46th Terzaghi Lecture

GEOSYNTHETIC REINFORCED SOIL: FROM THE EXPERIMENTAL TO THE FAMILIAR

R. D. Holtz, PhD, PE, D.GE
Professor Emeritus
University of Washington
Seattle, Washington USA

Kjellman paper drain installation,
Halmsjön, Sweden, 1946 or 47?

Two previous Terzaghi Lectures on Geosynthetics:

R. M. Koerner
(1996)

Geomembranes: properties and behavior

J.-P. Giroud
(2008)

Geotextile and granular filters

My two geosynthetics heroes…

Geosynthetics in Civil Engineering…

- From the experimental to accepted practice
  - Waste containment
  - Canal and pond liners
  - Drainage and erosion control
  - Construction
  - Transportation
  - Geotechnical

- “Geosynthetics - THE most important development in Civil Engineering practice in the 20th Century.”

  (J.-P. Giroud, 2008 Terzaghi Lecture)

- The first new civil engineering material in more than 100 yr…
- Other examples…

My plan:

1. Introduction
2. **Reinforced soil—a historical perspective**
3. Advantages and basic behavior of GRS
4. Design
5. Properties
6. Things we need still need to know and do—technical and professional issues
7. Successful examples
8. Final remarks

Some examples from nature and the ancients:

- Birds’ nests
- Beaver dams
- Adobe bricks

➢ Analogy with reinforced concrete?

Ziggurat of Aquar-Quf, near Bagdad

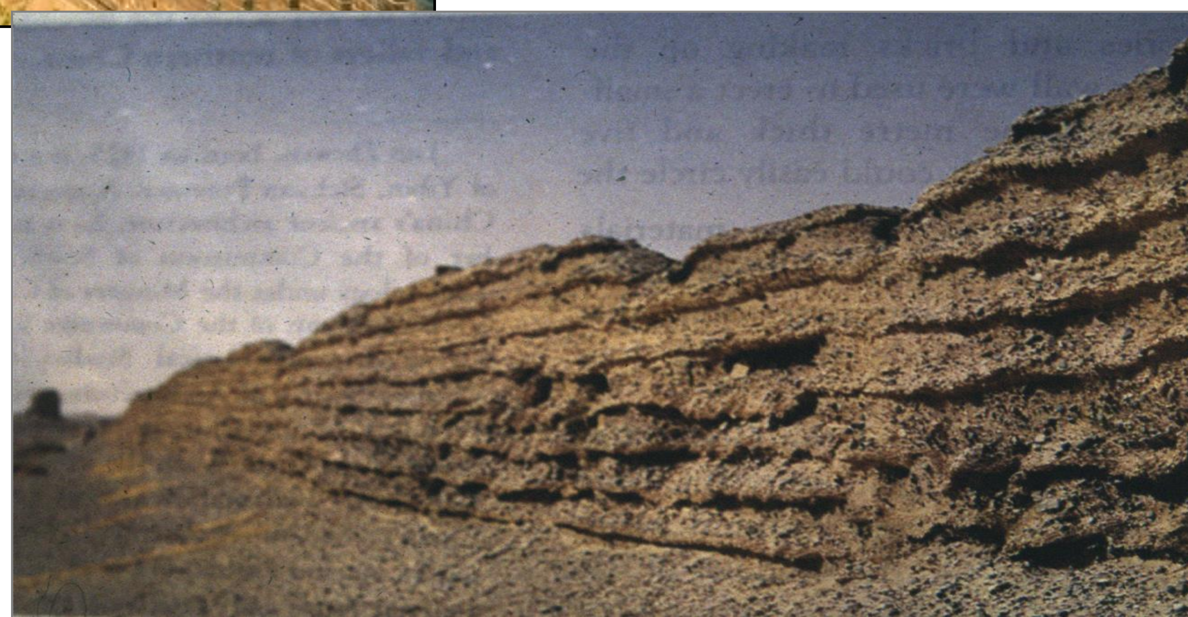
~ 1500 BC

Now 45 m high (originally ~ 87 m)

Dr. J.-P. Giroud at Aquar-Quf circa 1980

Great Wall of China

Western wall
(In the Gobi Desert near Dunhuang, China)



How I got into soil reinforcing and geosynthetics: Experience in Sweden, 1970-1975

Oleg Wager

(1915-1992)

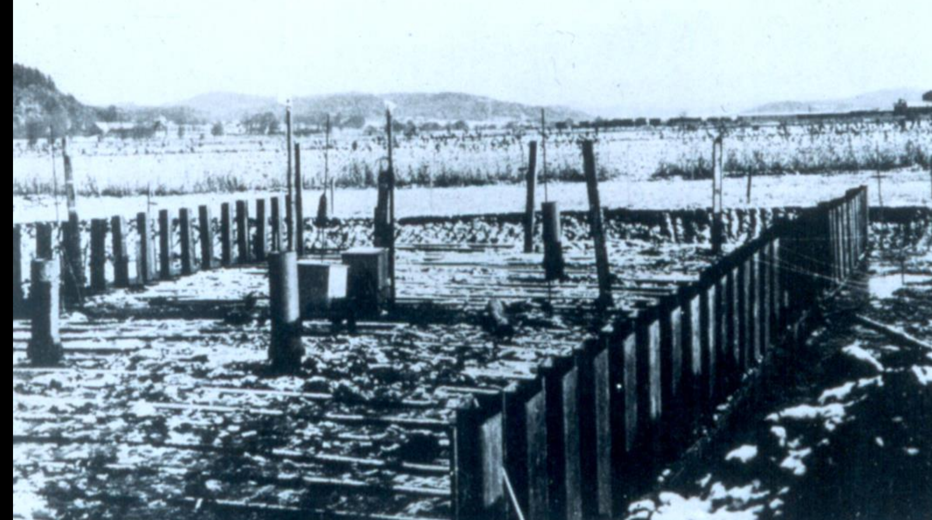
The inventor

Bengt Broms

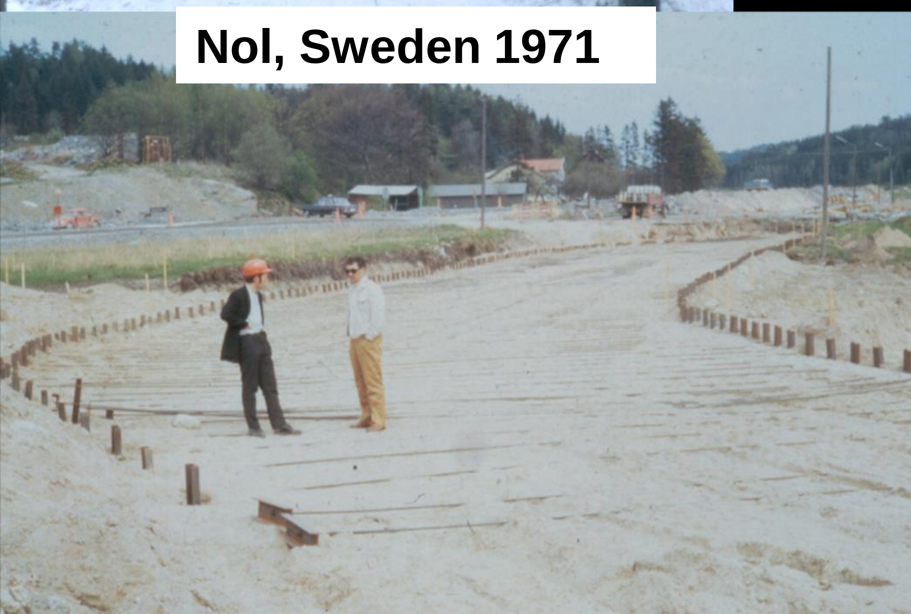
(1925 -   )

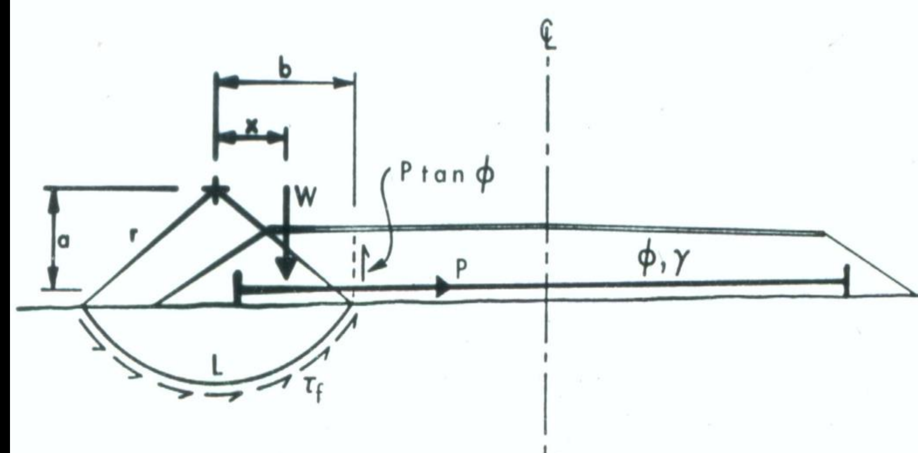
Boss & collaborator

Alvängen, Sweden 1966



Nol, Sweden 1971

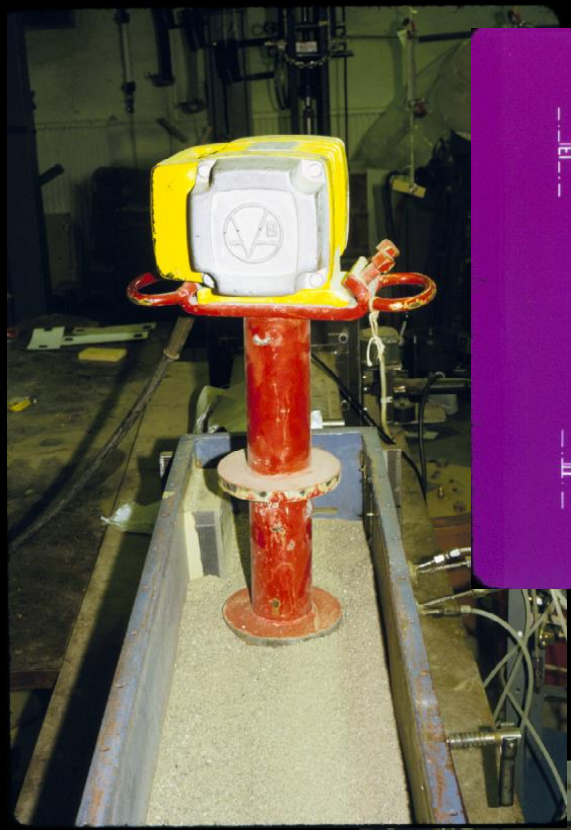


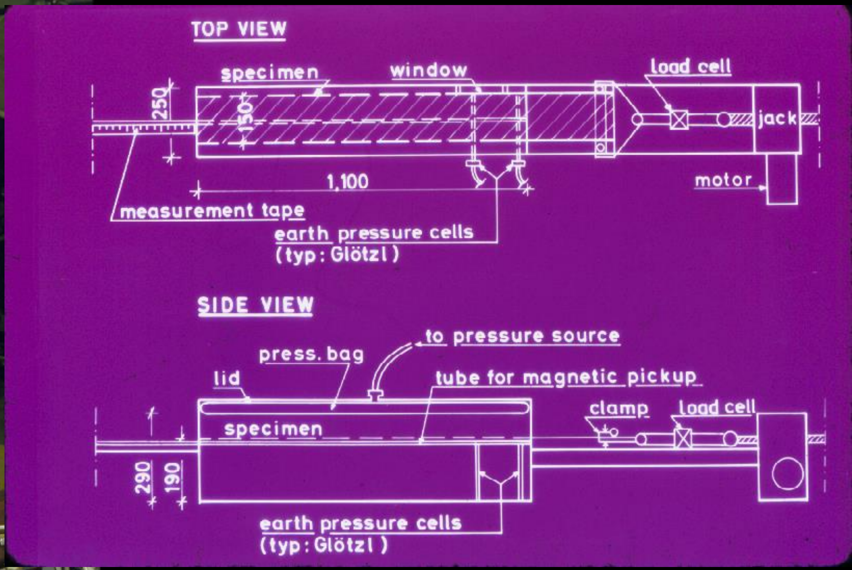


$$FS = \frac{\tau_f L r + Pa + P(\tan\phi)\, b}{Wx} \geq 1.5$$

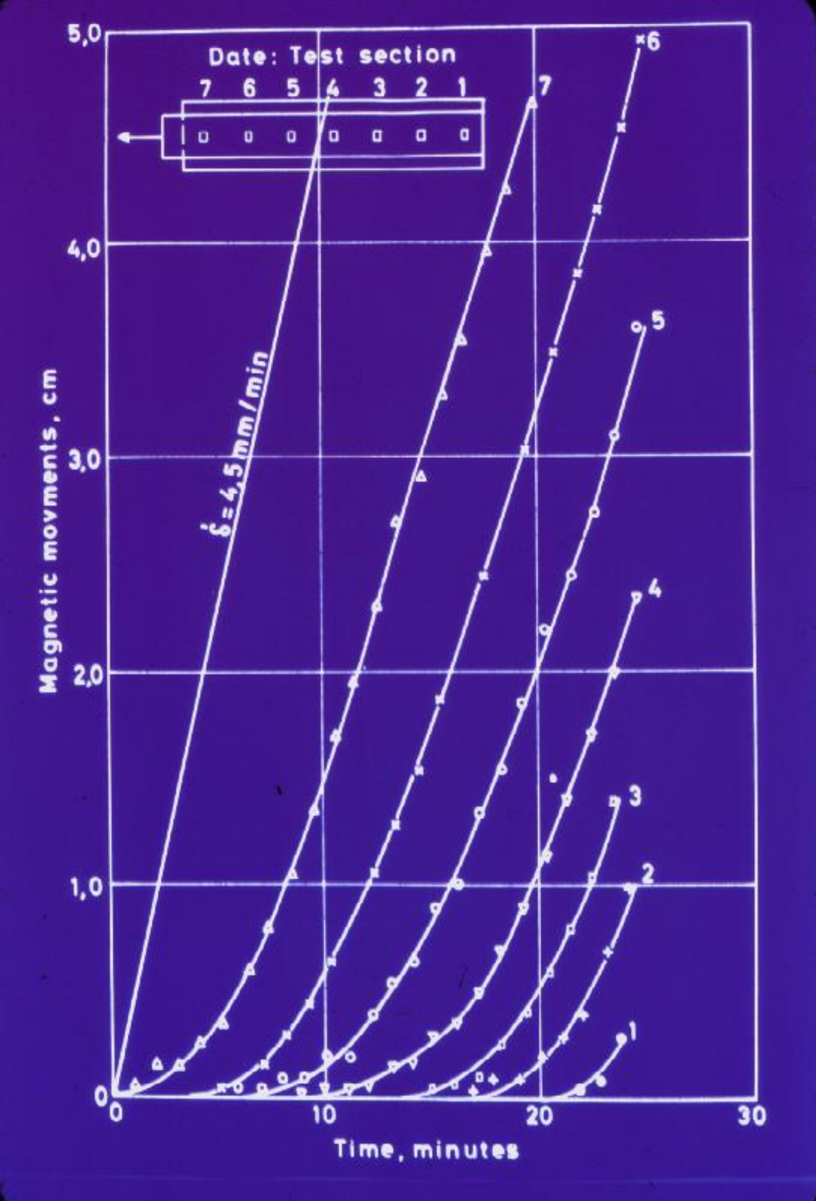
Nol, Sweden, 1971

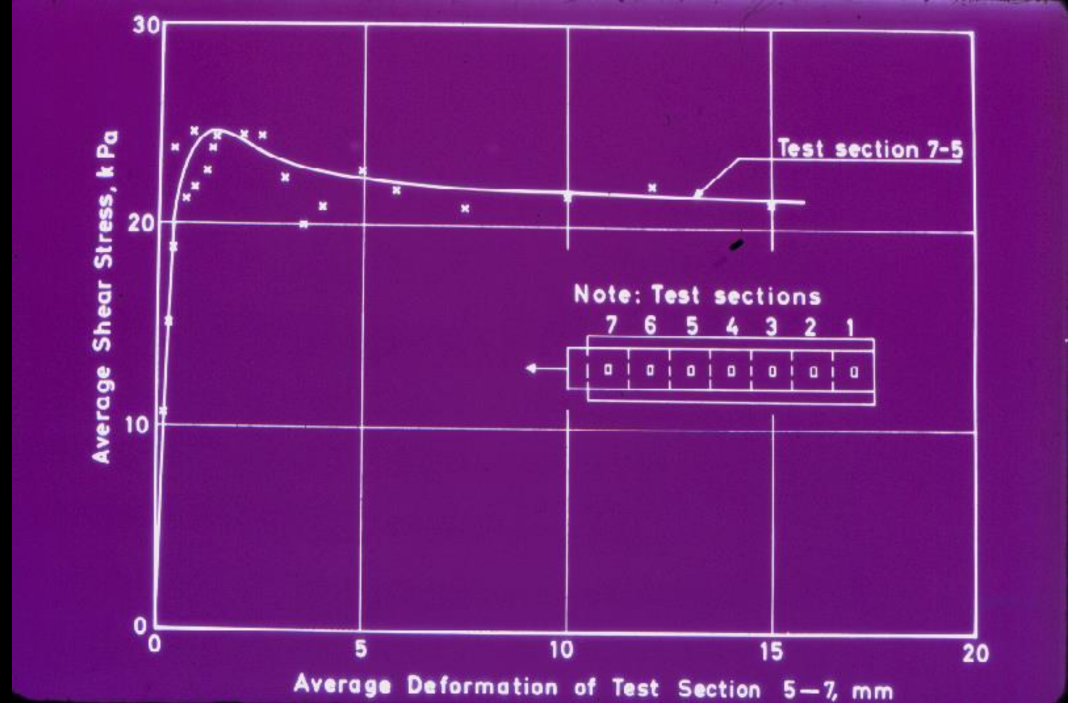
(Holtz & Massarsch, 1976; 1993
Harney & Holtz, 2006)

