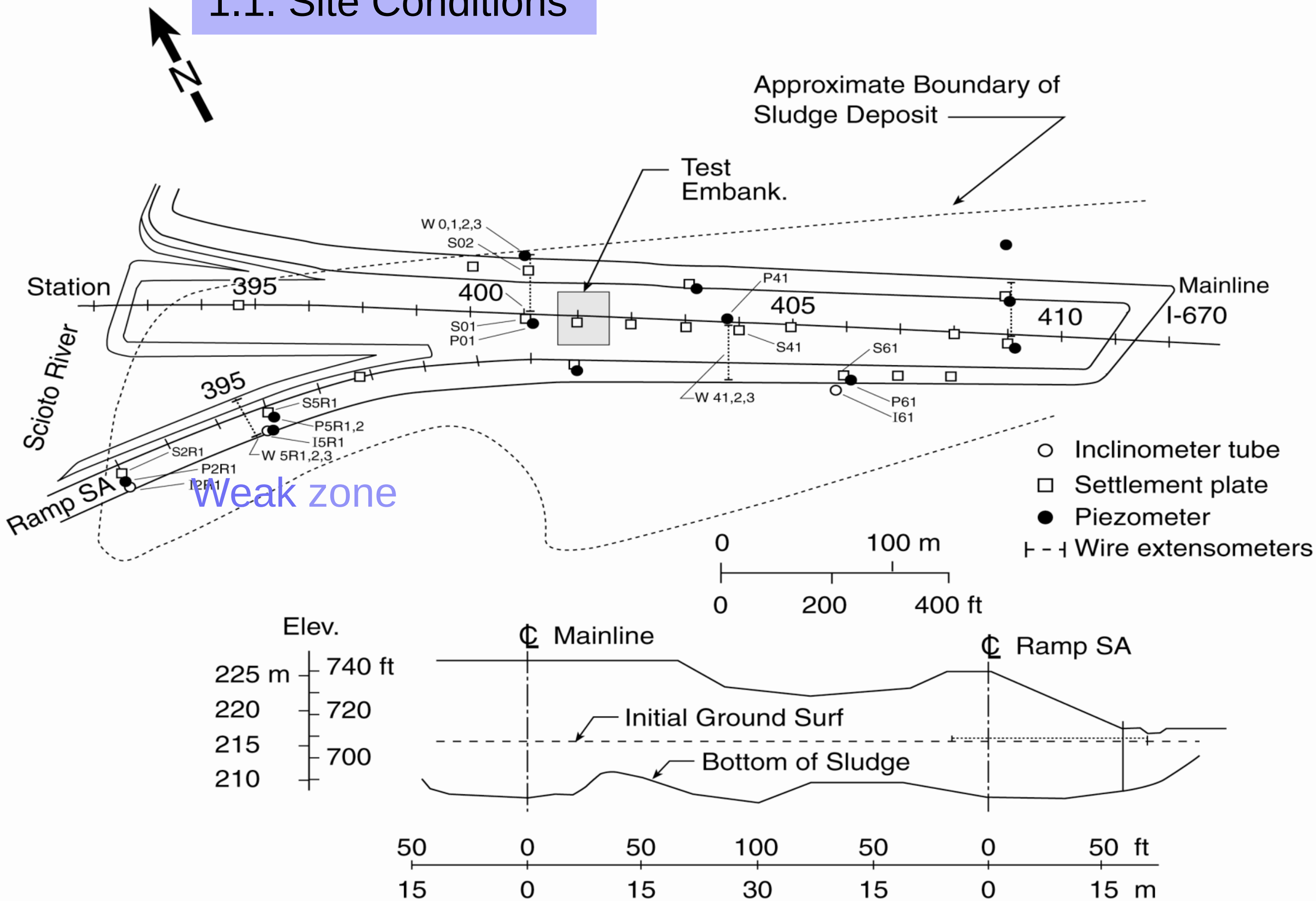


Fig 670-1

1.2. Material Properties:

$CaCO_3$ and $Al_m(OH)_n$

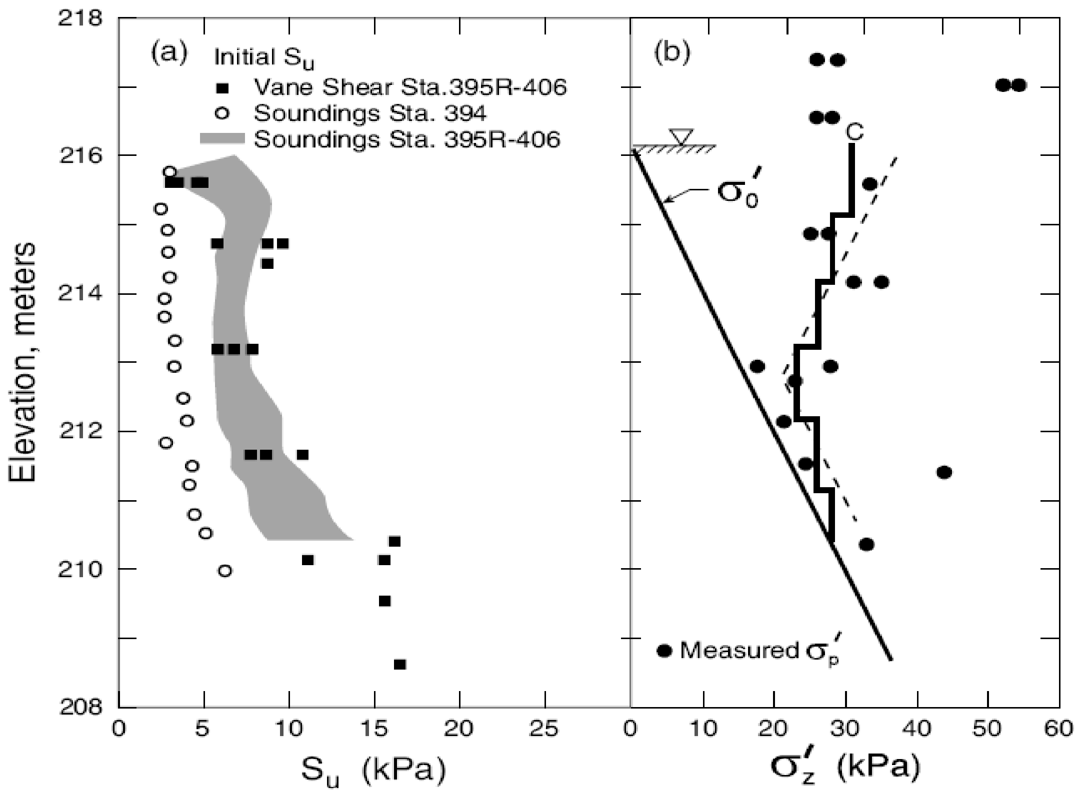
w=240%, w_L = 130% w_P = 45%

s_u=7 kPa, ϕ' =40°, c'=0

Will open structure collapse ?

What is σ_p' ? σ_p' = 25 kPa from early tests.

Details on type of tests used and reliability of measured σ_p' ? Are test specimens truly undisturbed?



Measurement of Soil Properties

Shear strength, s_u

Vane shear test and STS penetration test. COV ≈ 0.1-0.2 (Phoon and Kulhawy, 1999)

