27th Spencer J. Buchanan Lecture

Friday, October 18, 2019 at 2 PM

College Station Hilton

https://ceprofs.civil.tamu.edu/briaud/buchanan.html

Putting Numbers on Geotechnical Judgement

The 2019 Spencer J. Buchanan Lecture

By Dr. Gregory B. Baecher

Geotechnical Stability of Waste Fills

The 2018 Terzaghi Lecture

By Dr. Rudy Bonaparte

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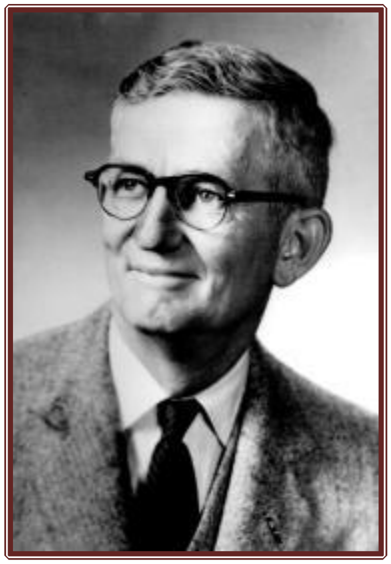
SPENCER J. BUCHANAN



Spencer J. Buchanan, Sr. was born in 1904 in Yoakum, Texas. He graduated from Texas A&M University with a degree in Civil Engineering in 1926, and earned graduate and professional degrees from the Massachusetts Institute of Technology and Texas A&M University.

He held the rank of Brigadier General in the U.S. Army Reserve, (Ret.), and organized the 420th Engineer Brigade in Bryan-College Station, which was the only such unit in the Southwest when it was created. During World War II, he served the U.S. Army Corps of Engineers as an airfield engineer in both the U.S. and throughout the islands of the Pacific Combat Theater. Later, he served as a pavement consultant to the U.S. Air Force and during the Korean War he served in this capacity at numerous forward airfields in the combat zone. He held numerous military decorations including the Silver Star. He was founder and Chief of the Soil Mechanics Division of the U.S. Army Waterways Experiment Station in 1932, and also served as Chief of the Soil Mechanics Branch of the Mississippi River Commission, both being Vicksburg, Mississippi.

Professor Buchanan also founded the Soil Mechanics Division of the Department of Civil Engineering at Texas A&M University in 1946. He held the title of Distinguished Professor of Soil Mechanics and Foundation Engineering in that department. He retired from that position in 1969 and was named professor Emeritus. In 1982, he received the College of Engineering Alumni Honor Award from Texas A&M University.

He was the founder and president of Spencer J. Buchanan & Associates, Inc., Consulting Engineers, and Soil Mechanics Incorporated in Bryan, Texas. These firms were involved in numerous major international projects, including twenty-five RAF-USAF airfields in England. They also conducted Air Force funded evaluation of all U.S. Air Training Command airfields in this country. His firm also did foundation investigations for downtown expressway systems in Milwaukee, Wisconsin, St. Paul, Minnesota; Lake Charles, Louisiana; Dayton, Ohio, and on Interstate Highways across Louisiana. Mr. Buchanan did consulting work for the Exxon Corporation, Dow Chemical Company, Conoco, Monsanto, and others.

Professor Buchanan was active in the Bryan Rotary Club, Sigma Alpha Epsilon Fraternity, Tau Beta Pi, Phi Kappa Phi, Chi Epsilon, served as faculty advisor to the Student Chapter of the American Society of Civil Engineers, and was a Fellow of the Society of American Military Engineers. In 1979 he received the award for Outstanding Service from the American Society of Civil Engineers.

Professor Buchanan was a participant in every International Conference on Soil Mechanics and Foundation Engineering since 1936. He served as a general chairman of the International Research and Engineering Conferences on Expansive Clay Soils at Texas A&M University, which were held in 1965 and 1969.

Spencer J. Buchanan, Sr., was considered a world leader in geotechnical engineering, a Distinguished Texas A&M Professor, and one of the founders of the Bryan Boy's Club. He died on February 4, 1982, at the age of 78, in a Houston hospital after an illness, which lasted several months.

The Spencer J. Buchanan '26 Chair in Civil Engineering

The College of Engineering and the Department of Civil Engineering gratefully recognize the generosity of the following individuals, corporations, foundations, and organizations for their part in helping to establish the Spencer J. Buchanan '26 Professorship in Civil Engineering. Created in 1992 to honor a world leader in soil mechanics and foundation engineering, as well as a distinguished Texas A&M University professor, the Buchanan Professorship supports a wide range of enriched educational activities in civil and geotechnical engineering. In 2002, this professorship became the Spencer J. Buchanan '26 Chair in Civil Engineering.