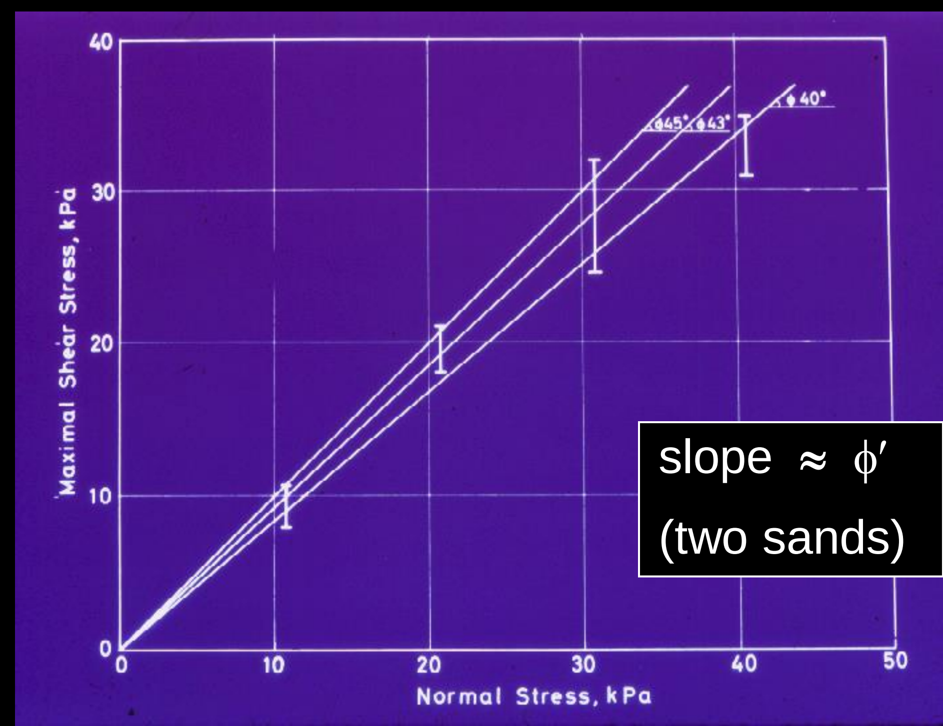




SGI, 1972-1973



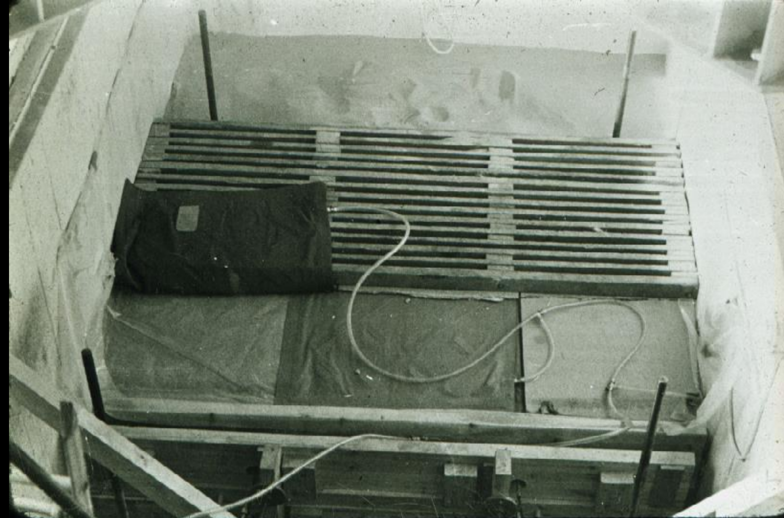


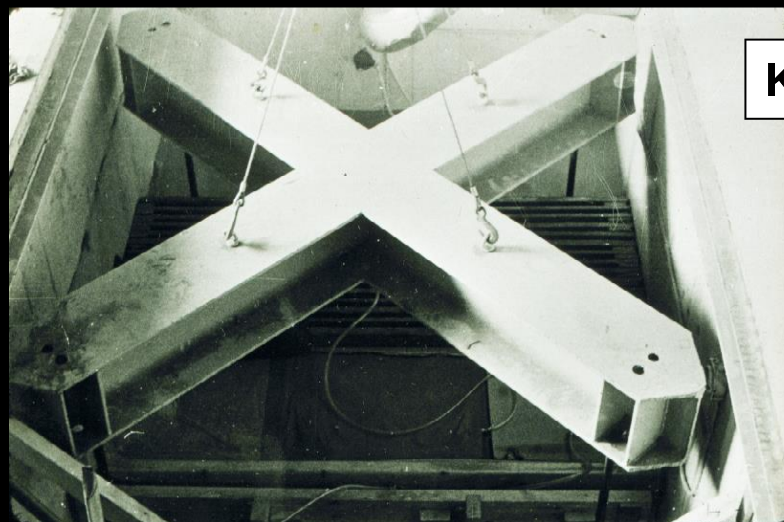


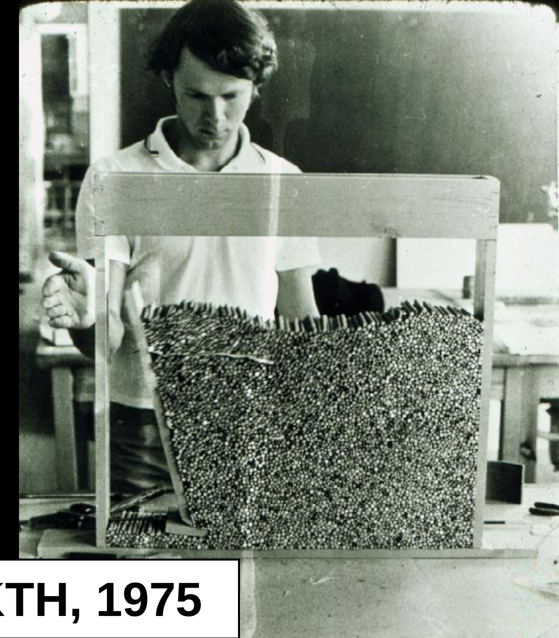
slope ≈ ϕ′
(two sands)

Holtz and Broms (1977)
***Conf on Fabrics…* Paris**

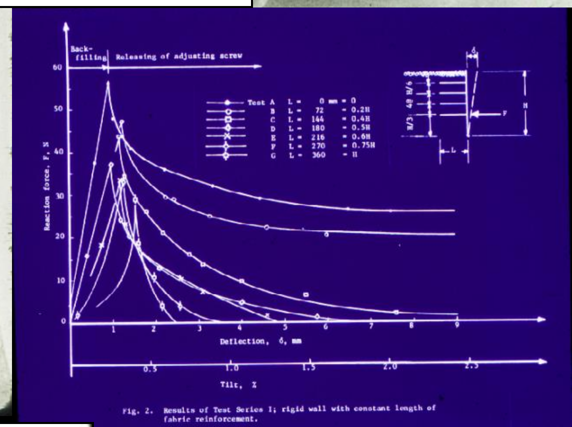
SGI, 1974

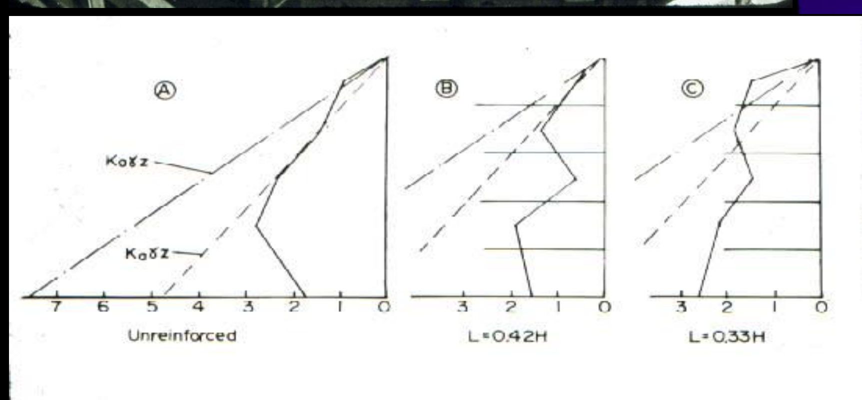






KTH, 1975





Holtz & Broms (1978) ***Symp. on Soil Reinf.,*** **Sydney**

Supplément aux

ANNALES DE L'INSTITUT TECHNIQUE DU BATIMENT ET DES TRAVAUX PUBLICS

DIX-NEUVIÈME ANNÉE ■ JUILLET-AOUT 1966 ■ N° 223-224

Série : MATÉRIAUX (30)

CENTRE D'ÉTUDES SUPÉRIEURES   SÉANCE DU 14 DÉCEMBRE 1965
SOUS LA PRÉSIDENCE DE M. **A. CAQUOT**, Membre de l'Institut.

LA TERRE ARMÉE

(Un matériau nouveau pour Travaux Publics)

par **H. VIDAL**,
Ingénieur de l'École Polytechnique, Ingénieur Civil E.N.P.C.
Architecte D.P.L.G.,

INSTITUT TECHNIQUE DU BATIMENT ET DES TRAVAUX PUBLICS

1966

Henri Vidal (1924 - 2008)

Fig. 4 - Disposition des grains et des armatures

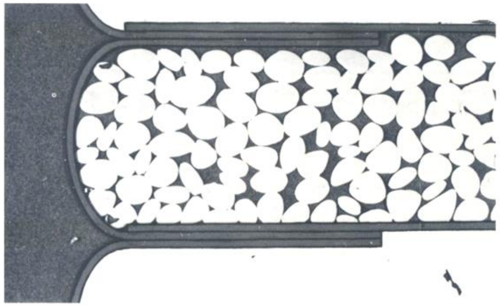


Fig. 5 - Schéma d'une peau métallique

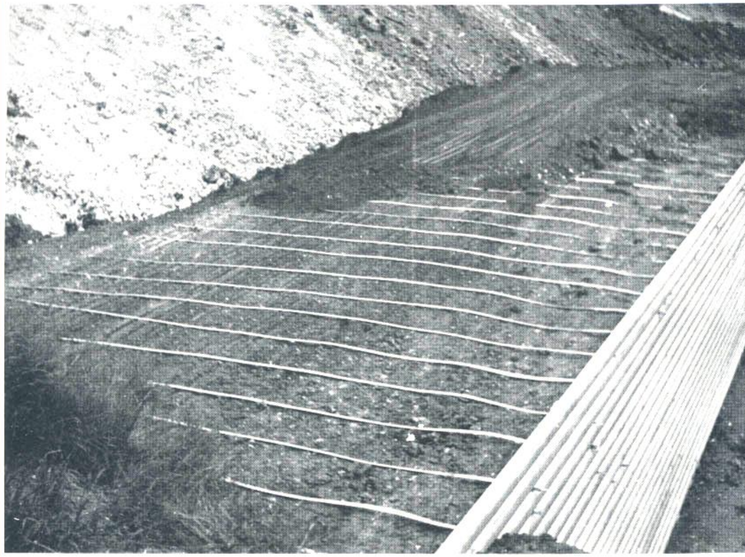
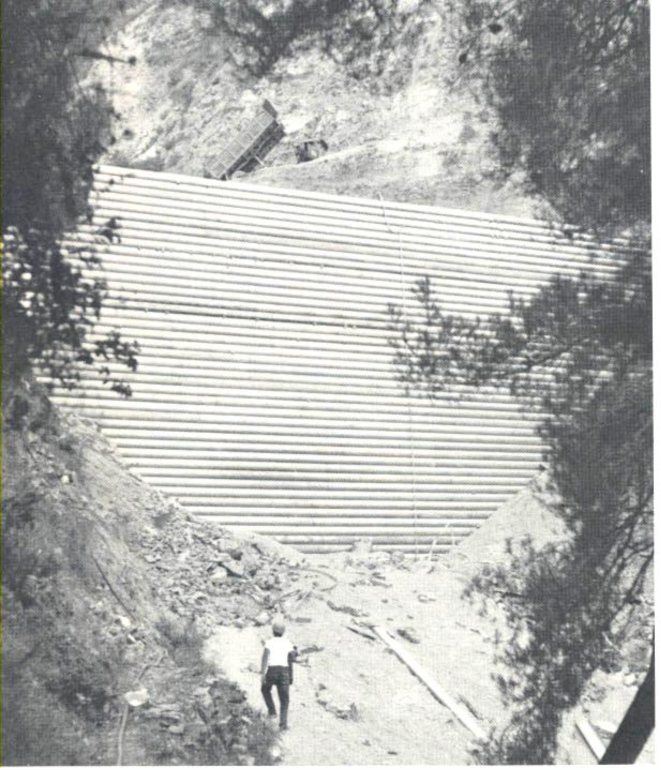
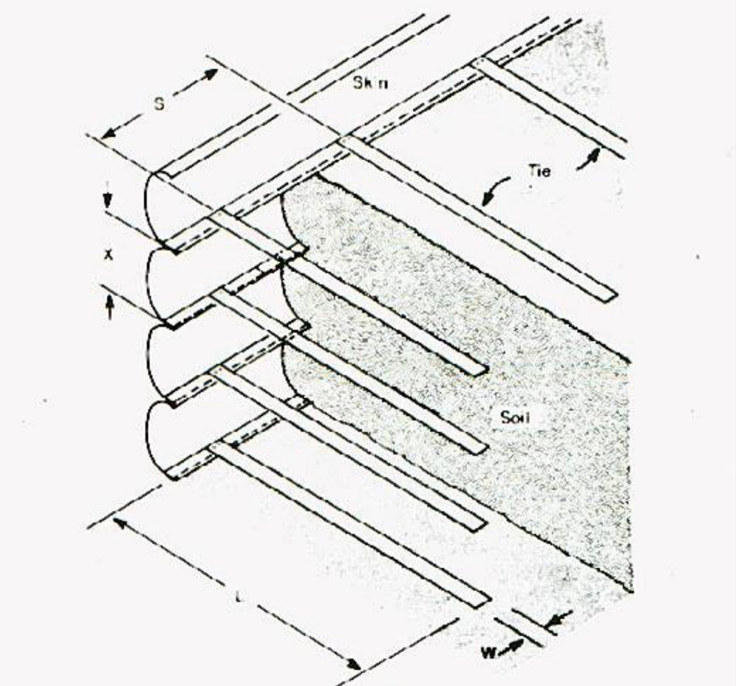
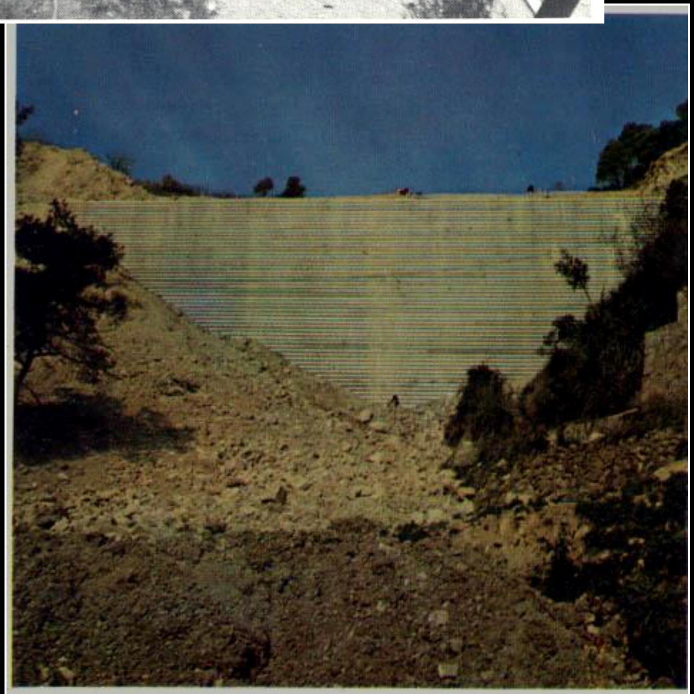


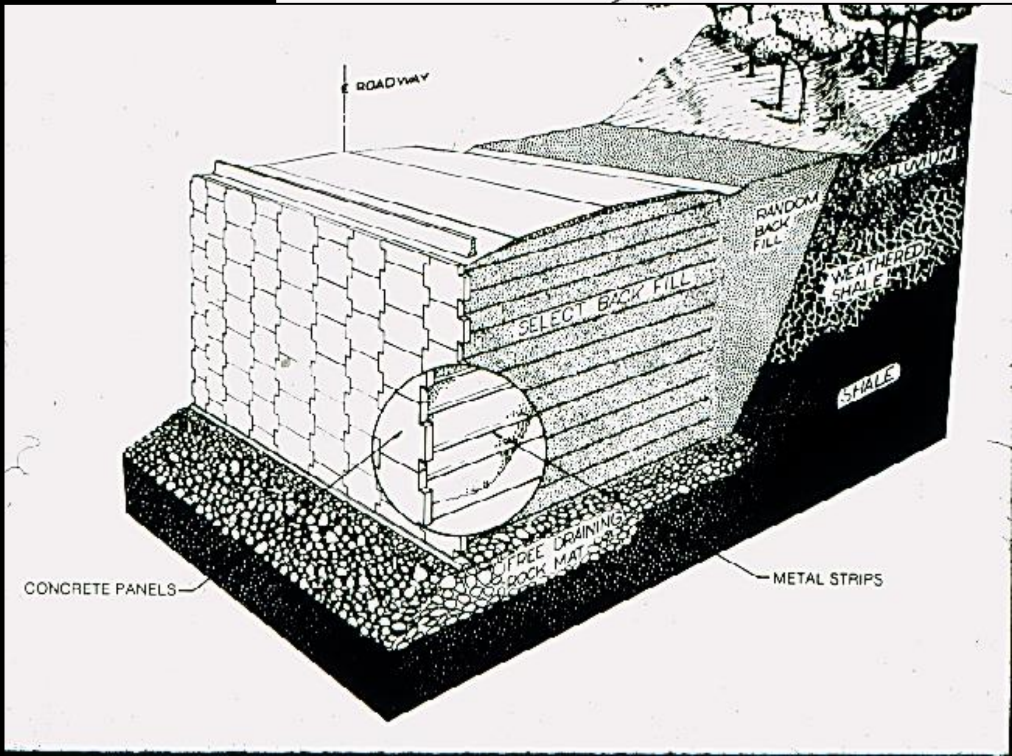
Fig. 1 - Construction d'un mur en terre armée

Autoroute A53, Nice-Menton, France (1967-8)





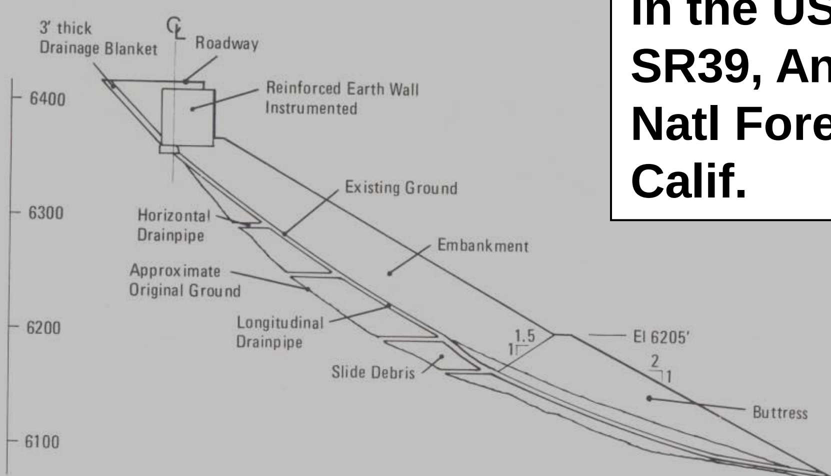




Terre Armée, near Paris, 1976

CALIFORNIA ROUTE 39 - AVALANCHE CLOSING THE ROADWAY

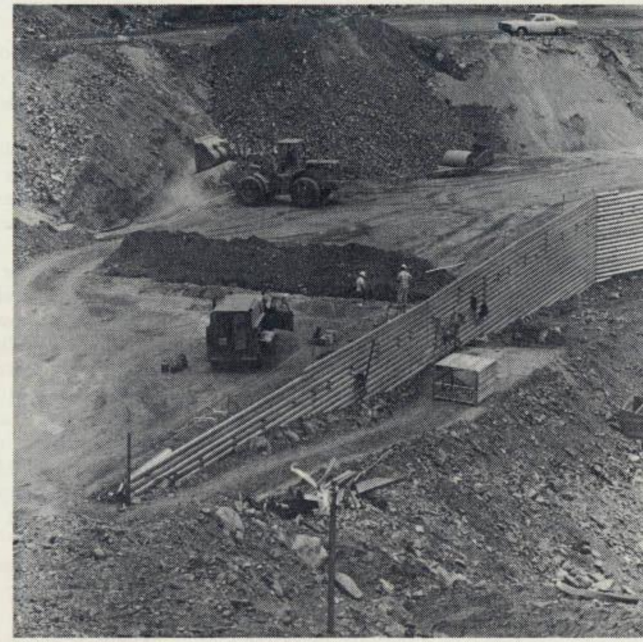
FIGURE 2

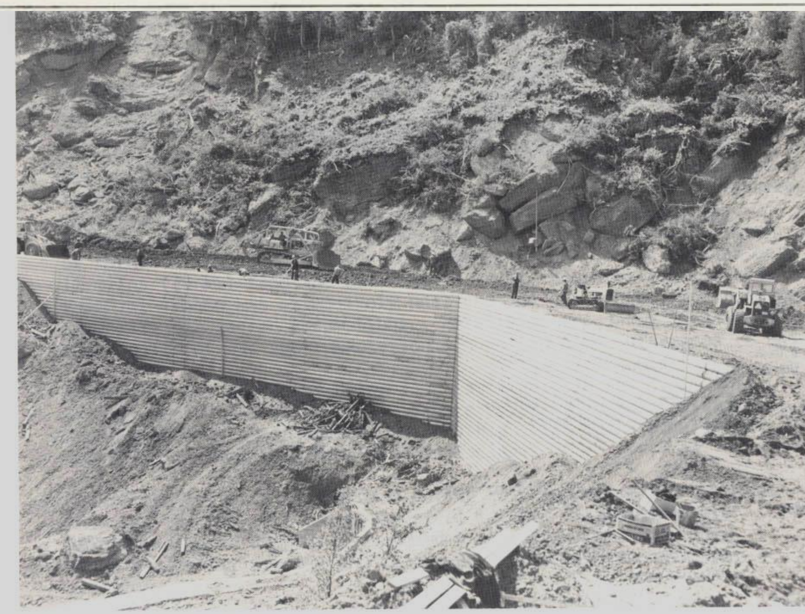


CALIFORNIA ROUTE 39 - CROSS SECTION OF
REMEDIAL SCHEME STATION 551+25

First RECo wall in the US, 1972: SR39, Angles Natl Forest, S. Calif.

A view of the "reinforced earth" retaining wall used for this first-of-its-kind construction technique on the North American continent.