Preconsolidation pressure σ_p

Oedometer test . COV ≈ 0.3 (Wu et al. 2111)

2. The Observational Method

Proposed design uses geotextile reinforcement and PVD for drainage.

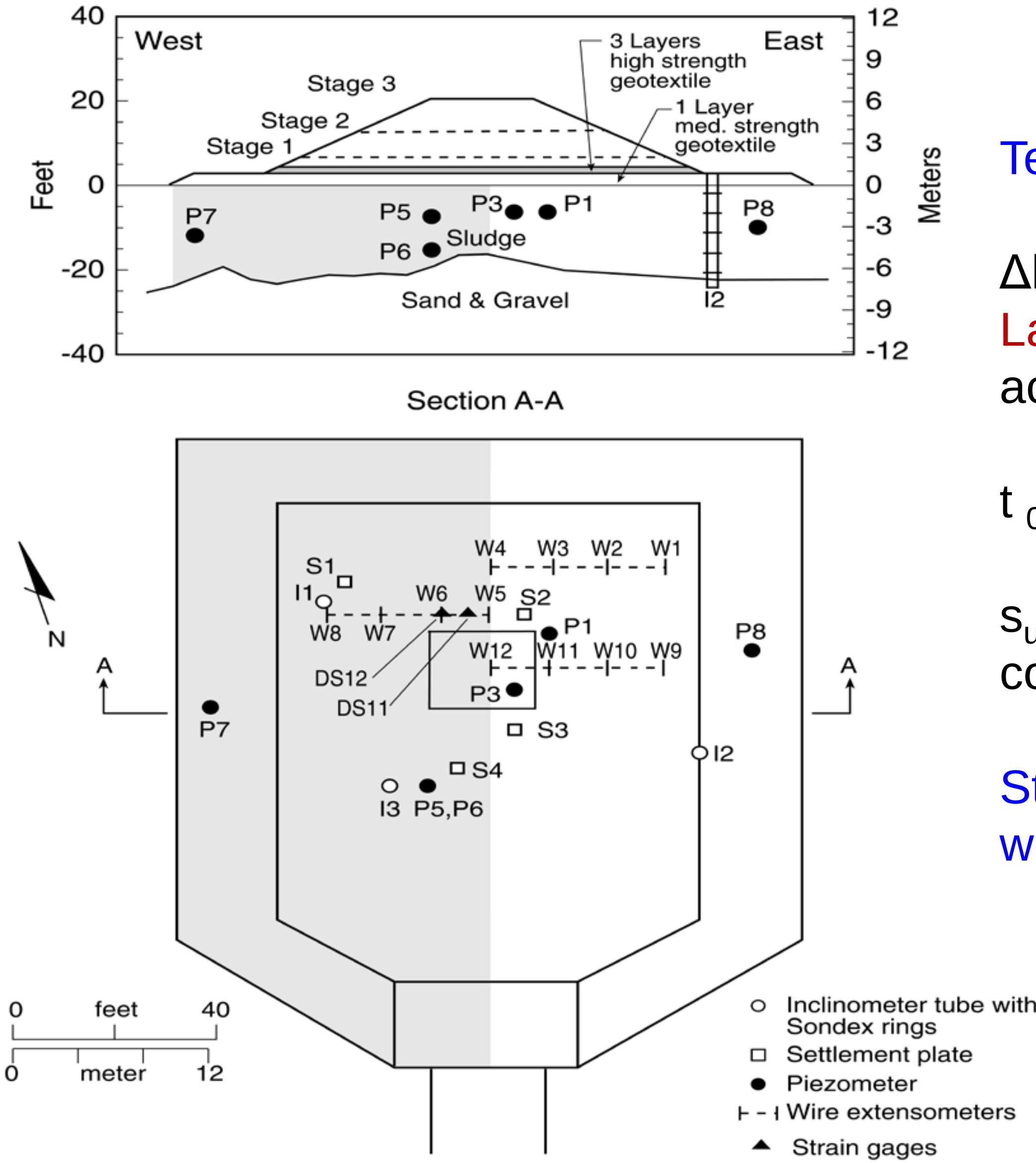
woven, multi-filament, polyprop.

k_n=876kn/m,k_s=16x103kn/m

2.1. Test embankment to measure consolidation and strength gain:

$F_s \geq 1.0$, stage 1, undrained

$F_s \approx 1.5$, stage 2, undrained



Test Embankment was stable.