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Spencer J. Buchanan Lecture Series

1993	Ralph B. Peck	"The Coming of Age of Soil Mechanics: 1920 - 1970"
1994	G. Geoffrey Meyerhof	"Evolution of Safety Factors and Geotechnical Limit State Design"
1995	James K. Mitchell	"The Role of Soil Mechanics in Environmental Geotechnics"
1996	Delwyn G. Fredlund	"The Emergence of Unsaturated Soil Mechanics"
1997	T. William Lambe	"The Selection of Soil Strength for a Stability Analysis"
1998	John B. Burland	"The Enigma of the Leaning Tower of Pisa"
1999	J. Michael Duncan	"Factors of Safety and Reliability in Geotechnical Engineering"
2000	Harry G. Poulos	"Foundation Settlement Analysis – Practice Versus Research"
2001	Robert D. Holtz	"Geosynthetics for Soil Reinforcement"
2002	Arnold Aronowitz	"World Trade Center: Construction, Destruction, and Reconstruction"
2003	Eduardo Alonso	"Exploring the Limits of Unsaturated Soil Mechanics: the Behavior of Coarse Granular Soils and Rockfill"
2004	Raymond J. Krizek	"Slurries in Geotechnical Engineering"
2005	Tom D. O'Rourke	"Soil-Structure Interaction Under Extreme Loading Conditions"
2006	Cylde N. Baker	"In Situ Testing, Soil-Structure Interaction, and Cost Effective Foundation Design"
2007	Ricardo Dobry	"Pile response to Liquefaction and Lateral Spreading: Field Observations and Current Research"
2008	Kenneth Stokoe	"The Increasing Role of Seismic Measurements in Geotechnical Engineering"
2009	Jose M. Roesset	"Some Applications of Soil Dynamics"
2010	Kenji Ishihara	"Forensic Diagnosis for Site-Specific Ground Conditions in Deep Excavations of Subway Constructions"
2011	Rudolph Bonaparte	"Cold War Legacy – Design, Construction, and Performance of a Land-Based Radioactive Waste Disposal Facility"
2012	W. Allen Marr	"Active Risk Management in Geotechnical Engineering"
2013	Andrew J. Whittle	" Importance of Undrained Behavior in the Analysis of Soil-Structure Interaction"
2014	Craig H. Benson	"Landfill Covers: Water Balance, Unsaturated Soils, and a Pathway from Theory to Practice"
2015	William F. Marcuson III	"Katrina in Your Rearview Mirror"
2016	Edward Kavazanjian	"Bio-Geo-Alchemy: Biogeotechnical Carbonate Precipitation for Hazard Mitigation and Ground Improvement."
2017	Jonathan D. Bray	"Turning Disaster into Knowledge"
2018	Paul W. Mayne	"Versatility of Cone Penetration Tests in GeoCharacterization"
2019	Gregory B. Baecher	"Putting Numbers on Geotechnical Judgement"

The texts of the lectures and a DVD's of the presentations are available by contacting:

Dr. Jean-Louis Briaud
Spencer J. Buchanan '26 Chair Distinguished Professor
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Fugro Sponsorship

Texas A&M University and the Zachry Department of Civil Engineering gratefully acknowledge Fugro's sponsorship of the Buchanan Lecture. This Sponsorship, which began in 2013, reinforces the strong ties between the department and Fugro.

-Jean-Louis Briaud

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AGENDA

The Twenty-Seventh Spencer J. Buchanan Lecture
Friday, October 18, 2019 College Station Hilton

2:00 p.m.	Introduction by Jean-Louis Briaud and
2:20 p.m.	Introduction of Professor Greg Baecher by Jean-Louis Briaud
2:25 p.m.	"Putting Numbers on Geotechnical Judgement." Professor Greg Baecher delivers the 2019 Buchanan Lecture
3:25 p.m.	Discussion
3:35 p.m.	Introduction of Professor Rudy Bonaparte by Jean-Louis Briaud
3:40 p.m.	"Geotechnical Stability of Waste Fills - Lessons Learned and Continuing Challenges." Professor Rudy Bonaparte delivers the 2018 Terzaghi Lecture.
4:40 p.m.	Discussion
4:50 p.m.	Closure and Group photos followed by a Reception at the home of Jean-Louis and Janet Briaud

Biographies

Gregory B. Baecher, PhD, NAE

Glenn L. Martin Institute Professor of Engineering Department of Civil and Environmental Engineering University of Maryland, College Park, Maryland 20742
Mobile +1 (202) 577-6925,
Email gbaecher@mac.com

Dr. Baecher is Glenn L Martin Institute Professor of Engineering at the University of Maryland. He holds a BSCE from UC Berkeley and a PhD in geotechnical engineering from MIT. He is the author of six books on risk, safety, and the protection of civil infrastructure; and 200+ technical publications. He is recipient of the USACE Commander's Award for Public Service, the Panamanian National Award for Science and Technology Innovation, GEOSnet Distinguished Achievement Award for contributions to geotechnical reliability, and is a member of the US National Academy of Engineering and of the UC Berkeley Academy of Distinguished Alumni.