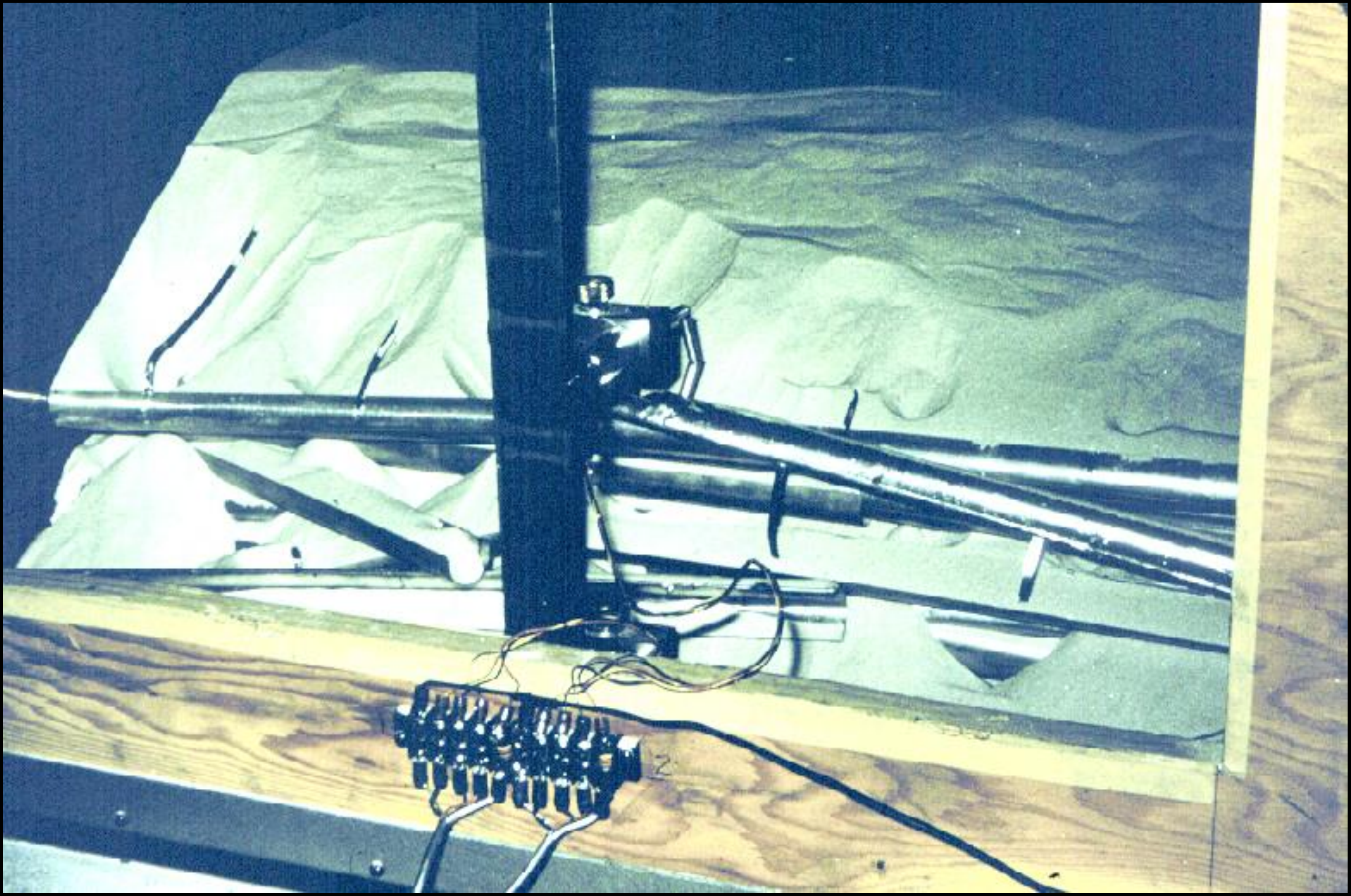
CALIFORNIA ROUTE 39 - REINFORCED EARTH WALL NEARING COMPLETION

FIGURE 4

Ken Lee's work at UCLA

--Two NSF projects, 1970-1975

(1931-1978)



I-24, Tennessee

… and walls with geosynthetics in 1971-77

1. Bidim wall in France, 1971-1972, reinforced with a polyester needlepunched nonwoven, 300 g/m²

Puig & Blivet (1973)
Bull. liaison Labo. Cent. P. et Ch.

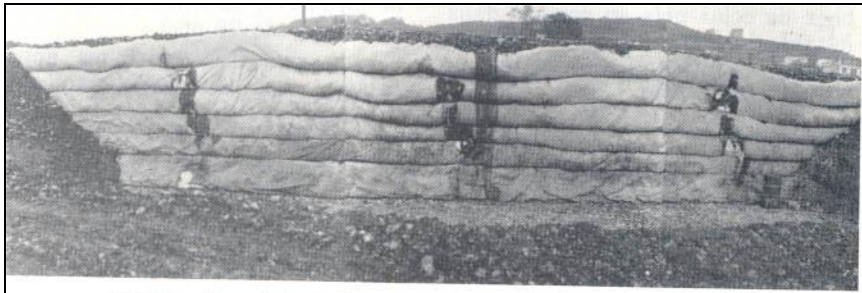


Fig. 15 - Vue générale du mur après le déblaiement (20 avril 71).

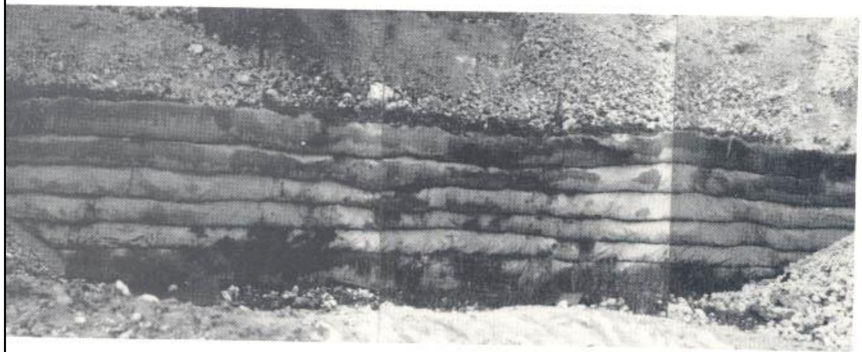


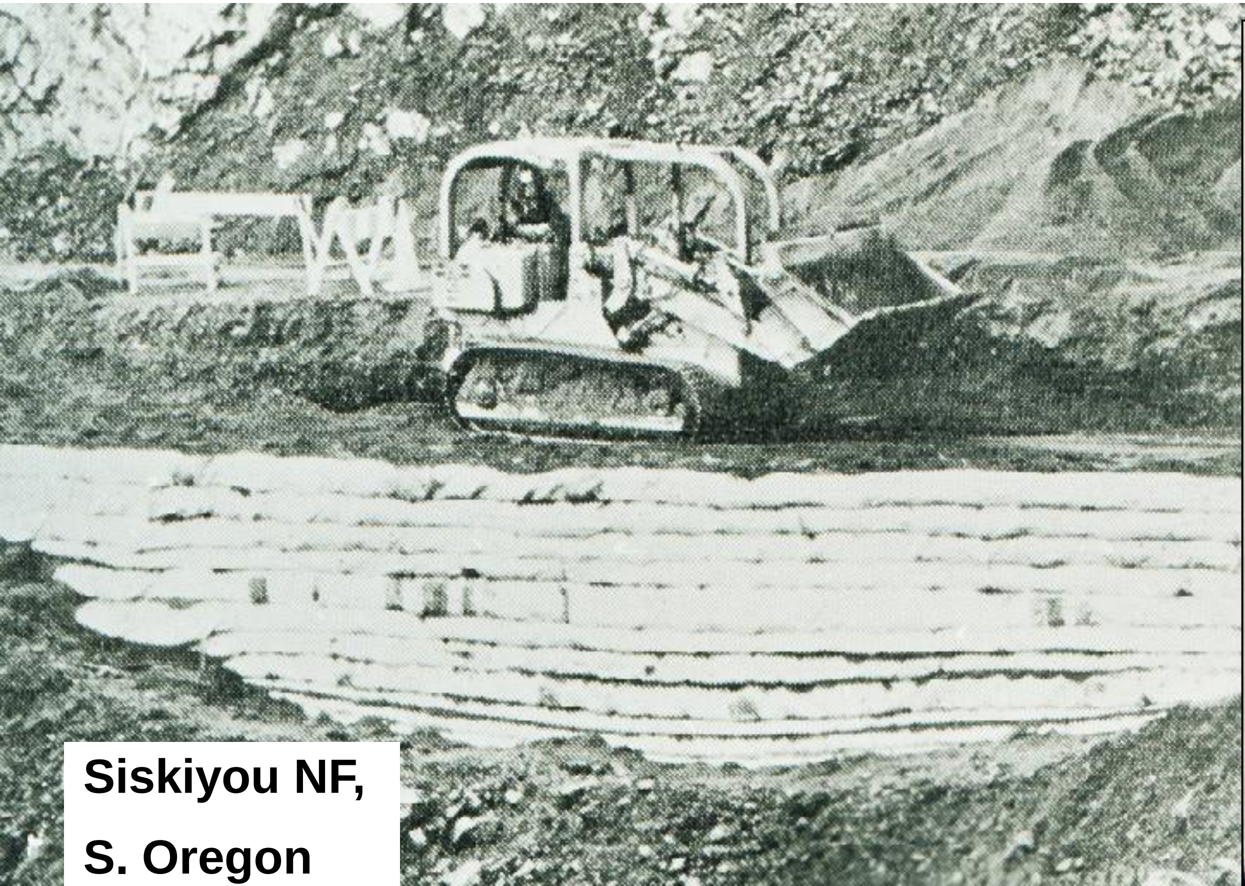
Fig. 16 - Vue après le chargement de la partie supérieure (8 novembre 71).

2. USFS walls in Oregon and Washington, 1972-1975

USFS: J. Steward, J. Mohney, B. Vandre

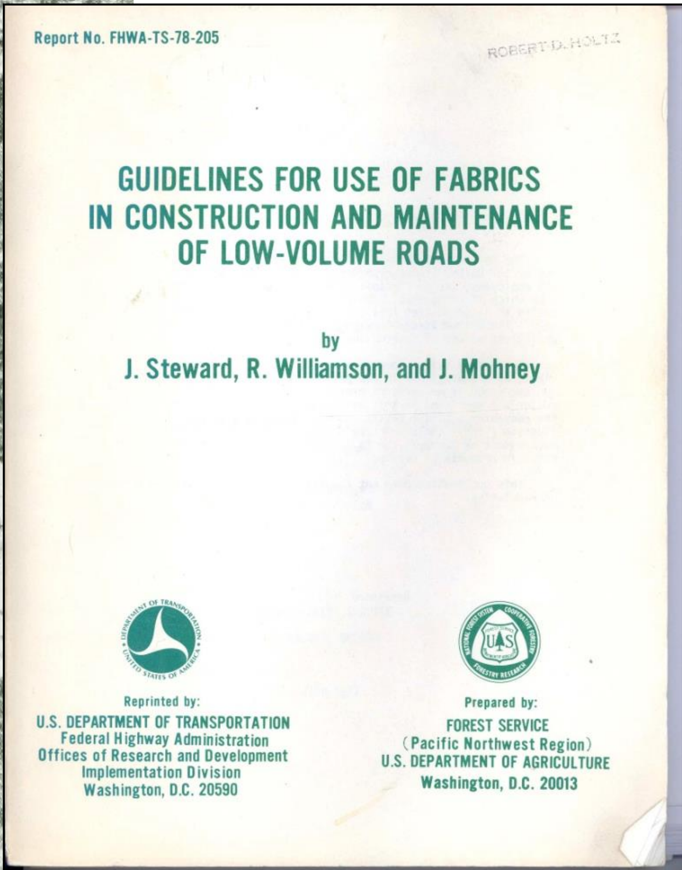
OSU: Prof. J. R. Bell

Dick Bell



Siskiyou NF,

S. Oregon



Report No. FHWA-TS-78-205

ROBERT D. HOLTZ

GUIDELINES FOR USE OF FABRICS
IN CONSTRUCTION AND MAINTENANCE
OF LOW-VOLUME ROADS

by
J. Steward, R. Williamson, and J. Mohney

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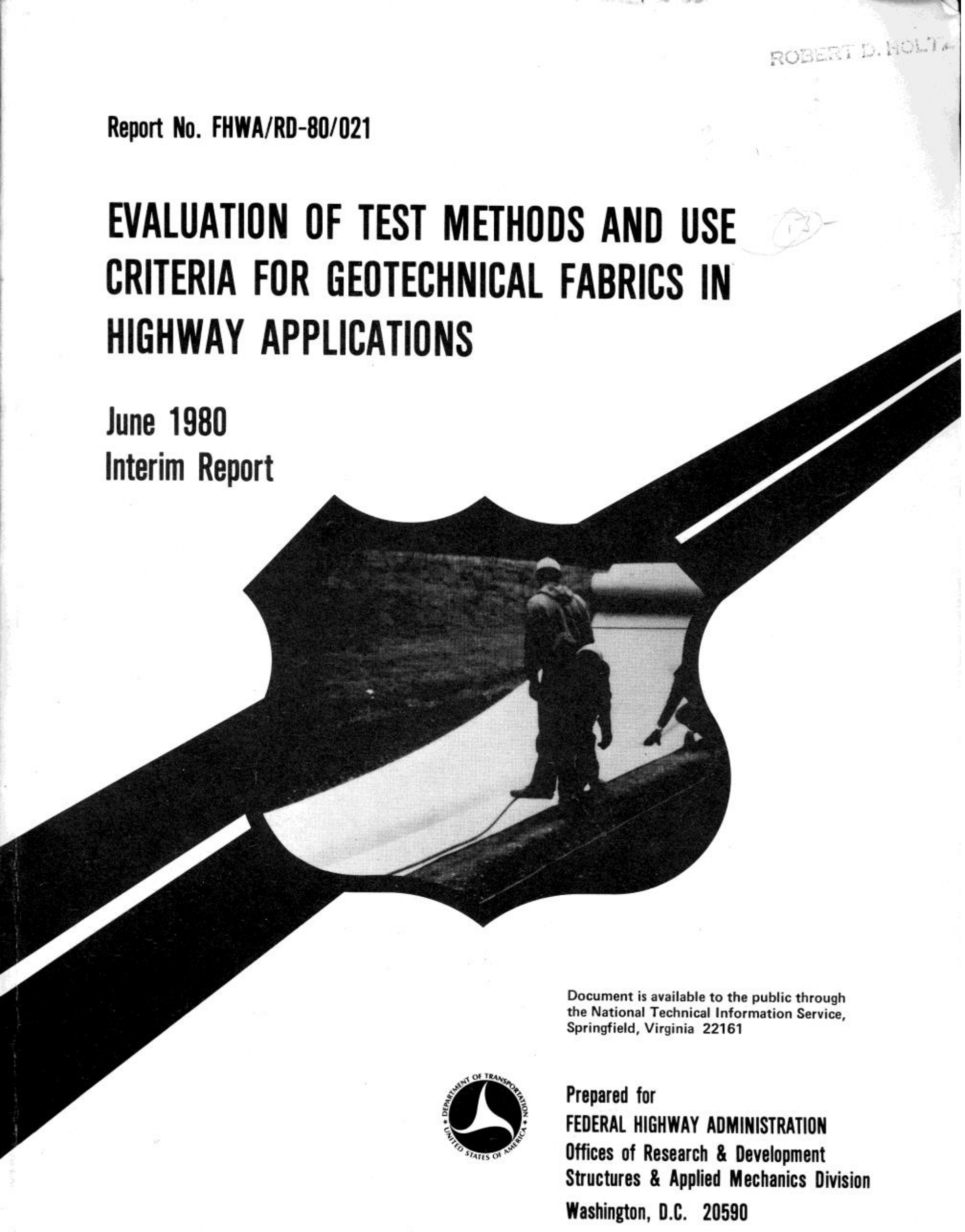
U.S. DEPARTMENT OF AGRICULTURE
Washington, D.C. 20013

Siskiyou NF,
S. Oregon

Olympic NF, Washington

Siskiyou NF, S. Oregon



ROBERT D. HOLTZ

Report No. FHWA/RD-80/021

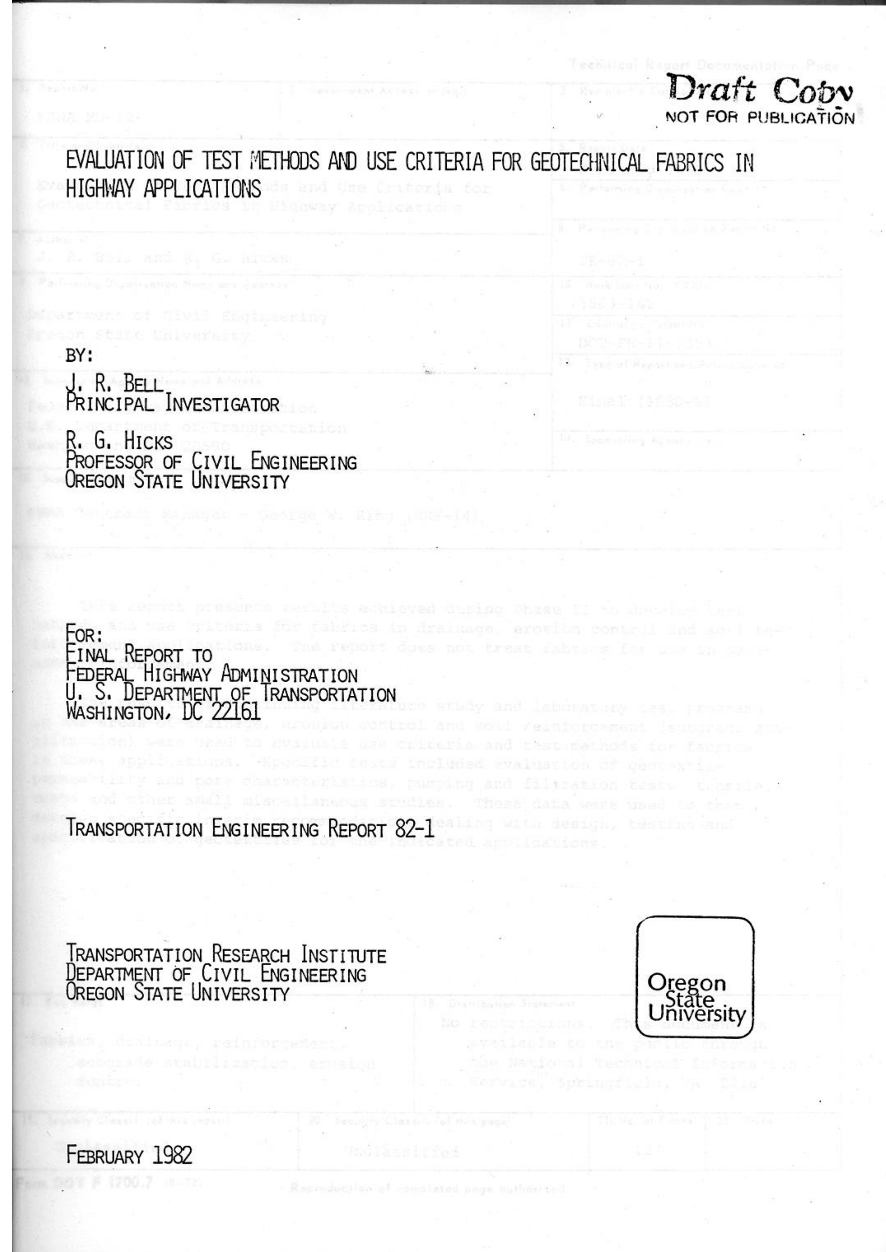
EVALUATION OF TEST METHODS AND USE CRITERIA FOR GEOTECHNICAL FABRICS IN HIGHWAY APPLICATIONS

June 1980
Interim Report

Document is available to the public through the National Technical Information Service, Springfield, Virginia 22161

Prepared for
FEDERAL HIGHWAY ADMINISTRATION
Offices of Research & Development
Structures & Applied Mechanics Division
Washington, D.C. 20590

Interim Report: FHWA/RD-80/021 (1980)



Draft Copy
NOT FOR PUBLICATION

EVALUATION OF TEST METHODS AND USE CRITERIA FOR GEOTECHNICAL FABRICS IN HIGHWAY APPLICATIONS

BY:
J. R. BELL
PRINCIPAL INVESTIGATOR
R. G. HICKS
PROFESSOR OF CIVIL ENGINEERING
OREGON STATE UNIVERSITY

FOR:
FINAL REPORT TO
FEDERAL HIGHWAY ADMINISTRATION
U. S. DEPARTMENT OF TRANSPORTATION
WASHINGTON, DC 22161

TRANSPORTATION ENGINEERING REPORT 82-1

TRANSPORTATION RESEARCH INSTITUTE
DEPARTMENT OF CIVIL ENGINEERING
OREGON STATE UNIVERSITY

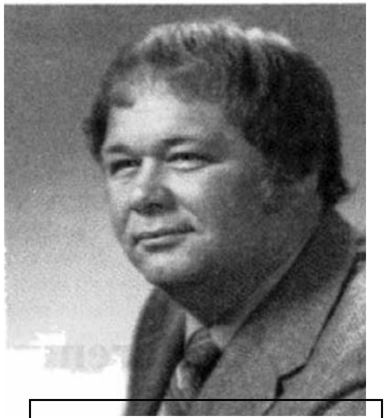
Oregon State University

FEBRUARY 1982

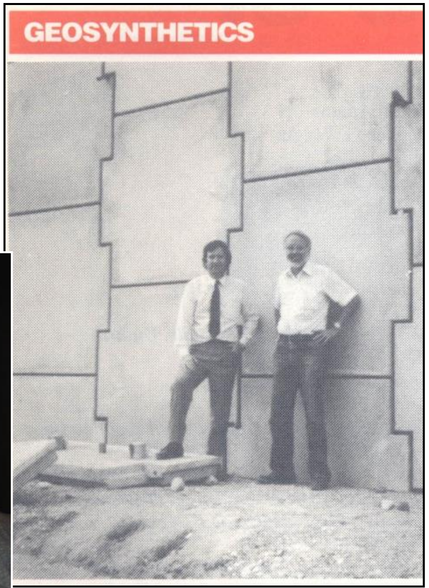
Draft final report, 1982 (never published by FHWA)