Δh = 0.15-036 m (I1),
Larger ε_r (W10-W12),
acceptable

$t_{0.5} \approx$ 15 days

$s_u/\sigma_c' = 0.33$ ($\varphi' = 41^\circ$) after consolidation

Staged construction should work.

Δh = horiz. displacement
t_{50} = time to 50% consol.
ε_r = reinf. strain

Fig 670-4

2.2. I-670 embankment – Results from test embankment were used to guide construction control.

Insure adequate consolidation during construction.

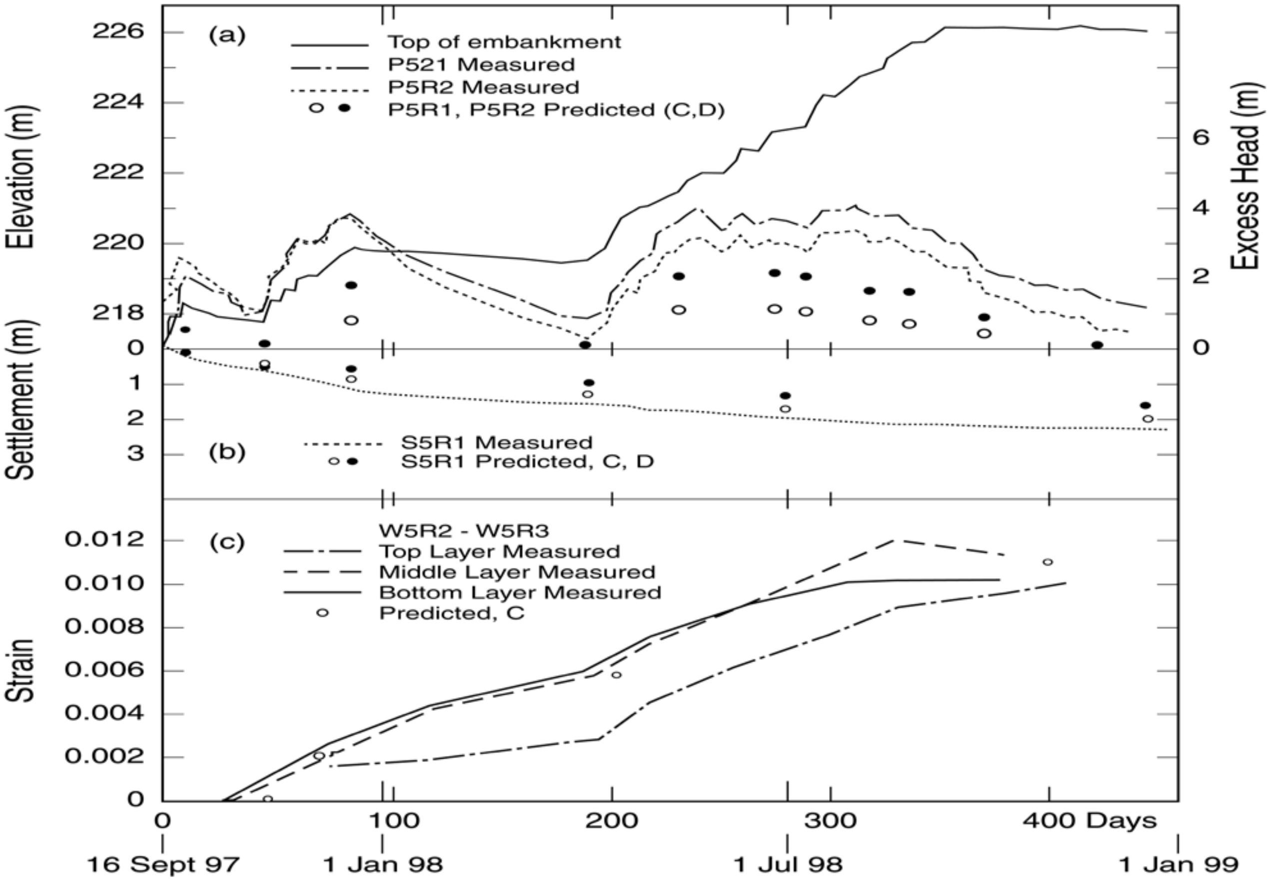
$U_H \geq 0.60$

$F_s \geq 1.40$ and $\varphi' = 27^\circ$ (conservative assumption)

Measured u, Δv, Δh, and ε_r
$\Delta h = 0.2 – 1.0$ m (Sta. 392); $t_{0.5} \approx 20$ days

Embankment was completed without failure.
Performance was acceptable.

Model predictions could not be done in time for construction control.