Dr. Rudolph Bonaparte, PhD, P.E.

Board Chairman at Geosyntec Consultants, Inc. and Professor of the Practice in the School of Civil and Environmental Engineering at the Georgia Institute of Technology

Dr. Rudolph Bonaparte is Board Chairman at Geosyntec Consultants, Inc., Atlanta, Georgia. He previously served as President and CEO for 20 years, building the firm to 1,200 employees in more than 60 offices in six countries. He is also a Professor of the Practice in the School of Civil and Environmental Engineering at the Georgia Institute of Technology. Dr. Bonaparte received his B.S. in Civil Engineering in 1977 from the University of Texas at Austin, and M.S. and Ph.D. degrees in Civil (Geotechnical) Engineering in 1978 and 1981, respectively, from the University of California, Berkeley. His practice focus is in geotechnical and geoenvironmental engineering. He is the author of more than 70 peer-reviewed technical papers and several book chapters on these topics. He is the recipient of the ASCE OPAL Lifetime Achievement Award in Design, the ASCE Terzaghi Lecture Award and James R. Croes Medal, and the Georgia ACEC Lifetime Achievement in Engineering Award. He was elected to the U.S. National Academy of Engineering in 2007. He is a licensed professional engineer in 17 states.

Putting Numbers on Geotechnical Judgement

The 2019 Spencer J. Buchanan Lecture

By Dr. Gregory B. Baecher

19th Buchanan Lecture

Putting numbers on geotechnical judgment

Gregory B. Baecher
University of Maryland

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19th Buchanan Lecture

Putting numbers on geotechnical judgment

Gregory B. Baecher
University of Maryland

Map

1. Judgment and probability
2. Primal guessing (Tonen)
3. Judgment and probability
4. Words of estimative probability (dam safety)
5. Bayes' factors (levee safety)
6. Experts and their opinions (how calibrated are you?)
7. Protocols of expert elicitation
8. Geology and models
9. Take-home lessons

2

Judgment and probability

WHEN YOU CAN MEASURE WHAT YOU ARE SPEAKING ABOUT, AND EXPRESS IT IN NUMBERS, YOU KNOW SOMETHING ABOUT IT, WHEN YOU CANNOT EXPRESS IT IN NUMBERS, YOUR KNOWLEDGE IS OF A MEAGER AND UNSATISFACTORY KIND; IT MAY BE THE BEGINNING OF KNOWLEDGE, BUT YOU HAVE SCARCELY, IN YOUR THOUGHTS ADVANCED TO THE STAGE OF SCIENCE.

LORD KELVIN, 3 MAY 1883,

BEFORE THE INSTITUTION OF CIVIL ENGINEERS

ONE GREAT GEORGE ST, WESTMINSTER, LONDON

Judgment and probability

THE LARGE HADRON COLLIDER

Oliver: "So, roughly speaking, what are the chances that the world is going to be destroyed? One-in-a-million? One-in-a-billion?"

Wagner: "Well, the best we can say right now is a one-in-two chance."

Oliver: "50-50?"

Wagner: "Yeah, 50–50… It's a chance, it's a 50–50 chance."

Oliver: "You come back to this 50–50 thing, what is it Walter?"

Wagner: "Well, if you have something that can happen and something that won't necessarily happen, it's going to either happen or it's gonna' not happen. And, so, it's kind of… best guess at this point."

Oliver: "I'm … not sure that's how probability works, Walter."