FHWA geosynthetics courses (~1978 -   )

- Started by Al Haliburton, Okla St. U.
- Second contract BRC & RDH
- ~150 courses in most states, etc
- Significantly increased use and improved state highway specs and practice

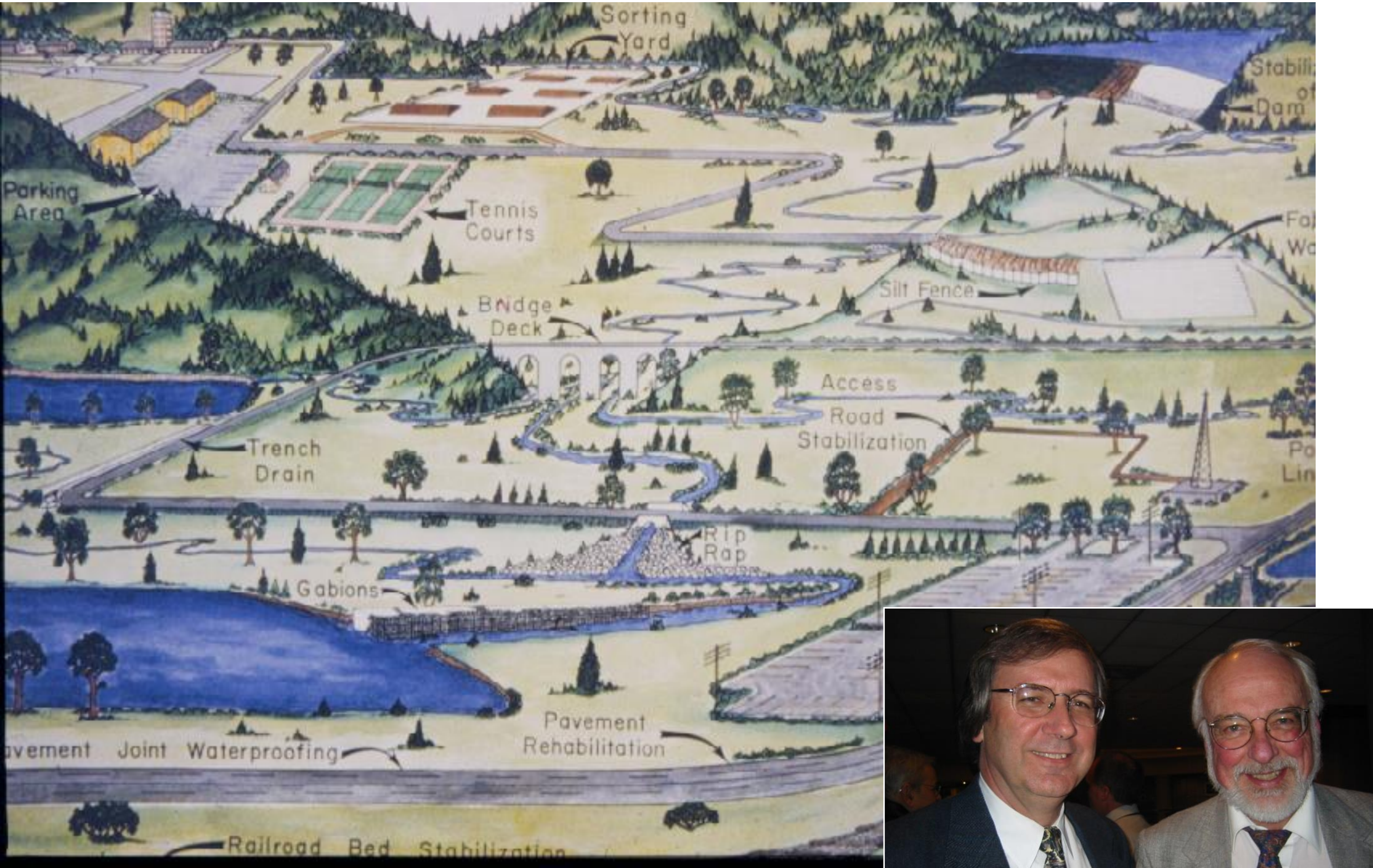


Al Haliburton (1935-1981)



Barry Christopher (left) and Bob Holtz, Co-editors of Geosynthetics

Cover of Christopher and Holtz (1983) *Geotextile Engineering Manual*, FHWA, FHWA-TS-86/203, 1044 pp.

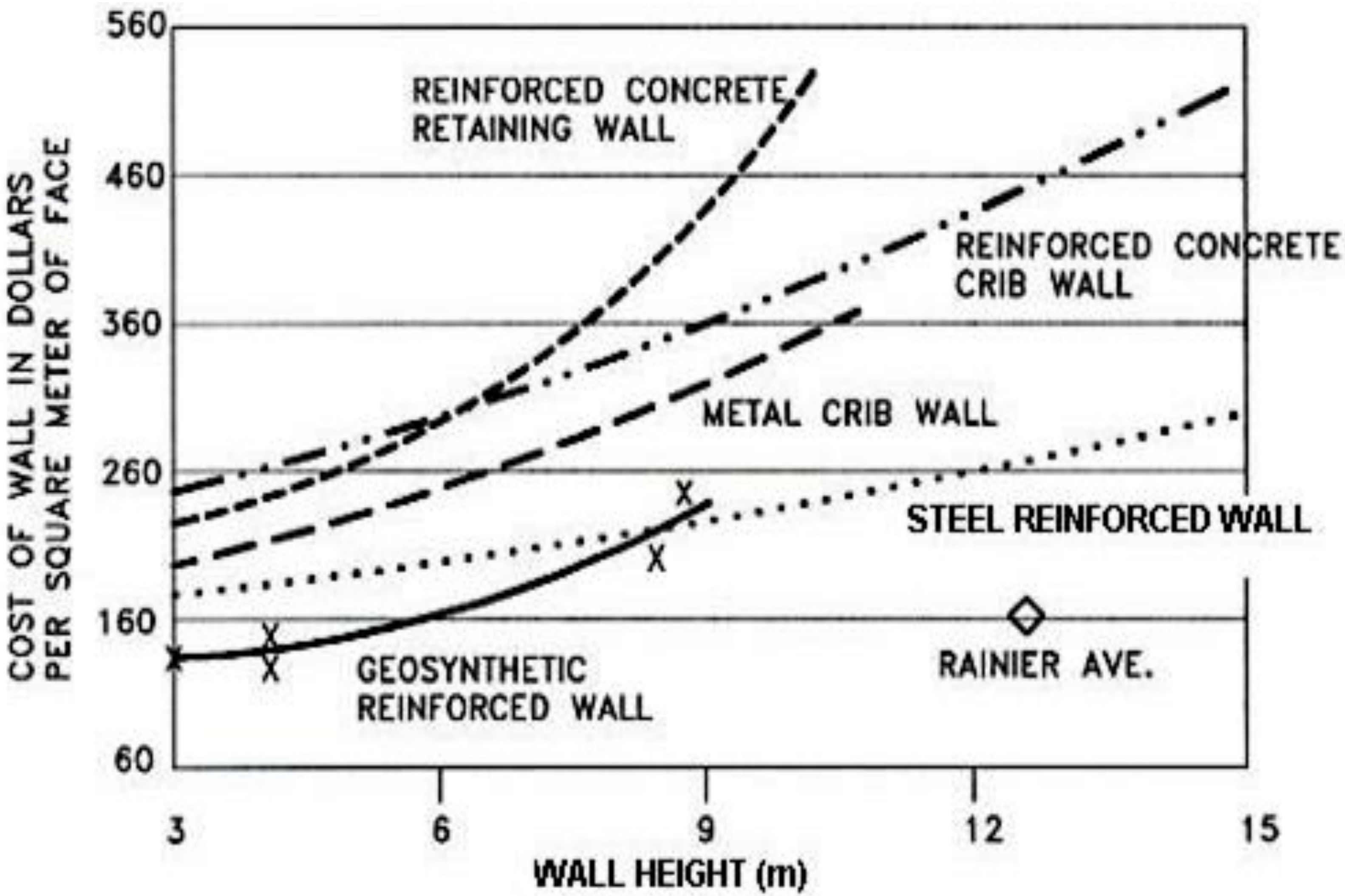


My plan:

1. Introduction
2. Reinforced soil—a historical perspective
3. **Advantages and basic behavior of GRS**
4. Design
5. Properties
6. Things we need still need to know and do—technical and professional issues
7. Successful examples
8. Final remarks

Advantages…

1. Cost:



Other advantages besides cost…

2. Flexibility
    - Settlement tolerance (∴ ¢¢ foundations)
    - Easy to change alignment, grade
    - Seismic stability
3. Simple, rapid construction
4. Attractive facing systems including “green” facings

Advantages (cont.)

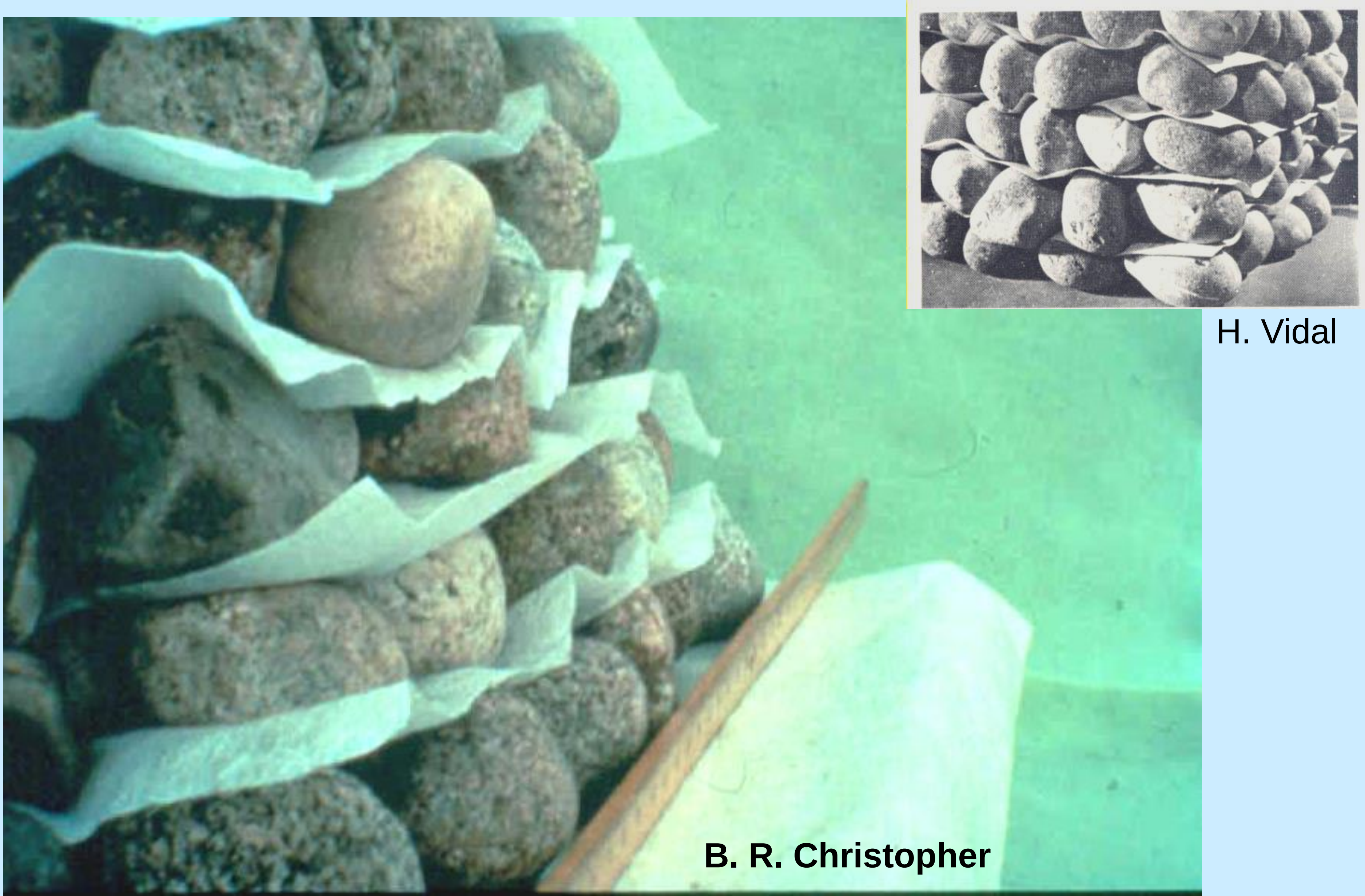
5. Steeper slopes
   - Cohesive > 2:1
   - Granular > angle of repose
6. Increased safety

For the same calculated FS, lower probability of failure (reliability greater) for a reinforced steeper slope than an unreinforced flatter slope

(Cheng & Christopher, 1991).

Why do we still design/construct unreinforced soil slopes?

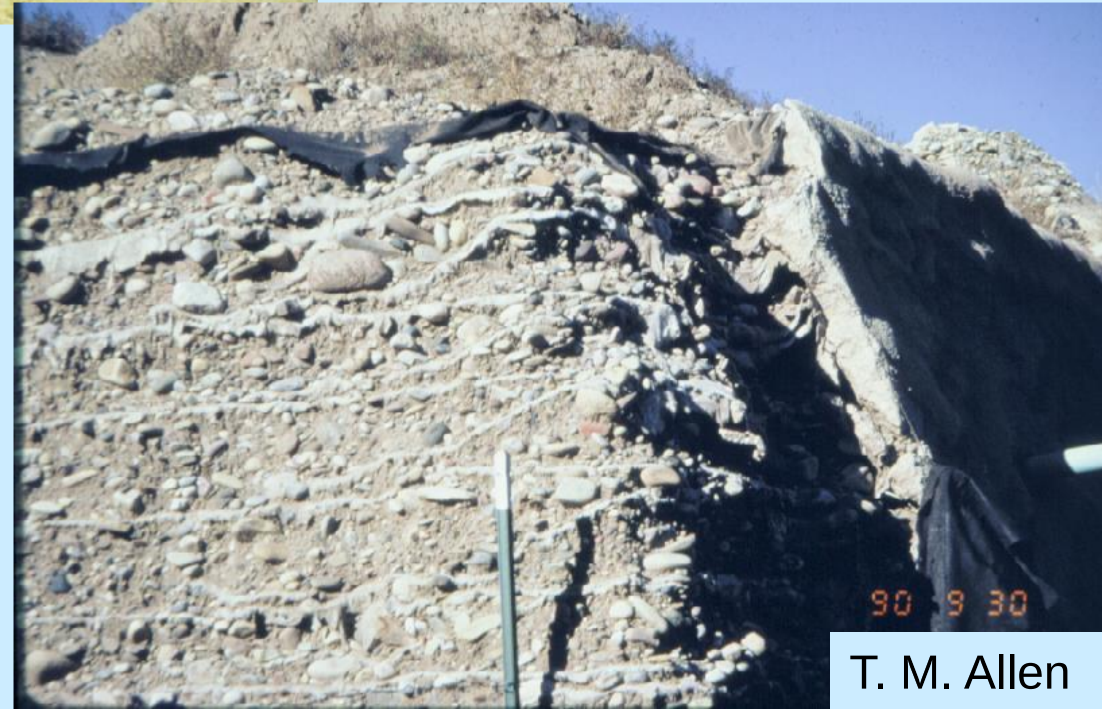
Basic behavior…



R. R. Berg

Glenwood Canyon, Colo.

Test walls, 1982-1990



T. M. Allen

Bob Barrett,
Colorado

Conclusions…

- Stress at face of wall/steep slope v small

- Therefore, face is only “local”… just necessary to hold soil between layers

  – not necessary to be structural, heavy, clunky (…unless the S_v is large.)
  – Japanese experience with EQs?

Fundamental studies on Texsol (1988-92)
Kim Wargo-Levine and Shaun Stauffer, UW

My plan:

1. Introduction
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4. **Design**
5. Properties
6. Things we need still need to know and do—technical and professional issues
7. Successful examples
8. Final remarks

DESIGN: GRS "walls"

- External stability – conventional
  - Bearing capacity, OT, sliding, overall slope
- Internal stability – several approaches
- Drainage
- Seismic design
- Material properties (*next section*)
  - Soil
  - Geosynthetic
  - Facing

External stability

Design – internal stability

Background (historical-traditional approaches)

- GRS <u>*walls*</u>: Combination of conventional EP theory (Rankine) and Terre Armée
  - Same failure modes (*rupture, pullout, creep of reinforcement*)
  - Design approach of Ken Lee (UCLA) and Dick Bell (OSU-USFS)

  → "Tieback wedge" approach

  – Very conservative

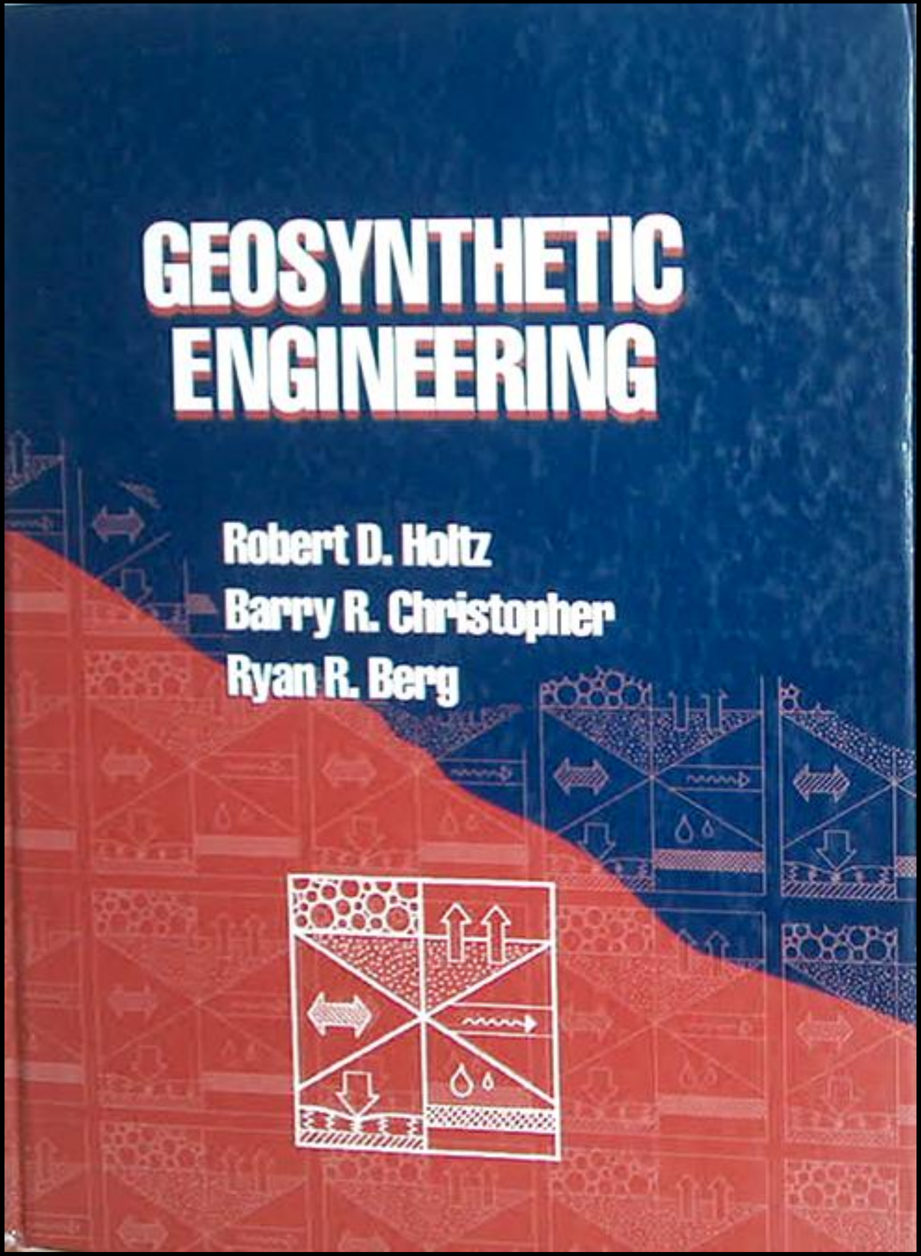
- GRS <u>*slopes*</u>: Used classical slope stability analyses + "tieback" forces

- *Question*: What's the difference between a GRS slope and a very steep GRS slope?
- When does a "very steep slope" become a "wall"??
- Does the soil know the difference?