Sta. 395R

Fig 670-9

3.0. Models of Observational Method

3.1. "Compute, on the basis of original assumptions, various quantities that can be measured in the field. On the basis of such measurements, gradually close the gaps in knowledge and, if necessary, modify the design." (Peck)

3.2. Bayes' Theorem.

$$P''[x_j|z_i] = P\,[z_i|x_j]\; P'\,[x_j] \;/\; \Sigma\; (z_i|x_j)\; P'[x_j] \qquad [1]$$

x_j = property z_j = performance

$P'\,[x_j]$ = Prior (m_x', σ_x', $\Omega_x' = \sigma_x'/ m_x'$),
$P''[x_j|z_i]$ = Posterior = updated property (m_x'', σ_x'')

$P\,[z_i|x_j]$ = Analytical models (simple, FEM)

m_x = mean, σ_x=stand. dev., Ω_x = COV = m_x/σ_x

Bayes' Theorem

$P'[x_j]$ = Original assump. about x ≈ test results

mx = mean = most likely value = best guess

σx = standard dev. ≈ uncertainty Material variability, test errors, etc.

$P\,[z_i \mid x_j]$ = Compute z from x, z = performance

$P''[x_j \mid z_i]$ = Updated x from observed z

System Identification.

Posterior or updated x" (m_x", σ_x") :

$m_x'' = m_x' + \sigma_x'^2 H'[H\sigma_x'^2 H' + \sigma_v'^2]^{-1} [z - H m_x']$

Prior: x = input (properties) (m_x' σ_x')

z = output (performance) = H(x); z σ_v

H = FEM (ABAQUS, PLAXIS, critical state)

It gives the best estimate of x" (= m_x") from observed performance z and estimated errors in x' and z .

Uncertainty about m_x"

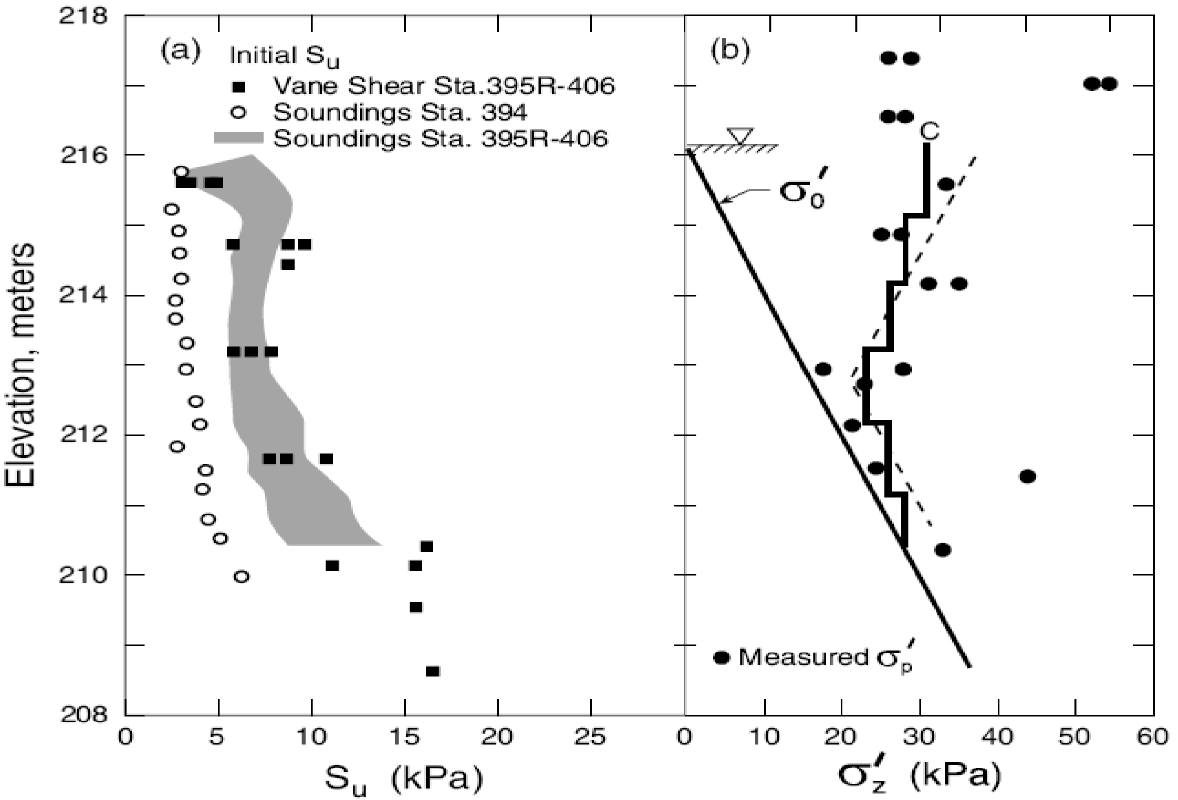
$\sigma_x'' = [H' \sigma_v^{-2} H \sigma_x'^{-2}]^{-1/2}$

Use results from test embankment to update properties.

Prior x': $\sigma_p' = 25$ kPa (limited data), λ, φ', $K_h = 0.25 \times$ lab K_h = "original assump."