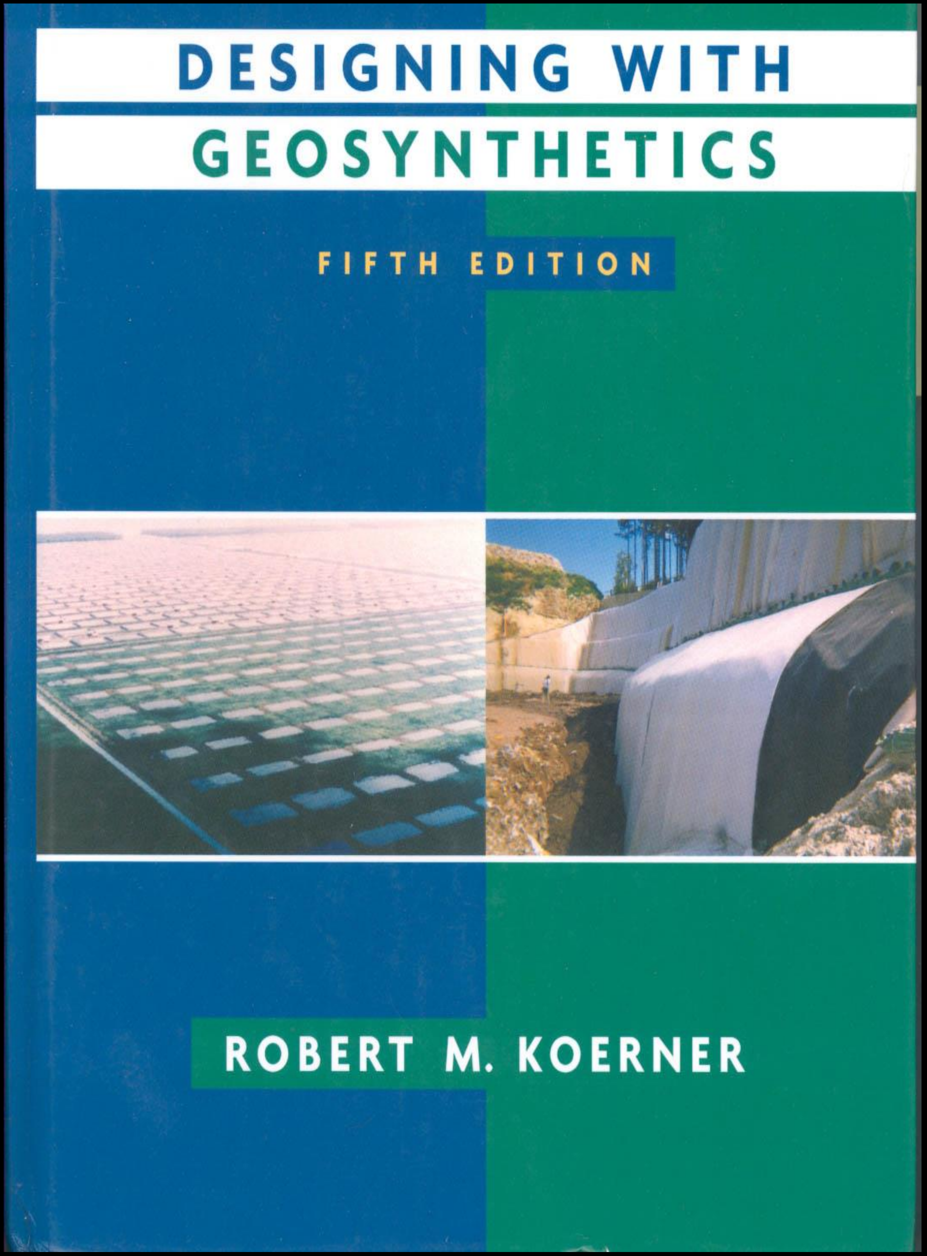
Design…

- *Koerner*: Our design approaches depend on traditional geotech designs for slopes and retaining walls…and on the way we teach these subjects in our graduate courses…HAS NOTHING TO DO WITH REALITY!

- So, let’s see what the “experts” say about this…



BiTech Publishers,
Richmond, BC



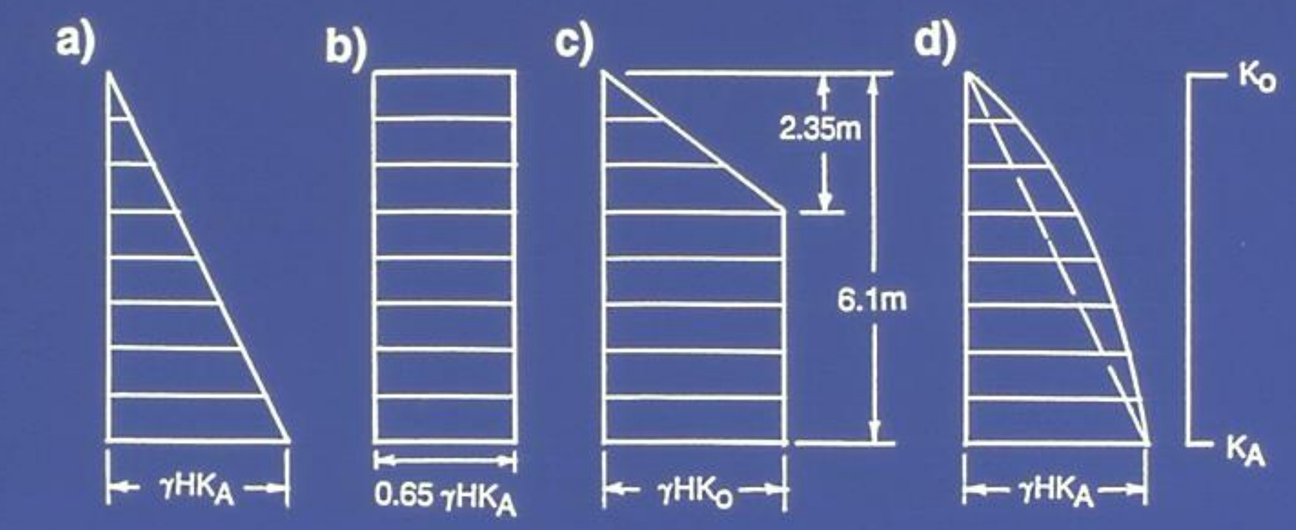
Prentice-Hall

Current Design Methods -- Internal stablilty

[redacted]

- Tieback wedge (Forest Service)
- Broms
- Leshchinsky
- FHWA -- AASHTO
- Others

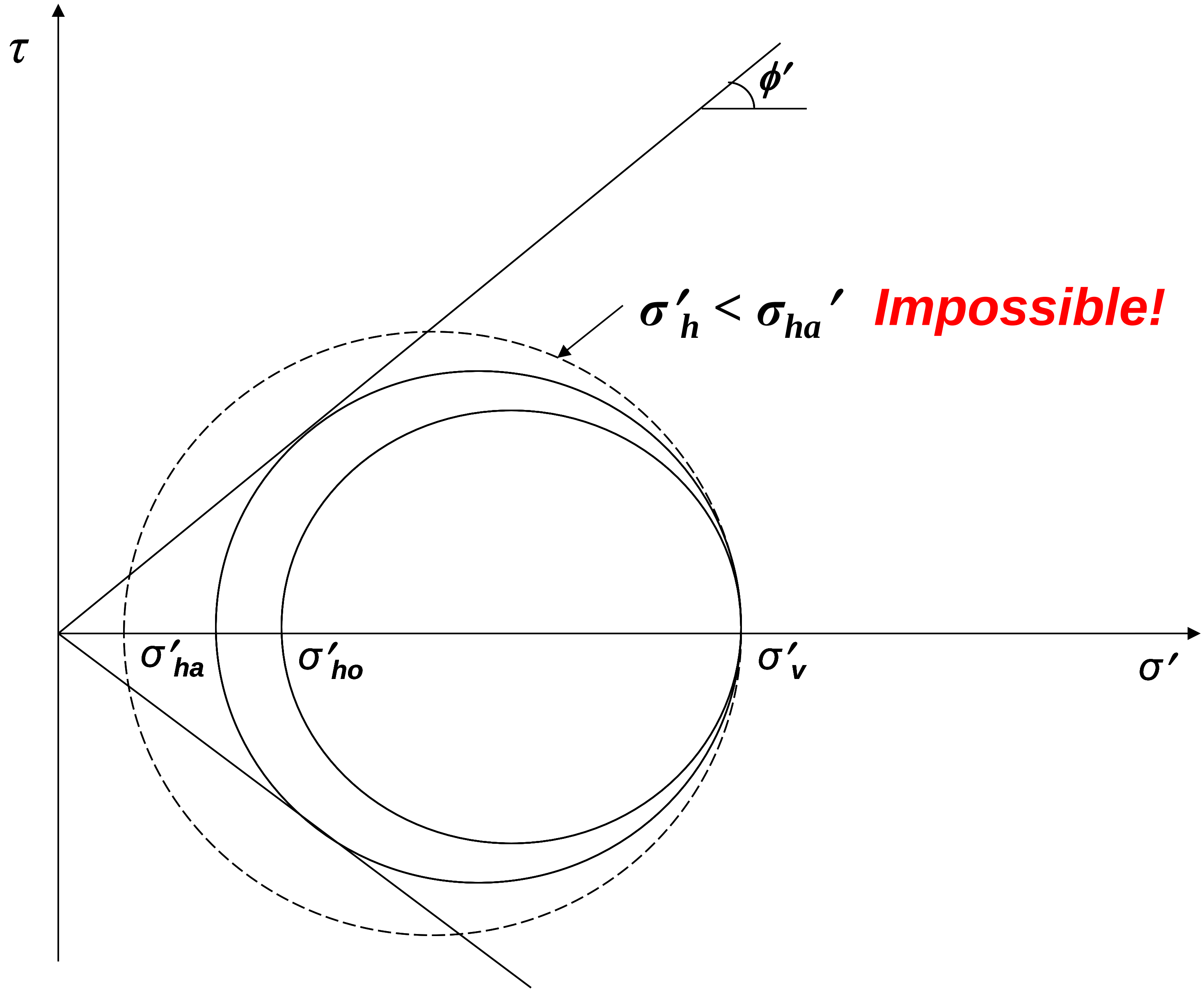
[redacted]



Empirical development of state of stress:

$$K_h = \frac{\sigma_h}{\sigma_v} = \frac{\text{Measured}}{\gamma h}$$

- Relate to K_a calculated from knowledge of ϕ'
- Problem: Measured K_h often less than K_a!
- Impossible!


τ
φ′
σ′h < σha′ Impossible!
σ′ha
σ′ho
σ′v
σ′

Field meas vs. theory? Why is $K_h << K_a$??

- **Properties**
  - MFEs curved, so ϕ' >> higher at low γh or σ_c
  - $\phi'_{\mathbf{TRIAX}} << \phi'_{\mathbf{PS}}$
  - At field densities, high ϕ'

- **Rankine theory** violated by presence of reinforcement
  (Boyle, 1995, PhD thesis, UW)

- **Apparent cohesion**
  - *"…a little c goes a long way!!"* …but always there??

- **Field meas ??**
  - Interpretation problems
  - Anomalies
  - etc etc..

Design: GRS *slopes*…

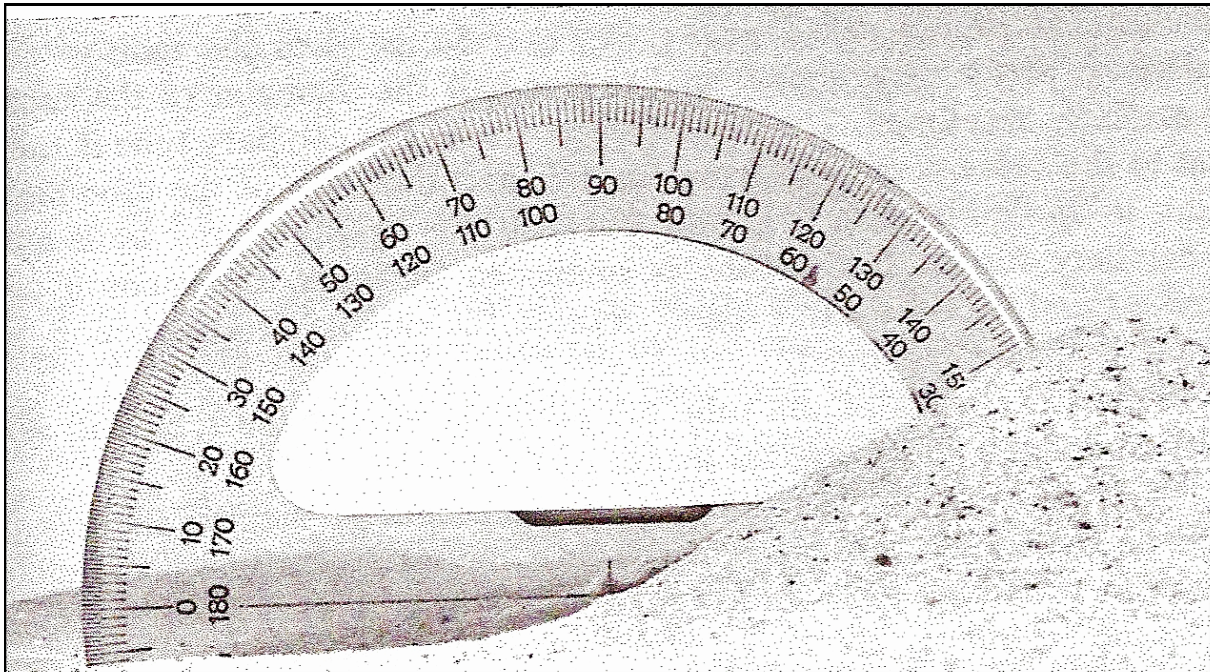
Combination of classical slope stability analyses

+ “tieback” forces

Consider

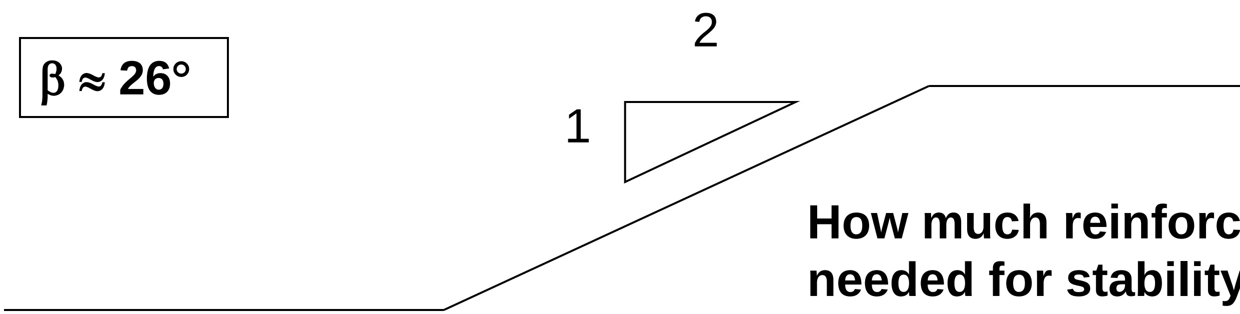
- how granular slopes actually fail
- how stability analyses are performed.

Start w/ a sand at its angle of repose and then increase the slope angle…



Holtz & Kovacs (1981)

$\beta \approx$ **26°**

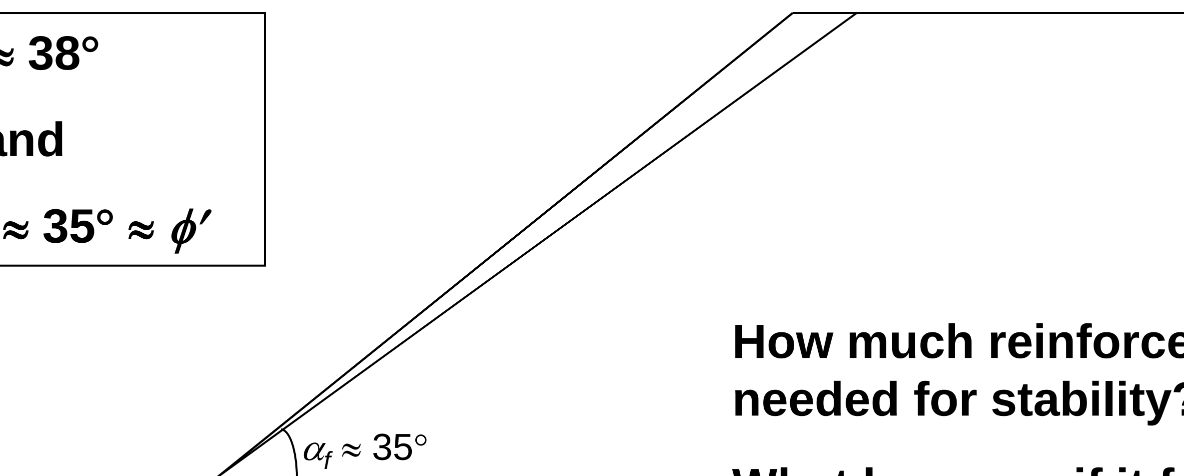


How much reinforcement is needed for stability??

$\beta \approx$ **38°**

Sand

$\alpha_f \approx$ **35°** $\approx \phi'$



How much reinforcement is needed for stability??

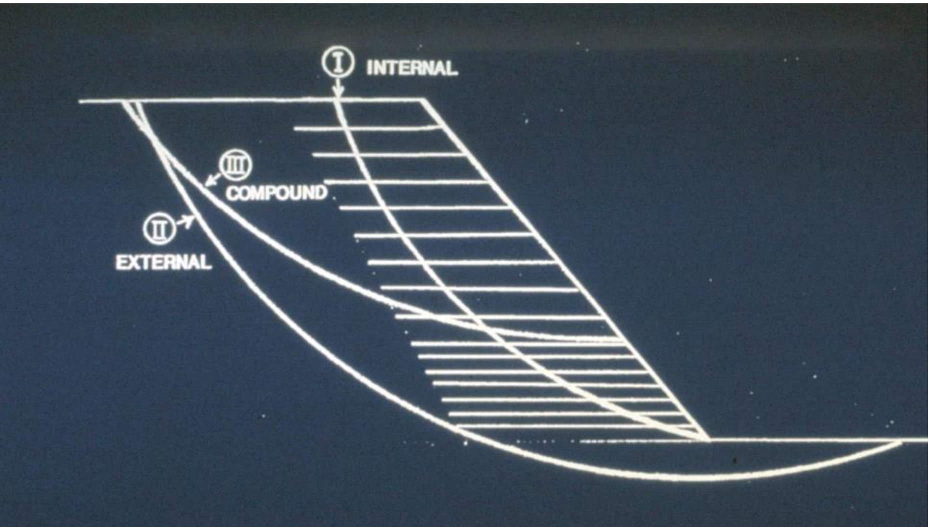
What happens if it fails?

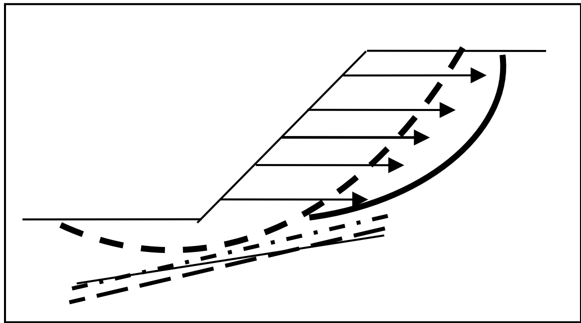
- **Richard Jewell and the pullout paradox…**

GRS slopes:
Design approaches and procedures

- Sliding wedge
  - One plane
  - Bilinear
- Circular arc
- Log spiral

- Murray
- Schneider & Holtz
- Leshchinsky et al.
- Jewell
- Schmertmann et al.
- Verduin & Holtz
- Others?





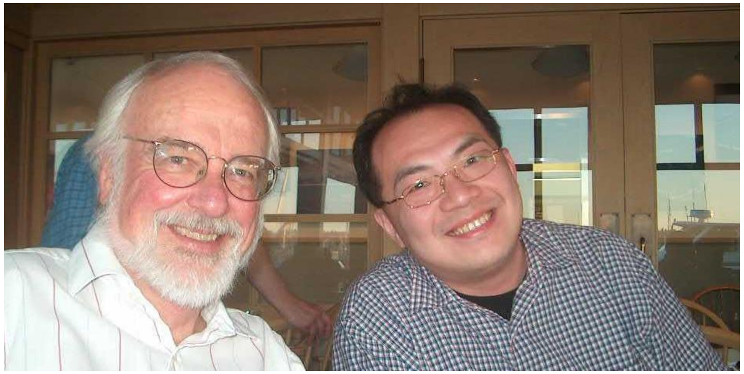
- For stability analyses, several commercial and govt-developed programs have subroutines for GRS

- PCSTABL4
- STABGM
- XSTABL
- UTEXAS3
- GSLOPE
- New Janbu
- Tenslo1
- Strata Slope
- RSS
- ReSSA

- ≈ OK
- See Duncan and Wright (2005) Chap 8

UW Research on GRS Walls:
Analytical (FLAC)

1. Wei-Feng Lee (PhD) -- Analysis of GRS walls; develop working stress analysis
2. Fadzilah Saidin (PhD) -- back analysis of an instrumented full scale GRS wall with poor draining backfill on soft soil



Wei Lee

Fazee Saidin

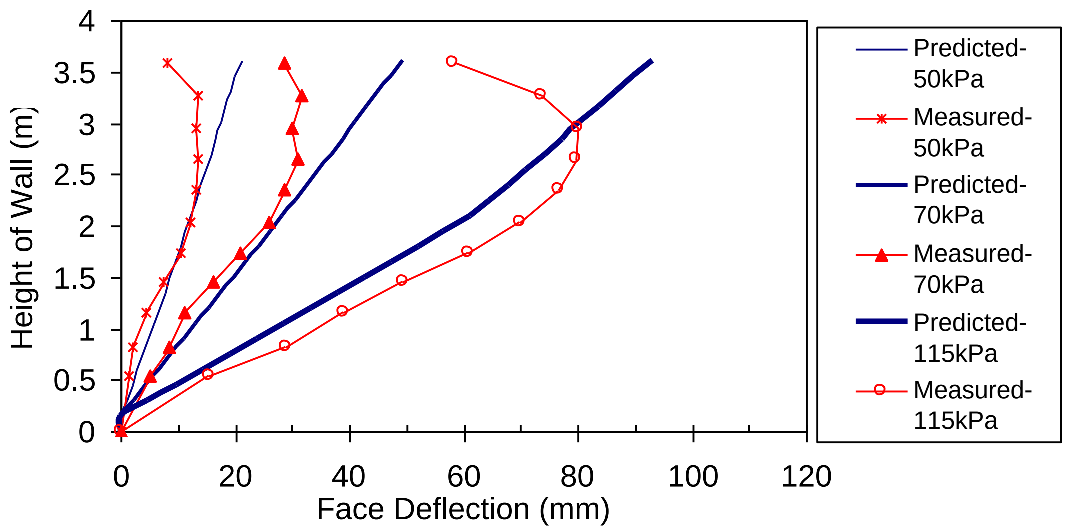
1. Wei Lee (PhD) -- Analysis of GRS walls; develop working stress analysis

- Model calibrated with field/lab data (Rainier Ave. wall)
- PS ϕ' & modulus @ low $\sigma_c \rightarrow$ correct dilation angle
- Class A predictions of three RMC test walls; ~ good agreement

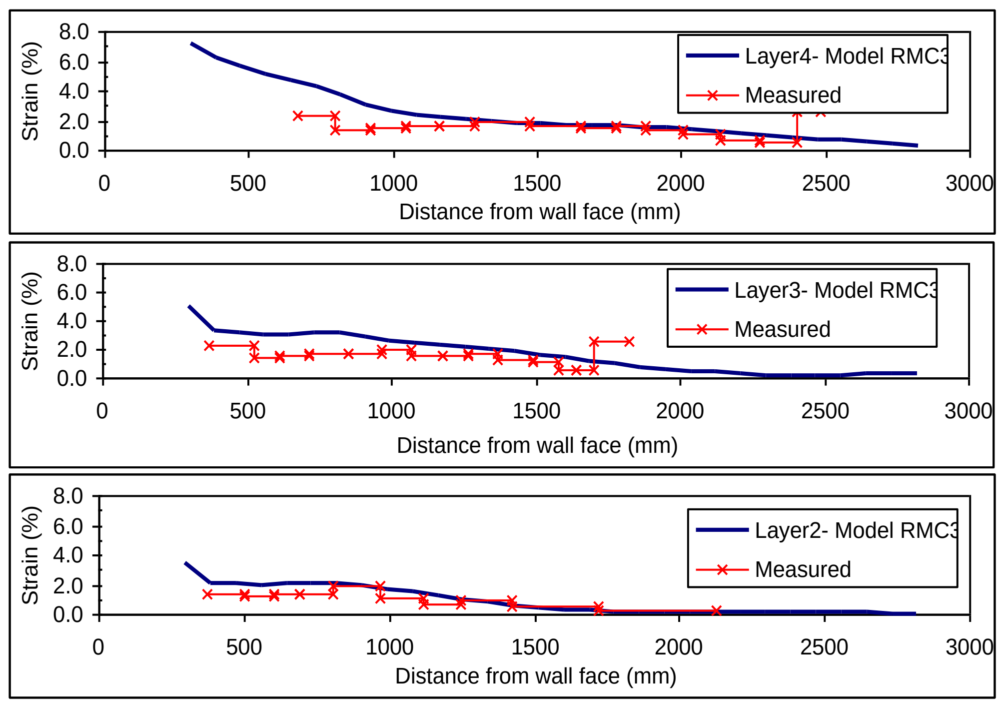
Conclusion: Both external and internal performance can be reproduced, ***IF*** :

- Correct material properties
- Boundary conditions correctly simulated

Wall Deflection – Wall 1



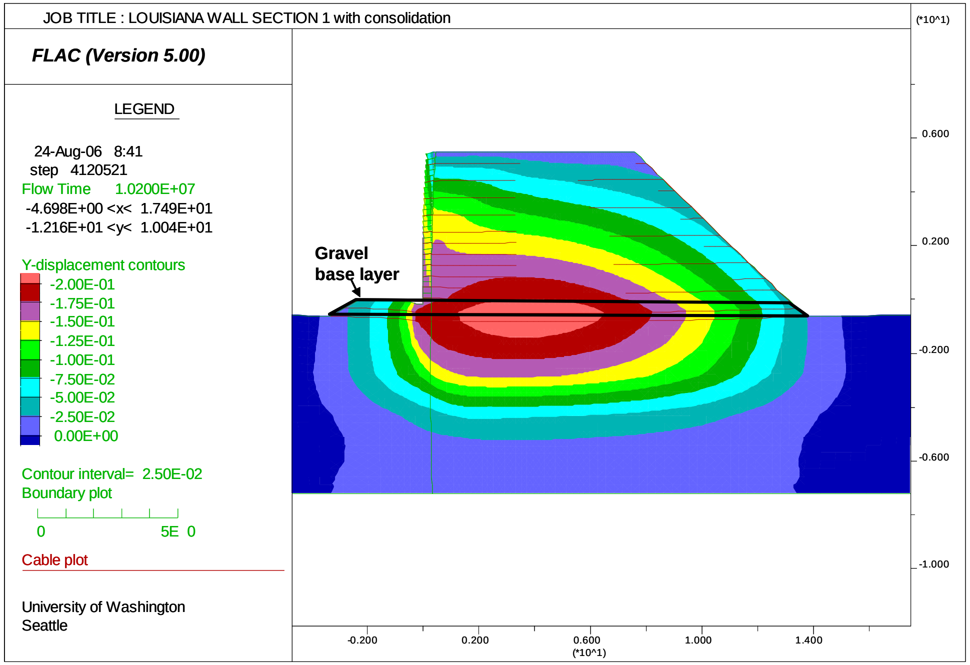
Reinforcement Strain - Wall 3 (50 kPa surcharge)



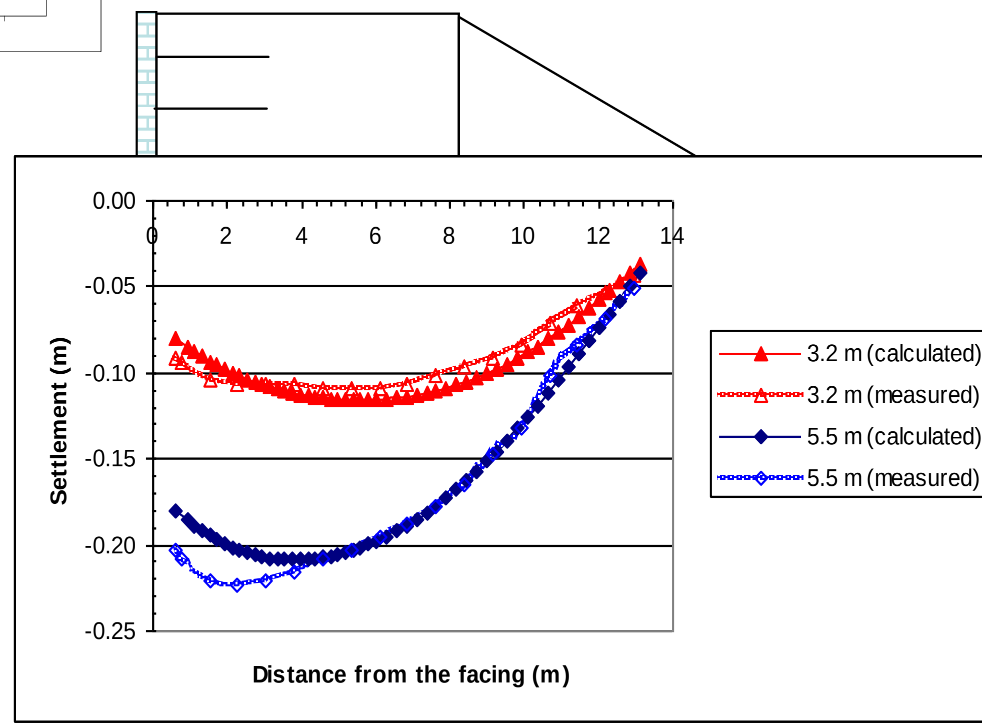
W.-F Lee (2000) PhD Thesis UW

2. Fazee Saidin (PhD) -- back analysis of an instrumented full scale GRS wall with poor draining backfill on soft soil

- Instrumented 6 m LTRC wall
- Numerical simulation (FLAC) of GRS wall on soft foundation
- Considered effects of settlement, infiltration, compaction, etc.



Some results--settlements

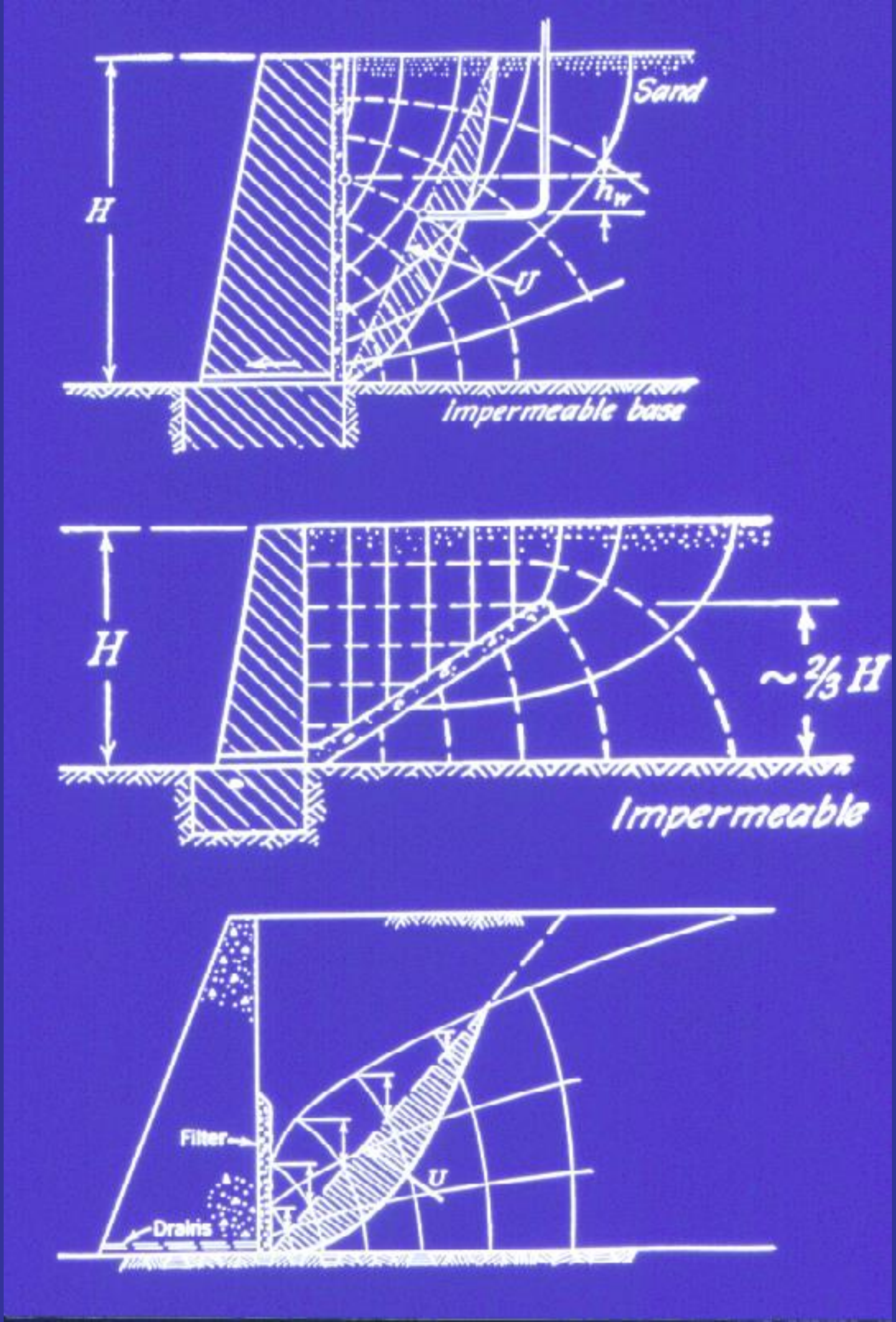


F. Saidin (1997) PhD Thesis, UW

Design recommendations

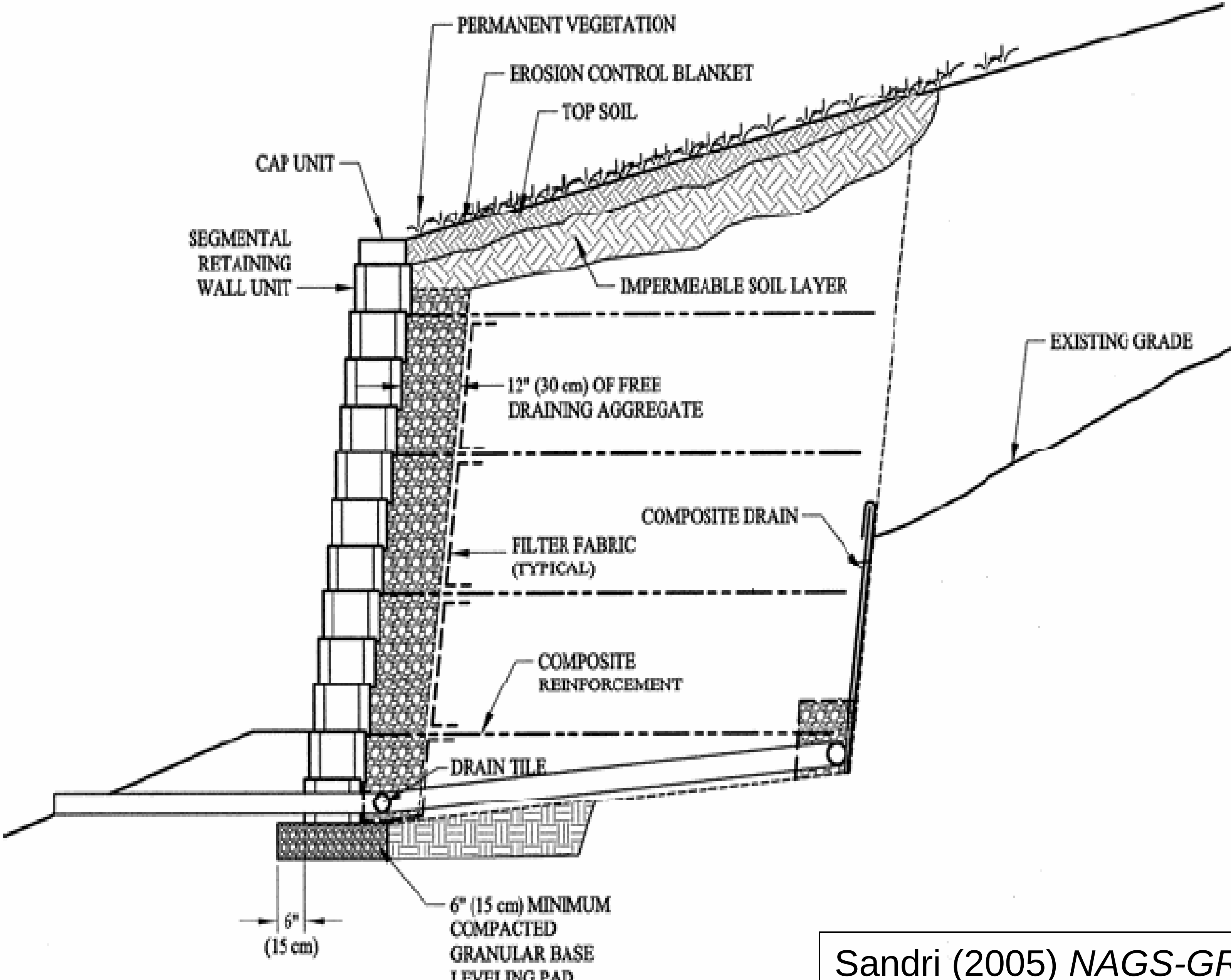
- Traditional design methods ≈ OK for GRS walls on soft foundations
- Reinforced base layer → more uniform settlements
- Traditional settlement analysis ≈ OK
- Rate of construction important
- Adequate provisions for drainage critical

DRAINAGE! DRAINAGE! DRAINAGE!



Terzaghi (1943)

Theoretical Soil Mechanics



Sandri (2005) *NAGS-GRI19*

Other approaches to design:

- Composite material approach
  - UC Davis 1970s
  - Lee et al. (2007) *Proceedings of Geosyn. 2007*
- K-Stiffness method
  - Empirical – many case histories
  - Independent of reinforcing material
  - More accurate estimate of reinforcement loads
  - Step-by-step design procedures developed with a limit states design approach consistent with current design codes (i.e., LRFD)

Allen, Bathurst, Holtz, Lee, and Walters (2003) CGJ and (2004) JGGE

So, what to do for design of GRS ?

If you want to use traditional LE methods…

1. Use correct soil properties: γh + $\phi'_{\mathbf{PS}}$ (not so easy)
   - not many PS devices available
   - hard to conduct triax/PS tests at low confining pressures
   - Use correct dilatancy angle (…important if want to do advanced modeling, e.g., with FLAC…and you want the correct answer!!)

2. For internal stability of steep GRS slopes, design as a … well, a very steep slope

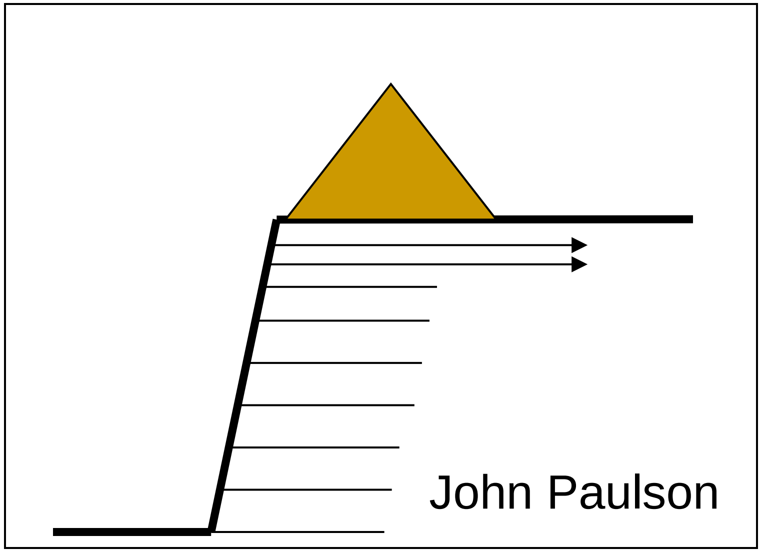
   As slope angle increases $\rightarrow$ more or stronger reinforcing
   - Use SN or tieback programs…w/ adjustments for geometry and properties of reinforcement (??)
   - See Pockoski & Duncan (2000) “Comparison of Computer Programs for Reinforced Slopes” Center for Geotech Practice & Research, Va. Tech

Traditional LE methods (cont.)