Posterior: $m_x'' = m_x' + \sigma_x'^2 H' [H\sigma_x'^2 H' + \sigma_v^2]^{-1} [z - Hm_x']$ = "updated" properties:

Posterior: σ_p' = "close the gaps in knowledge" = Line C

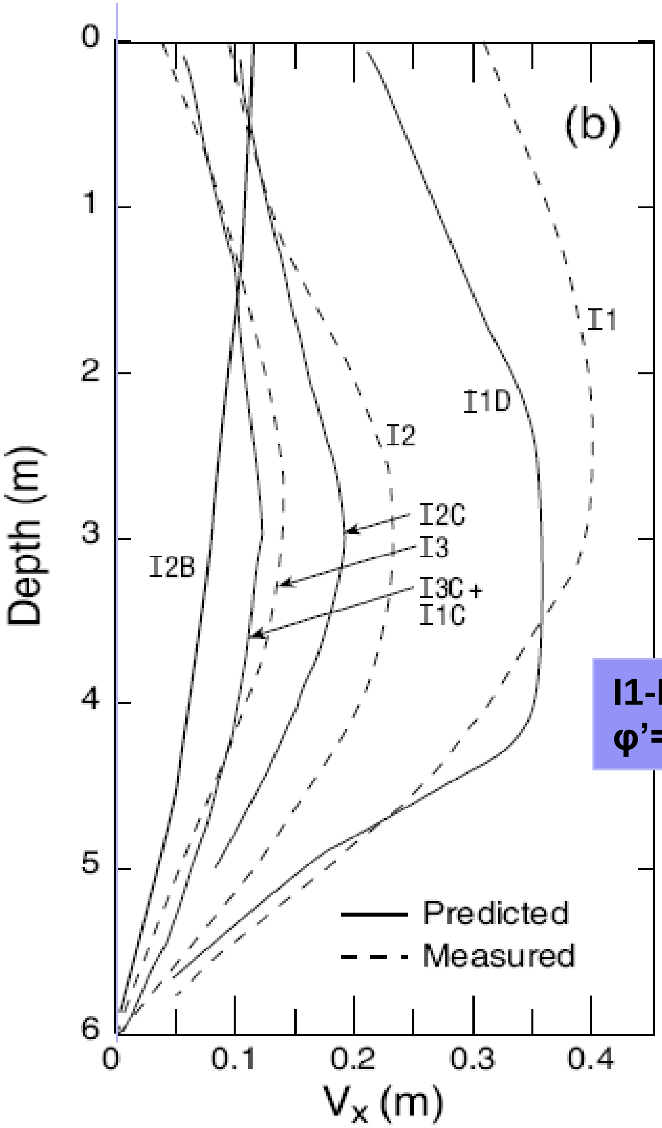


3.3. FEM Predictions A, B, C, D (or C-) (Lambe) for test embankment.

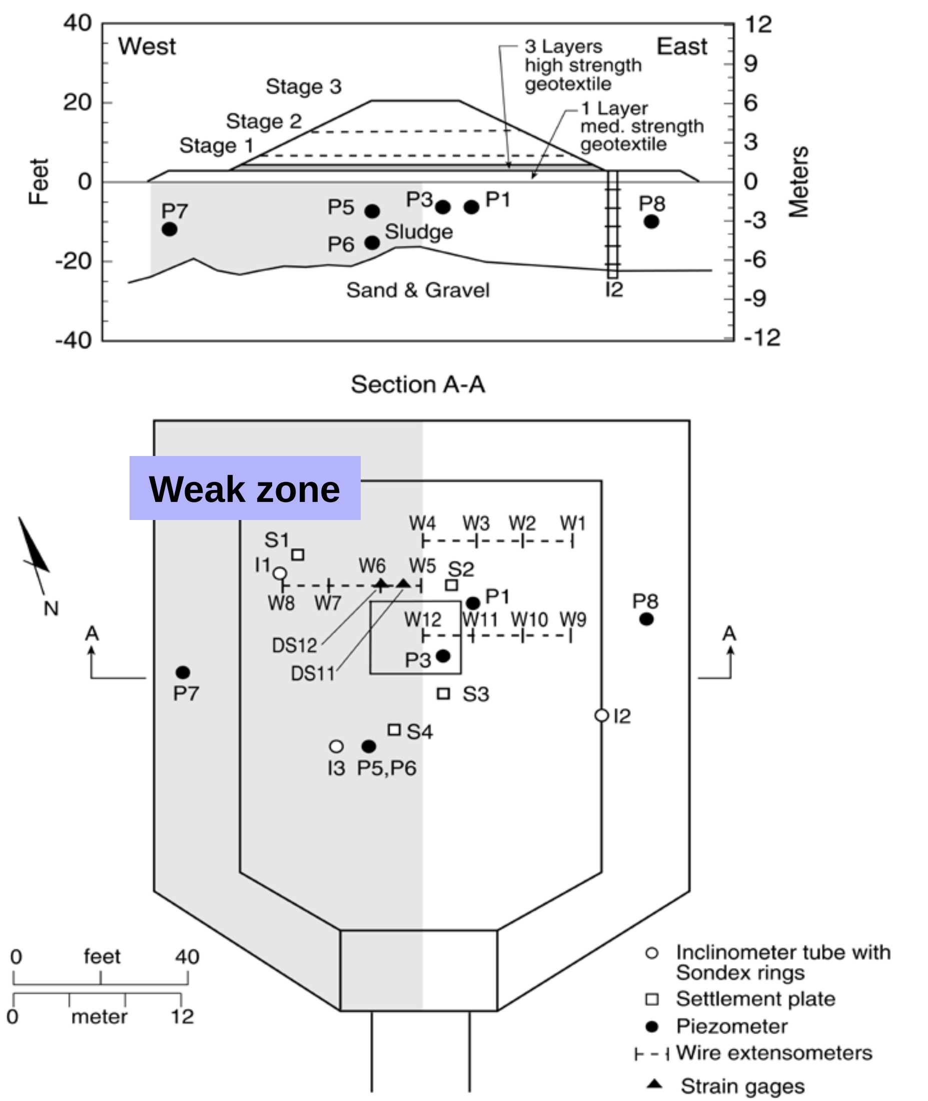
Predictions ≈ "if necessary, modify the design"