3. Use thin layers of weaker reinforcing -- ¢¢, and better face control
4. Pullout? Not a problem—based on our research at SGI, KTH (described earlier)
   – Geosynthetic will rupture before it pulls out
   – If a problem, easily taken care of in design
5. …and don't forget:

Drainage! Drainage! Drainage!

Also, try K-Stiffness Method*



***Let us know how it works**

My plan:

1. Introduction
2. Reinforced soil—a historical perspective
3. Advantages and behavior of GRS
4. Design
5. Properties
6. Things we need still need to know and do—technical and professional issues
7. Successful examples
8. Final remarks

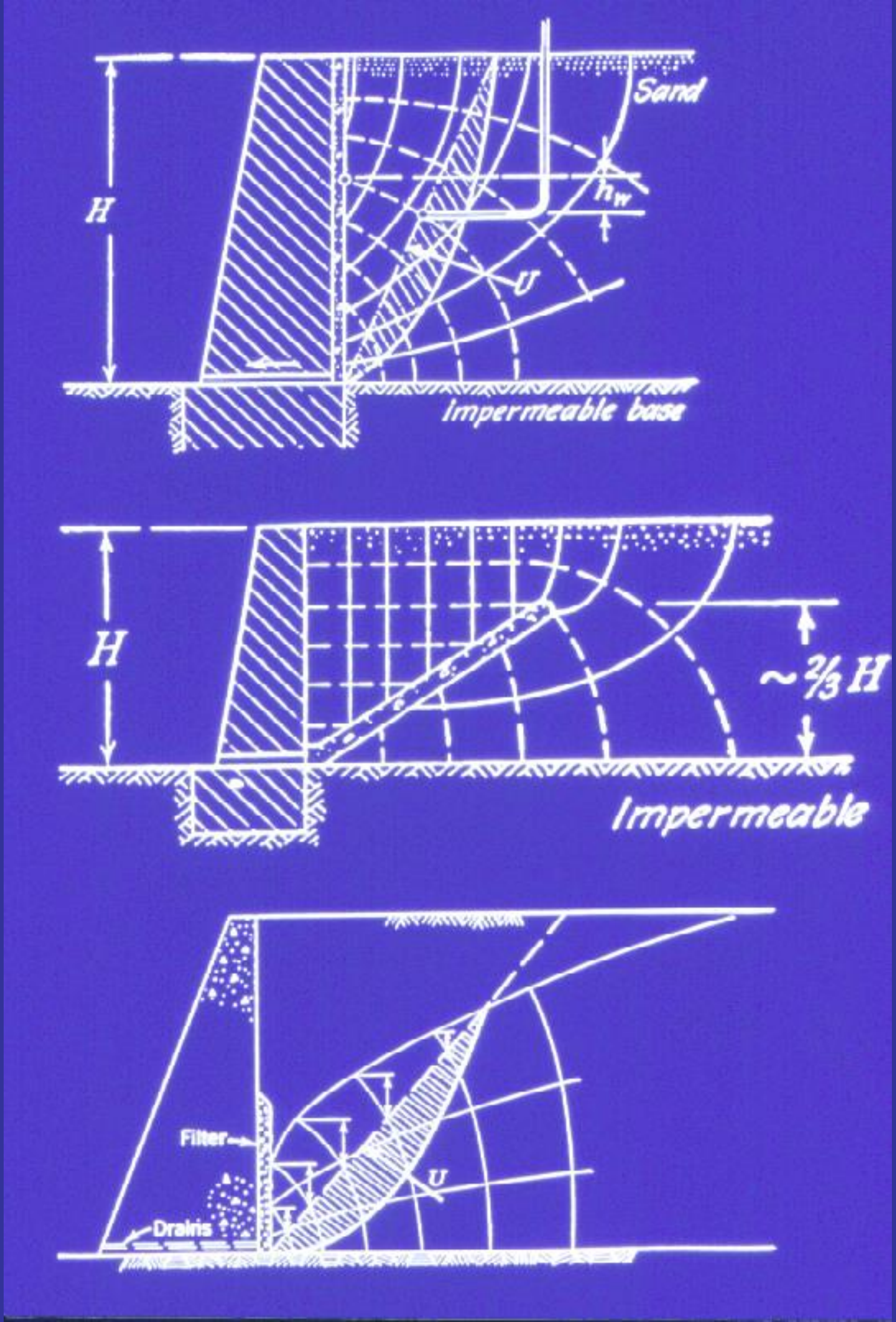
Material Properties

- ***Soils***
- ***Geosynthetics***
- ***Facing***

Soil Properties:

As usual…

- Use clean granular backfill
- ReCo/FHWA specs
- Foundation/slope



Terzaghi (1943)
Theoretical Soil Mechanics

Drainage,
drainage,
drainage!

This is a DESIGN and CONSTRUCTION issue.

Material Properties (cont.)

GEOSYNTHETIC PROPERTIES:

- ***Tensile strength***
- ***Soil-geosynthetic friction***
- ***Creep (?)***
- ***Durability***
- ***Installation damage***

2. Geosynthetic properties:

CRITERIA or PARAMETER	PROPERTY*
1. Design requirements:	
Mechanical	
Tensile strength/modulus	Wide width strength/modulus
Seam strength	Wide width strength
Tension creep	Tension creep
Soil-geosynthetic friction	Soil-geosynthetic friction angle **(?)**
Hydraulic	
Piping resistance	Apparent opening size
Permeability	Permeability/permittivity
2. Constructability Requirements:	
Tensile strength	Grab strength
Puncture resistance	Puncture resistance
Tear resistance	Trapezoidal tear strength
3. Durability:	
UV stability (if exposed)	UV resistance
Chemical and biological (if reqd)	Chemical and biological resistance

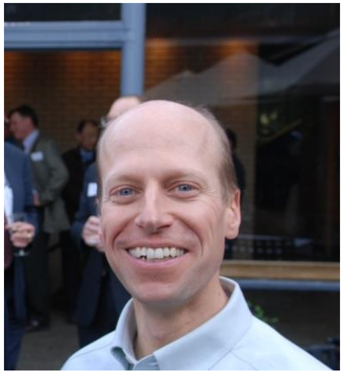
*All have ASTM standard tests.

UW Research on GRS Walls (1991 – 2007)

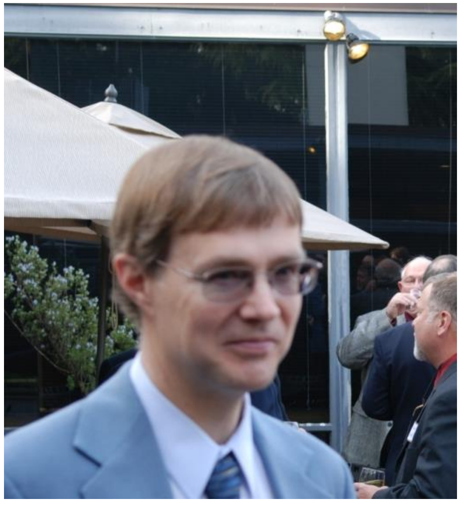
- **Analytical** (FLAC) -- already summarized
- **Experimental**
  - Stanley R. Boyle (PhD) – In-isolation and in-soil load-elongation tests; strain gages on geosynthetics

Sponsored by WSDOT

T. M. Allen, contract monitor



Stan Boyle

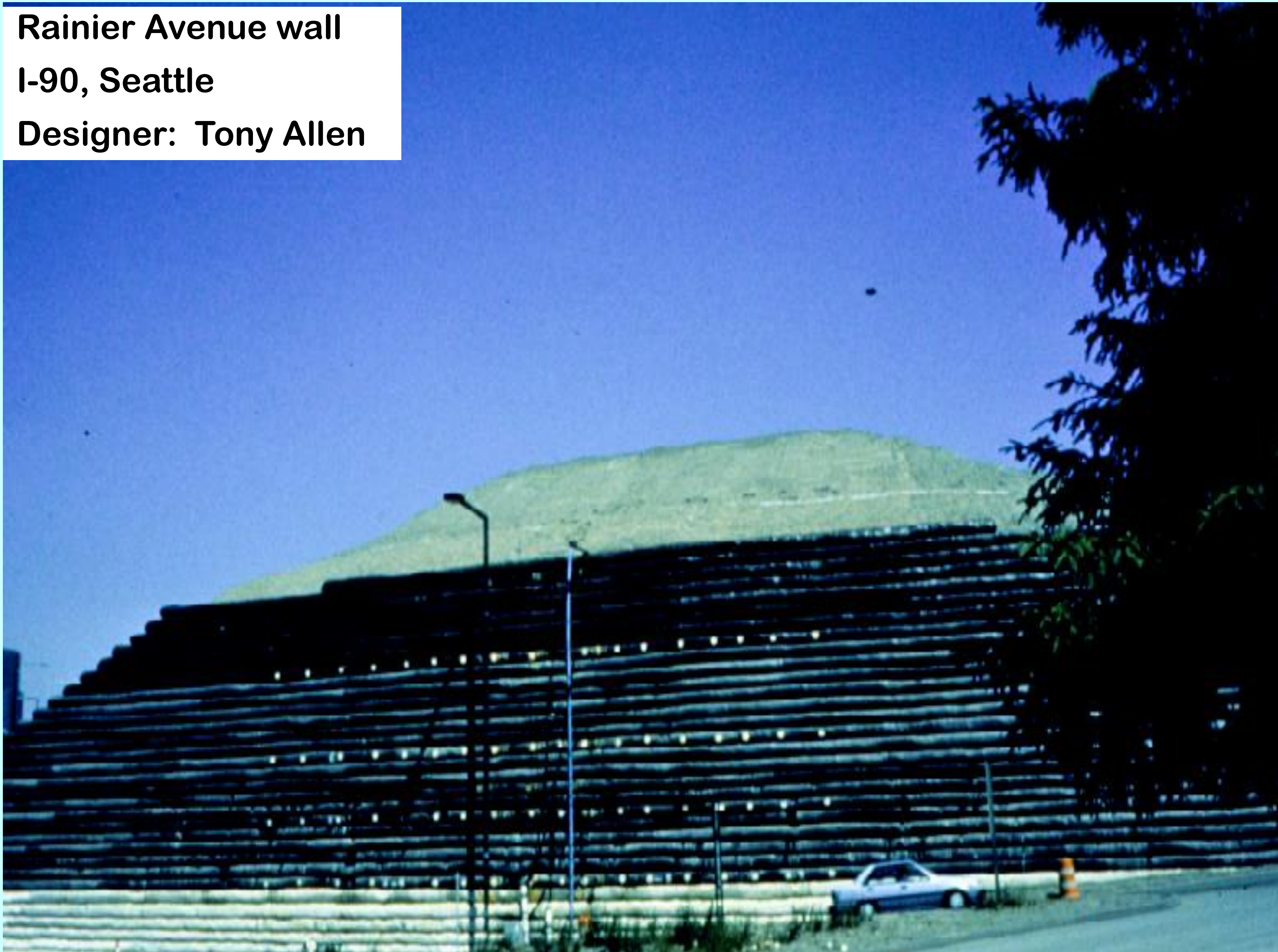


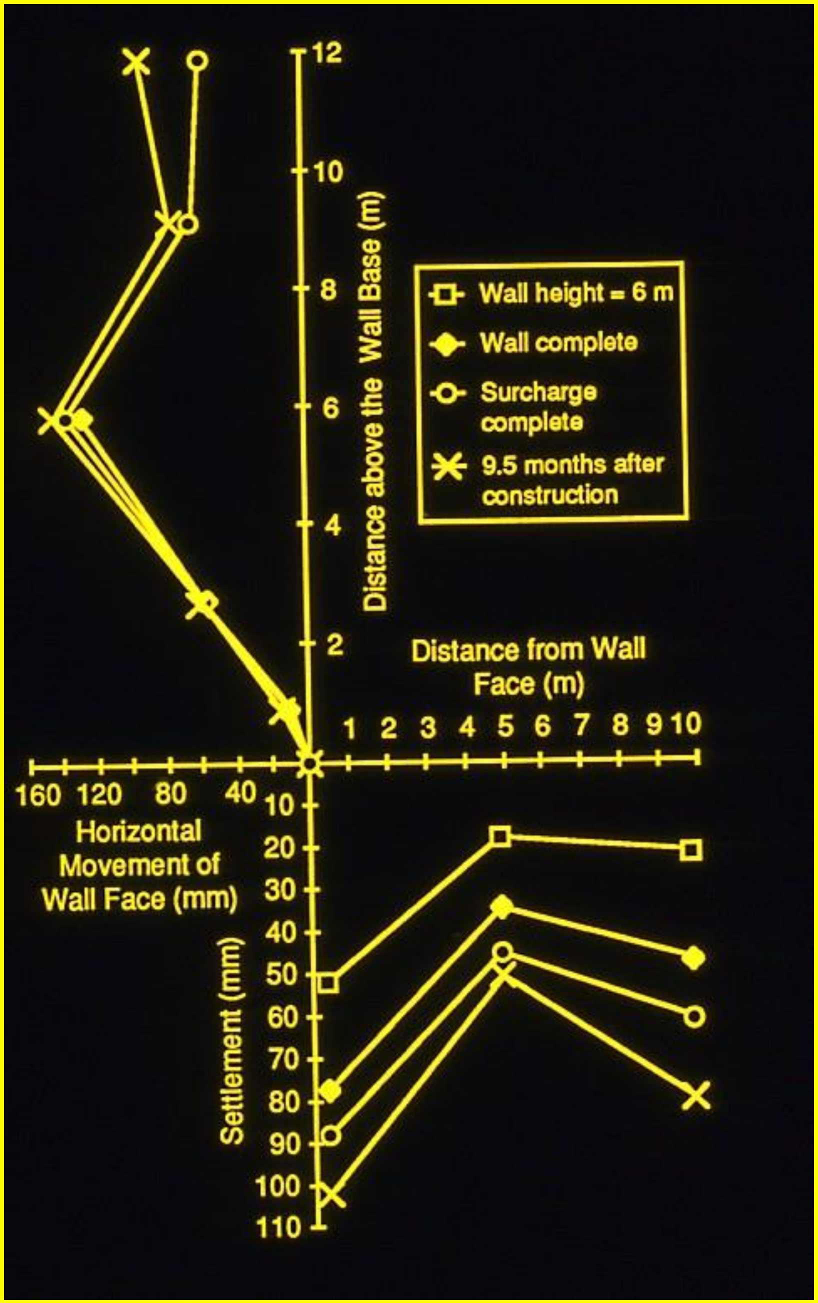
Tony Allen

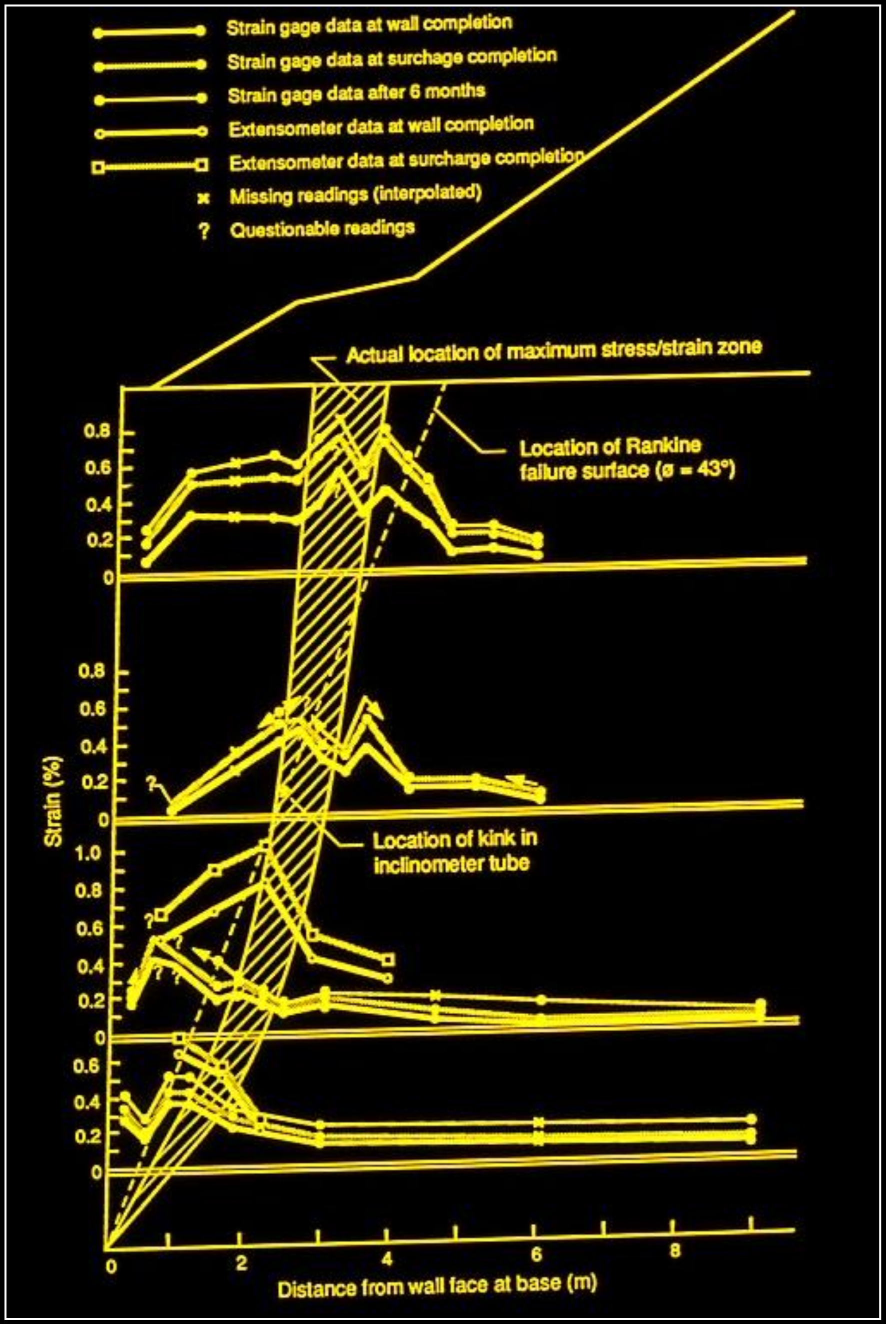
Rainier Avenue wall

I-90, Seattle

Designer: Tony Allen

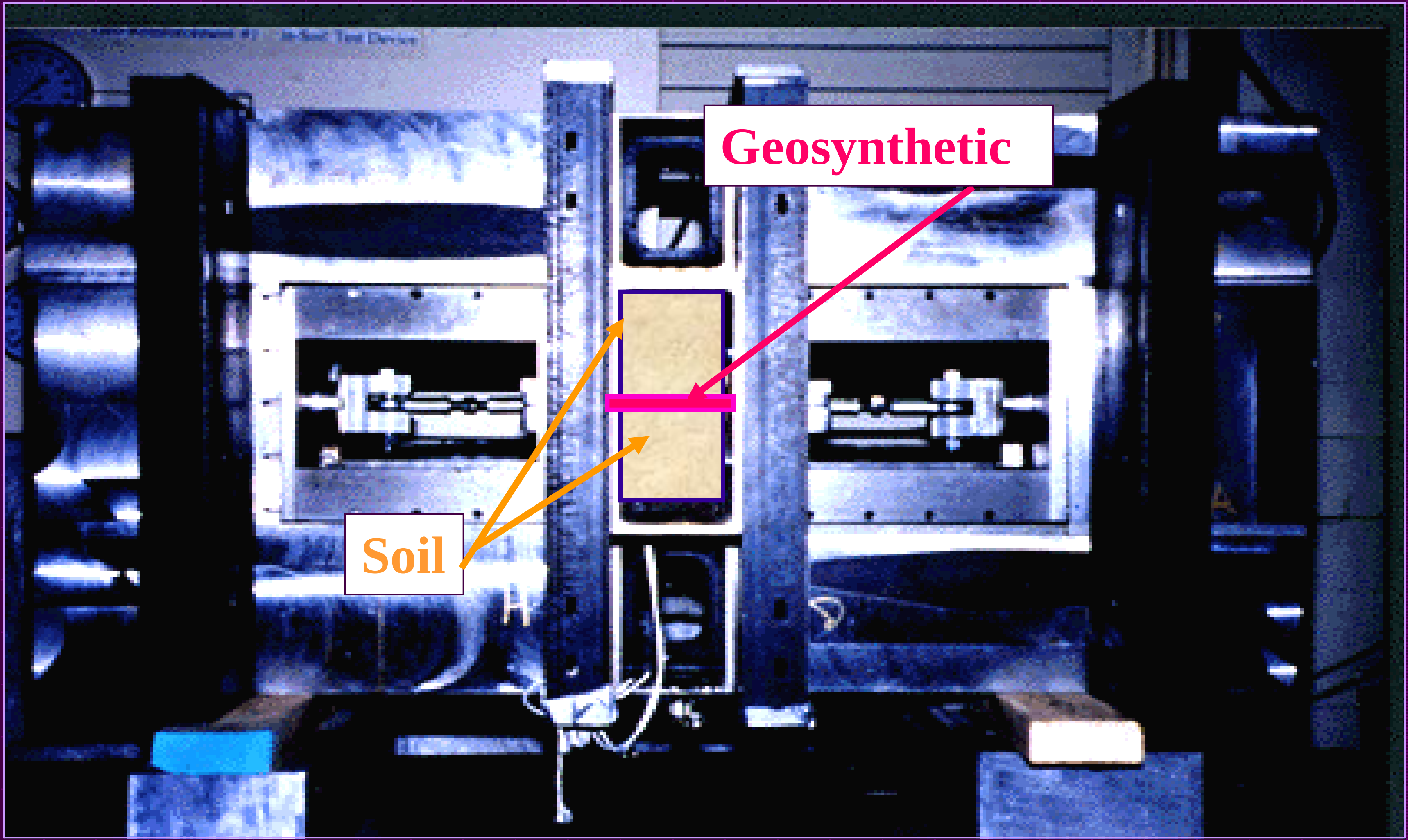


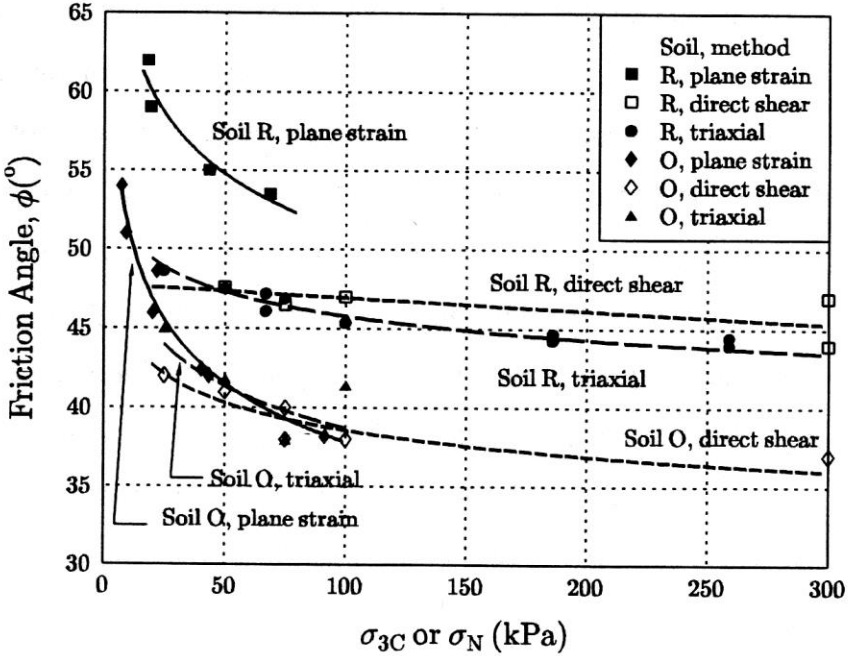




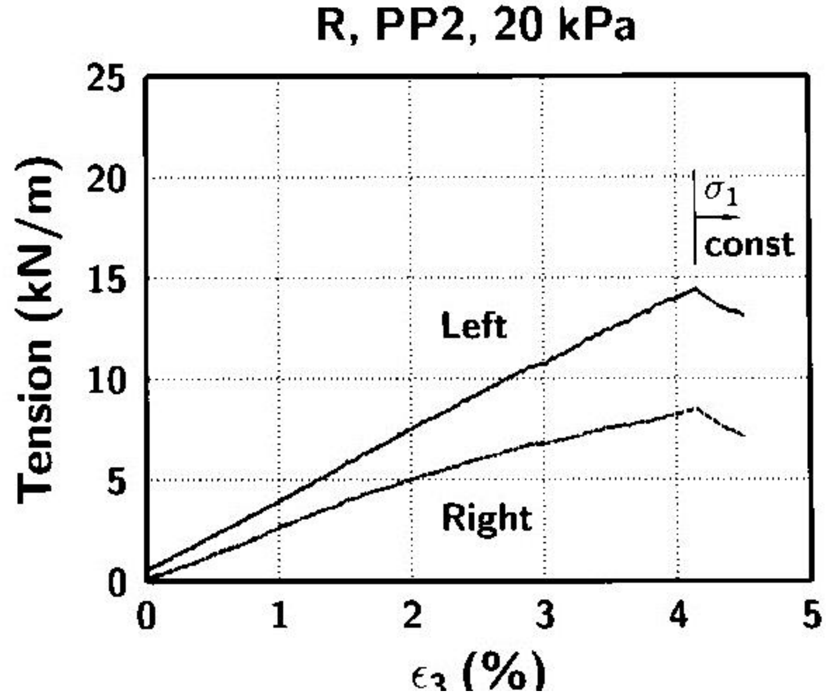
Allen, Christopher & Holtz (1992)

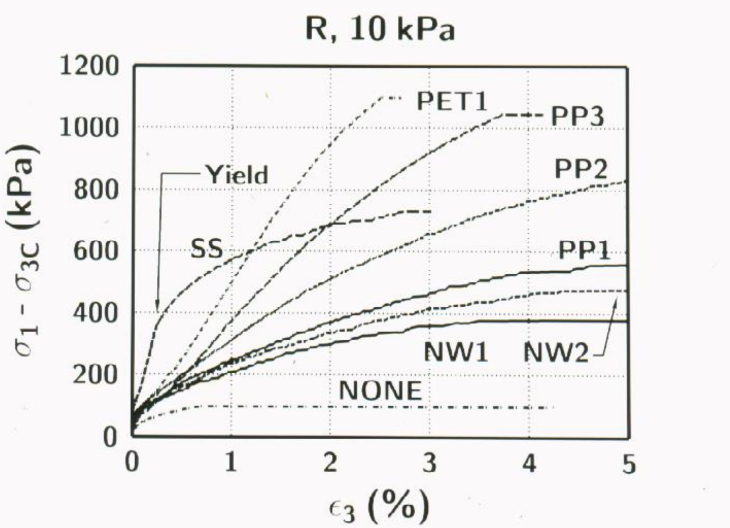
Unit Cell Device – Boyle (1995)





Boyle (1995) Fig. 6.5



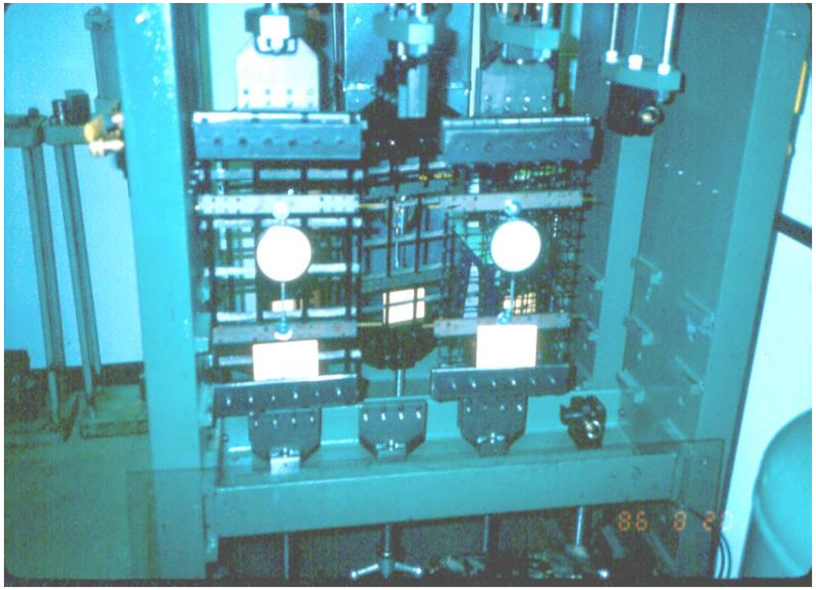


Boyle (1995) Fig. 6.9b

“Bottom line” for GRS wall designers…

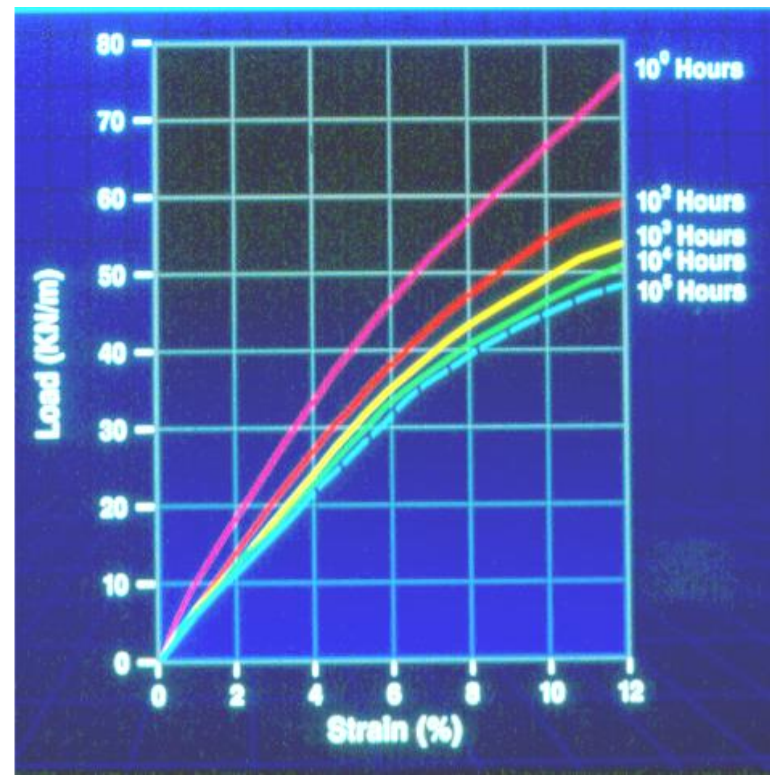
- Geosynthetics are much more efficient reinf than steel, because strengths of both sand and geosynthetic are used more or less equally. With steel reinfd soil, steel does most of the work… & sand just goes along for the ride. Not so with geosynthetics.
- Creep of GRS “walls” *not* really a problem *at working stresses*. When loading stops, GRS deforms as the geosynthetic relaxes. The GRS system is at equilibrium and no longer moves.
- Also shown by field measurements of real GRS walls [Rainier Ave wall; Norway steep slope (Fannin and Herman, 1990; Fannin, 2001)].

If you still think creep is a problem:



Unconfined creep test

Isochronous load vs. strain curves -- Geogrid (after McGown)



In-soil creep rate??

If you still think creep is a problem:

- See Bob Koerner, Grace Hsuan, and Scott Thornton
- Use Isochronous load vs. strain curves and time-temperature superposition; stepped isothermal method (SIM) Analysis -- ASTM D 6992
- Use BS 8006 (10 000 hr data $\rightarrow \approx$ 120 yr)
- Jon Fannin: BS8006 procedure and AASHTO with

  $RF_{CR} \rightarrow$ **≈ same** $\boldsymbol{T_{al}}$ ***!***

- Finer grained backfills???? (*Avoid* if possible…)

My plan:

1. Introduction
2. Reinforced soil—a historical perspective
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6. Things we need still need to know and do—technical and professional issues
7. Successful examples
8. Final remarks

Things we need still need to know and do:

1. Technical

GRS is quite mature... but we could use:

- A simpler ("poor-man's") PS device…with *Δvol* measurements
- A seismic design procedure better than M-O pseudo-static….even though we know GRS structures are safer than conventional in EQs
- PBEE? (Most promising…)

Steve Kramer

Things we need still need to know and do:

2. Professional issues

1. **Too many failures!** Most due to
   - Poor quality backfill
   - Poor drainage; saturated backfill
   - Construction problems
   - Inadequate global or external stability
   - Unexpected surcharges
   - …and…and…

2. **Disconnect** between wall designer, geotech of record, and site civil

   …complicated by wall designs supplied by materials suppliers and distributors

Things we need still need to know and do: *2. Professional (cont.)*

3. Other problems

- Lack of proper inspection
- No control of construction by designer
- Economic pressures
- "Value engineered" or "contractor supplied" designs, with no $$ for checking alternates by competent professionals
- Poor training for workers

Question: Is liability avoided by use of vendor-supplied designs?

- If not, then why give away billable design hours?

➢ Fixing problems always more expensive than proper inspection and control by the designer…

Things we need still need to know and do:

2. Professional (cont.)

4. Jurisdictions that require a GRS “wall” design to be stamped by a registered structural engineer (who usually knows nothing about soil reinforcing and geosynthetics, and only a little about soils and drainage issues…and they are not responsible for construction inspection).

The result? Too many failures! Costly, potentially tragic, and not acceptable!

- How to fix this current state of affairs?
  G-I? ASFE? IGS? ISSMGE?
  Us as individuals?
- Many of these issues are not unique to GRS
- But they threaten a wonderful technology

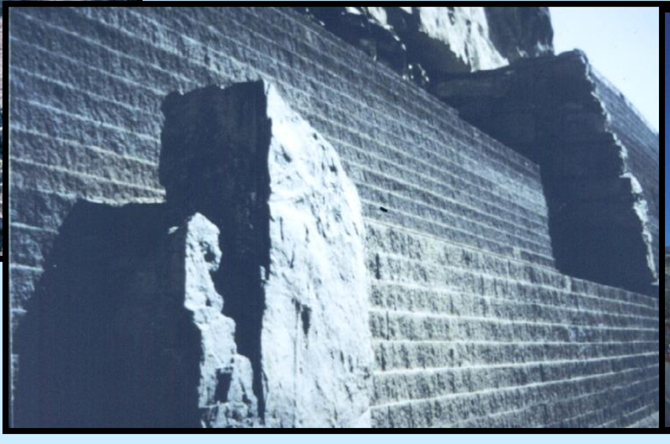
…and a wonderful profession

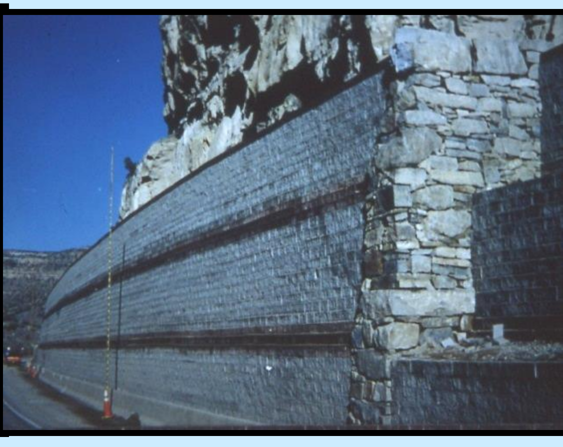
Outline

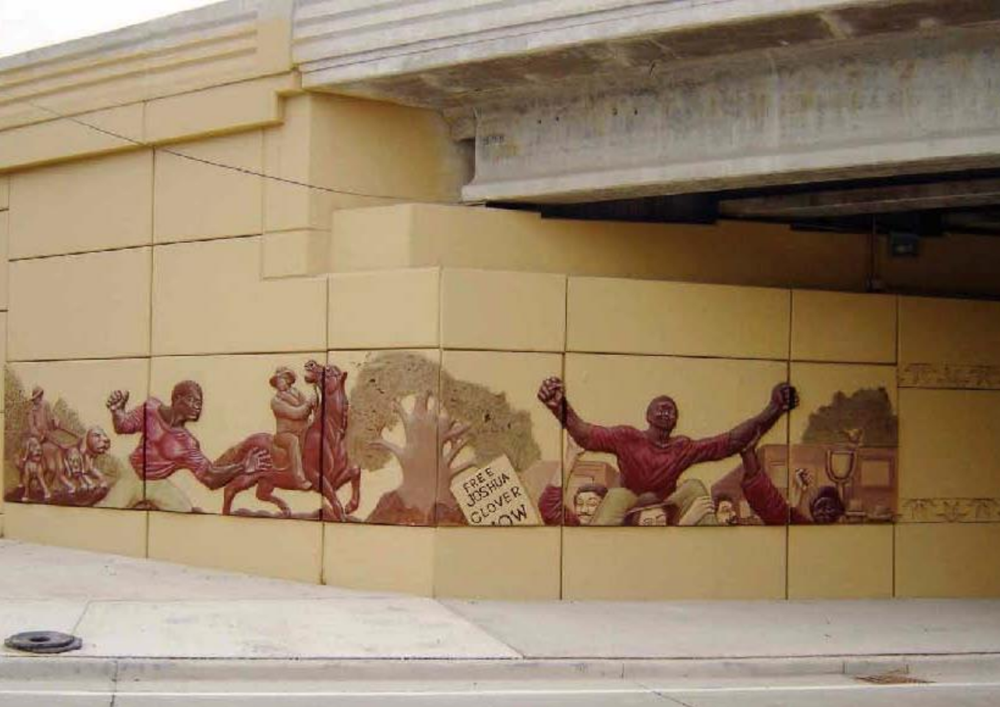
1. Intro
2. Acknowledgements
3. Reinforced soil—a historical perspective
4. Advantages/disadvantages/ characteristics
5. Basic principles/behavior of GRS
6. Design
7. Properties
8. Things we need still need to know and do—technical and professional issues
9. Successful examples
10. Final remarks

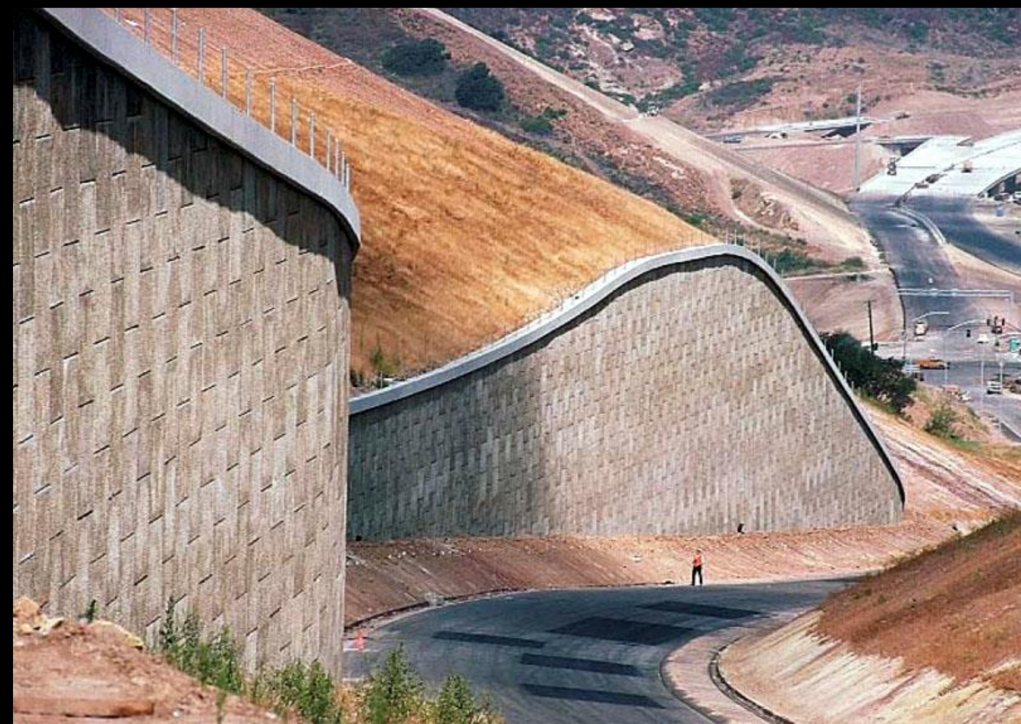
Founders Meadows Structure (I-25, Exit 184), near Denver, Colo

Colorado – Bob Barrett






FREE
JOSHUA
GLOVER




Austin, Texas


Colorado


Tijuana, Mexico


Olympia, Wash.

Taiwan




Colombia


Intercambio Vial de la Uribe


Autopista del Café


Geosistemas PAVCO

Medellin

“Not everyone in Colombia is a drug trafficker or a guerrilla!”

Civiling. Luis Fernando Cano, Medellin

N. California

N. Idaho


Yeager Airport, Charleston, W. Virginia

GRS wall along JR Kobe Line

F. Tatsuoka

And finally…

GRS slopes/walls

- from experimental, small scale, low risk…& not being readily accepted…to
- ≈ routine….

Prediction 1: GRS will soon be the “standard steep slope” and “standard wall”

Advantages

Examples

However: a few *technical* and *professional* issues remain--G-I, ASCE, ASFE? IGS, ISSMGE?

Prediction 2 for my academic colleagues: GRS and other types of reinforced walls will change the way we teach EP theory and the design of backfilled retaining structures…

--maybe change our approach slope stabilization…

Finally, I want to acknowledge with thanks:

- My former professors, colleagues, bosses, and students …. who taught me geotech and geosynthetics engr
- My UW colleagues, SLK and PA, who are still courageously trying to teach me modern developments in geotech engr…
- The G-I Board for this honor
- My wife, Cricket Morgan, for her patience and support throughout the years.

& I thank you, Ladies & Gentlemen, for your kind attention