A : before measurements,
measured properties (prior)
B: during measurements
measured properties (prior)
actual construction schedule
C: after measurements,
updated properties (posterior)

How good are updated properties?
improved except I1 → Type D

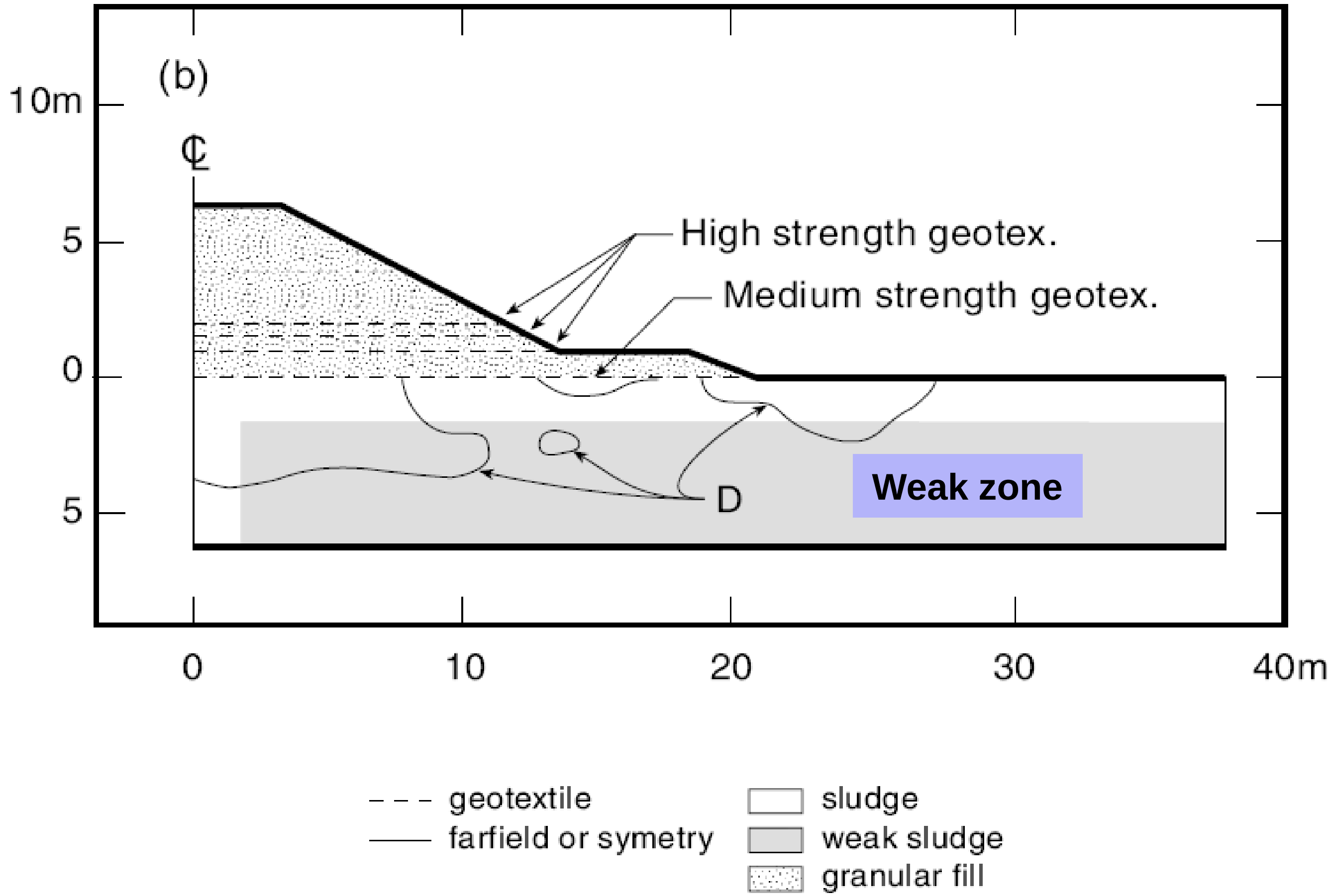


I1-D:
φ'=38˚



West
East
Stage 3
Stage 2
Stage 1
3 Layers high strength geotextile
1 Layer med. strength geotextile
Feet
Meters
40
20
0
-20
-40
12
9
6
3
0
-3
-6
-9
-12
P7
P5
P3
P1
P6
P8
Sludge
Sand & Gravel
I2
Section A-A
Weak zone
S1
I1
W8
W7
W6
W5
W4
W3
W2
W1
S2
P1
W12
W11
W10
W9
DS12
DS11
P3
P8
P7
S3
S4
I2
I3
P5,P6
A
A
N
0
feet
40
0
meter
12
Inclinometer tube with Sondex rings
Settlement plate
Piezometer
Wire extensometers
Strain gages

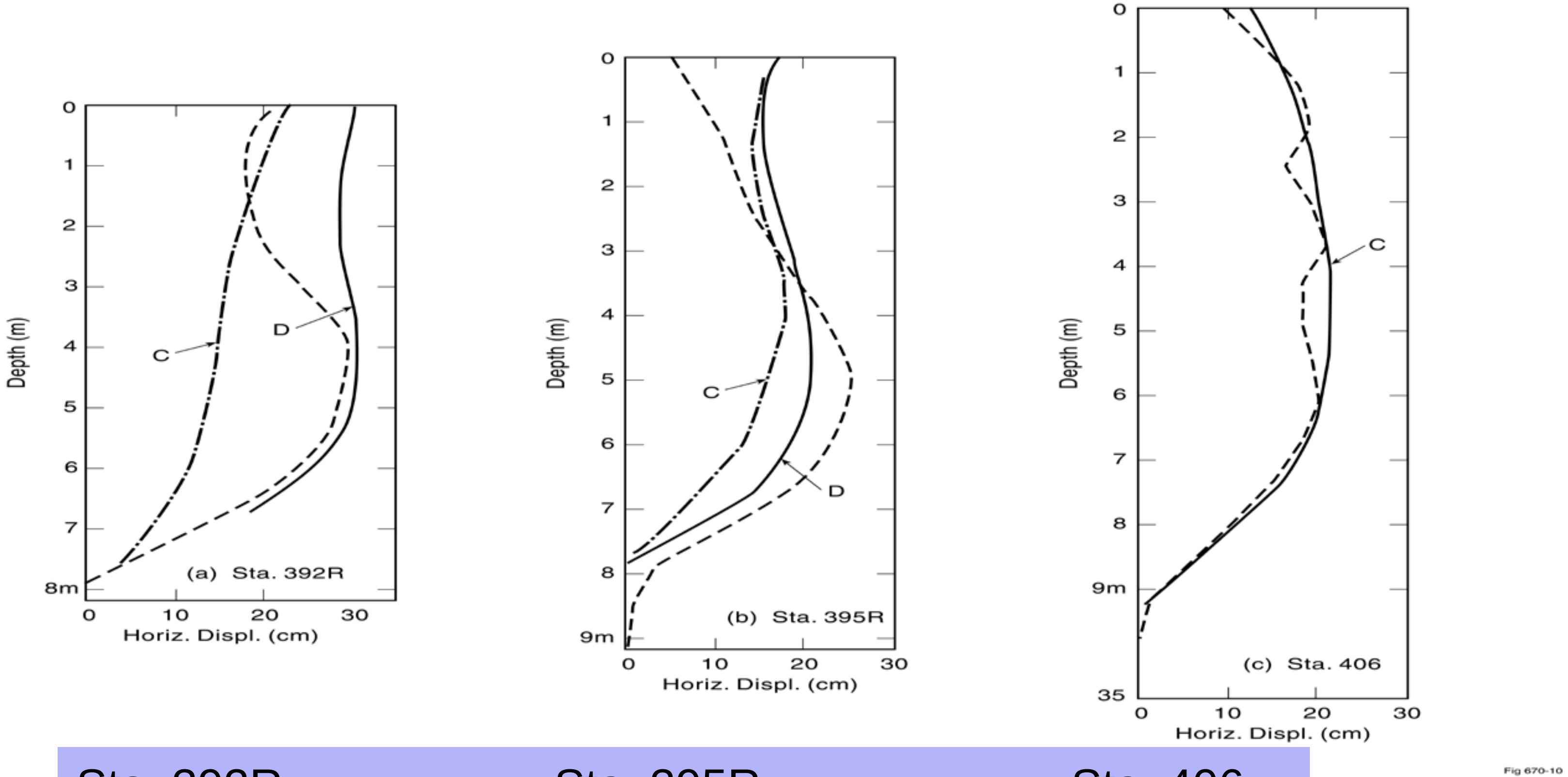
Fig 670-4



I1-D: $\varphi' = 38^\circ$, $\tau = 0.9\ \tau_c$

$F_s \geq 1.1$; failure was not imminent.

3.4. FEM Predictions C(C+) and D for I-270 full-scale embankment
≈ “if necessary modify design”



Sta. 392R	Sta. 395R	Sta. 406
D: φ’ = 36°	D: φ’ = 38 °	C: φ’ = 41°
> 27°(assumed)		

3.4. FEM- Predictions C, and D for I270 embankment.

		Station 392R	395R	401*	402
Meas.					
(vane)	Initial			0.33	0.33
s_u/σ_{zc}'	Consolidated	0.23	0.28	0.33	0.34
φ'	Initial			41°	41°
	Consolidated	34°	37°	41°	42°
Prediction (FEM) φ'		36° (D)	38°(D)		41°(C)

Large deformations at 392R and 395R; failure was not imminent.

Conservative approach (F_s=1.4, φ'=27°) was successful.

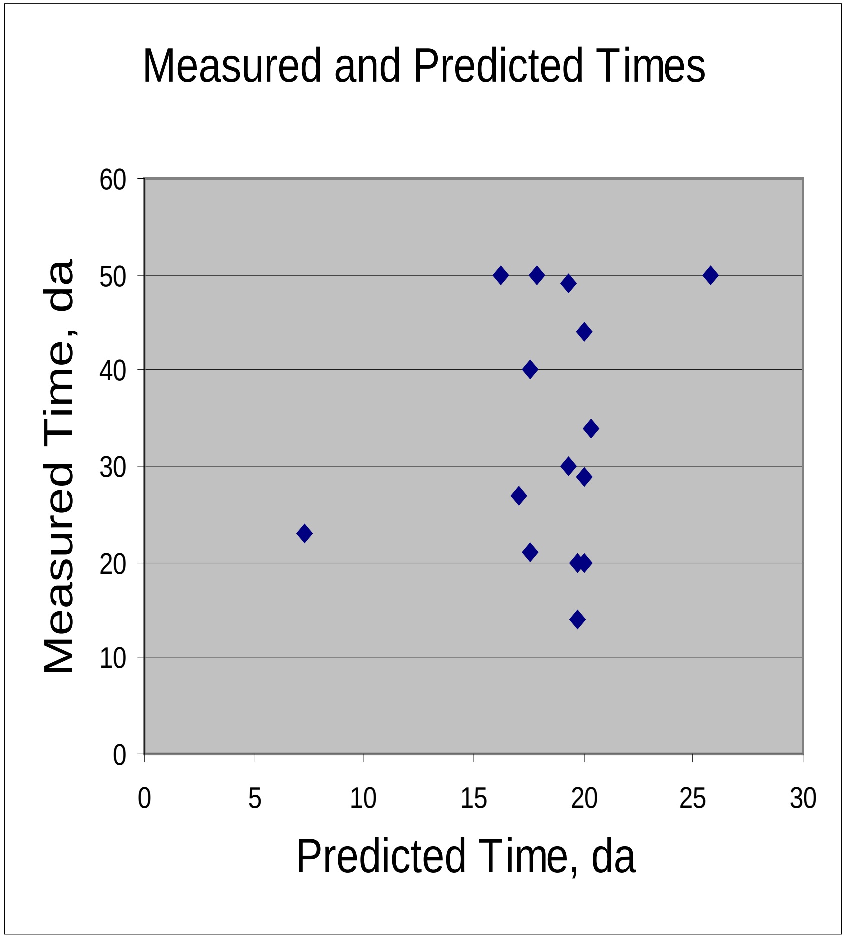
3.5 Applications of Models to Practice

Models were not used in this project. The results from the project showed that the models give reasonable results and can be used on future projects.

Updating can provide revised input parameters.

Models can explain why predicted performance differs from observed performance (eg. Sta. 392).

4. Simple Models. Radial Consolidation (Barron, Hansbo)



Model error (systematic)

m(N) =1.86 (1st), 1.70 (2nd)

Errors: analytical model, material model- m_k, m_s, c_h, etc

Random variations

Ω(N) = 0.30 (1st) , 0.30 (2nd)
Errors: c_h, c_z, H, etc

Model error is large (c_h)

Sources of Error - Rate of Consolidation $t_{0.5}$.

Variable	COV
c_h	0.11
c_z	0
H	0.10
measurement error	0.13
Combined random error	0.20
m_k	0.07
m_z	0.06
c_h	0.50
analysis	0.19
Combined systematic error	0.54

Material model error is large (uncertainty about continuity of sand partings).
Update c_h. c_h”= 0.62 x c_h’= 0.62 (0.25 lab c_h) = 0.16 lab c_h

Update c_r with measured pore pressure from test embankment

$P''[x_j|z_i] = P\,[z_i|x_j]\,P'\,[x_j]\ /\ \Sigma\ (z_i|x_j)\,P'[x_j]$ [1]

$P'\,[x_j] = \text{Prior}\,(m_x', \sigma_x', \Omega_x' = \sigma_x'/\,m_x'),$

$m_x'\ 1.8\ \text{x}10^{-2},\ \sigma_x' = 0.67\text{x}10^{-2}, \text{cm}^2/\text{sec}$

$P''[x_j|z_i] = \text{Posterior} = \text{updated property}\ (m_x'', \sigma_x'')$

$m_x'' = [m_x'(\sigma^2/n) + \bar{x}\sigma_x'^2]/[\sigma^2/n + \sigma_x'^2]$ [10a]

$= 1.38\ \text{x}10^{-2}$

$\sigma_x'' = \{\,[\sigma_x'^2\,(\sigma^2/n)]\ /[\sigma_x'^2 + (\sigma^2/n)]\}^{1/2}$ [10b]

$= \sigma_x'' = 0.27\text{x}\ 10^{-2}, \text{cm}^2/\text{sec}$

σ, n = c_r from measured $t_{0.5}$

Predicted $t_{0.5}$ for I-670 was too small

Update c_r with measured pore pressure from I-670 embankment, first stage

$P'[x_j] = \text{Prior}(m_x', \sigma_x', \Omega_x' = \sigma_x'/m_x')$,

$P''[x_j|z_i] = P[z_i|x_j]\,P'[x_j] \,/\, \Sigma\,(z_i|x_j)\,P'[x_j]$ [1]

m_x' 1.8×10^{-2}, $\sigma_x' = 0.67 \times 10^{-2}, cm^2/sec$

$P''[x_j|z_i]$ = Posterior = updated property (m_x'', σ_x'')

$m_x'' = [m_x'(\sigma^2/n) + \bar{x}\sigma_x'^2]/[\sigma^2/n + \sigma_x'^2]$ [10a]

$= 0.62 \times 10^{-2}$

$\sigma_x'' = \{[\sigma_x'^2(\sigma^2/n)]/[\sigma_x'^2 + (\sigma^2/n)]\}^{1/2}$ [10b]

$= \sigma_x'' = 0.08 \times 10^{-2}, cm^2/sec$

Predicted $t_{0.5}$ for I-670, second stage was good.

Cr from test embankment over a small area was not representative of entire site.

5. Summary and Conclusions

5.1. “Advanced” and simple models can be useful to observational method

5.2.Sensitivity analysis can identify the input parameters that have the largest influence on a particular performance mode.

5.3. There may be several sources of error. Models can be used to evaluate their significance. Uncertainty about soil properties may not be the major source of error.

5.4. Models cannot account for unknown site conditions (no data).

5.5. Errors in material models can be large. In radial consolidation, K_h in-situ is difficult to evaluate. It depends on the nature of the stratification and the size of the flow domain.

“A natural soil is never homogeneous. Its properties change from point to point” (Terzaghi, 1936)

Acknowledgements: S.M. Gale and B.C. Christopher

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