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TONEN (1978-1980)

Primal guessing: MIT in the 70's

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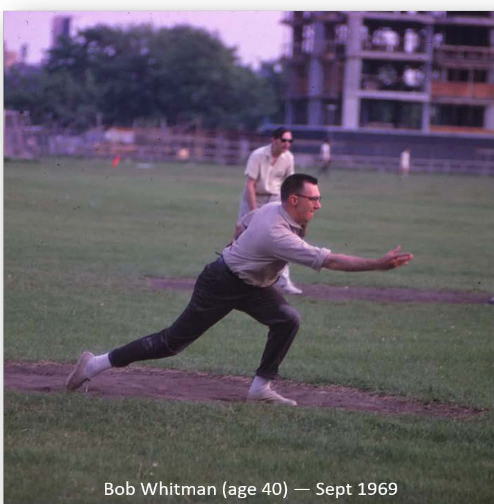
MIT in the 70's


Bob Whitman (age 40) — Sept 1969


Allin Cornell (age 31) — Sept 1969

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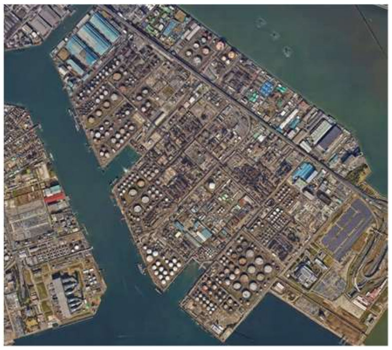
TONEN



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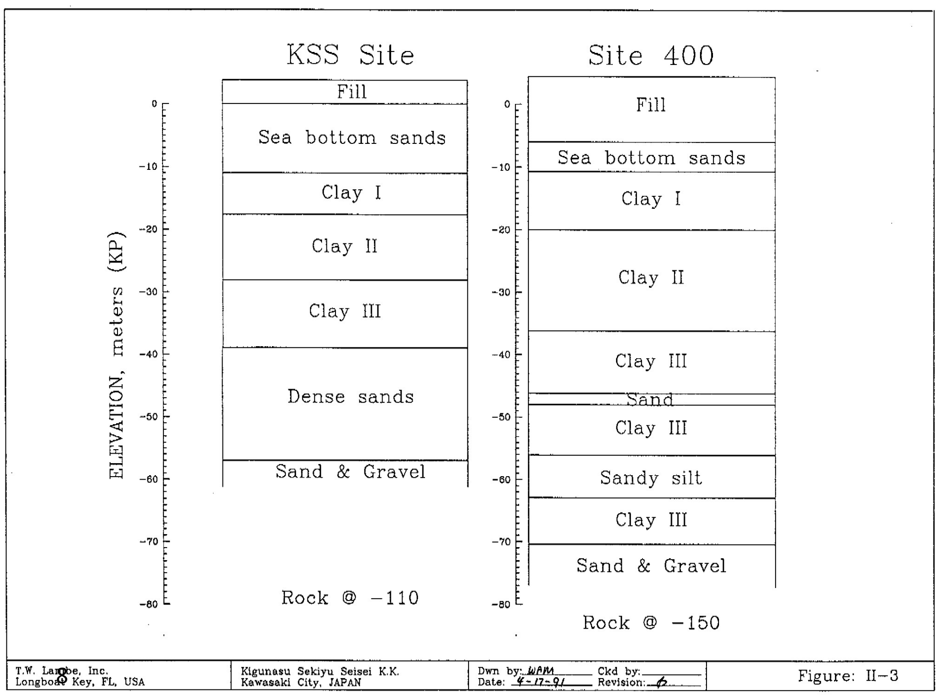

KSS Site
Site 400
ELEVATION, meters (KP)
0
-10
-20
-30
-40
-50
-60
-70
-80
Fill
Sea bottom sands
Clay I
Clay II
Clay III
Dense sands
Sand & Gravel
Rock @ -110
Fill
Sea bottom sands
Clay I
Clay II
Clay III
Sand
Clay III
Sandy silt
Clay III
Sand & Gravel
Rock @ -150
T.W. Lambe, Inc.
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Ckd by:
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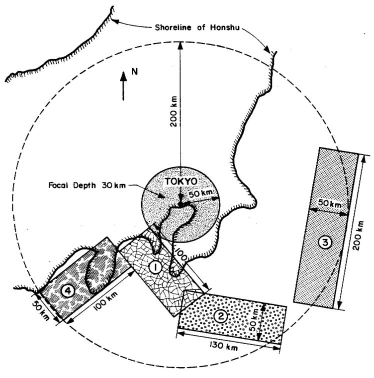
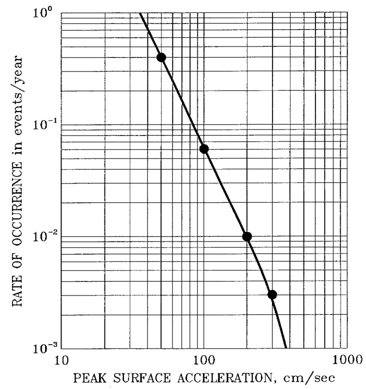
Figure: II-3

8

TONEN

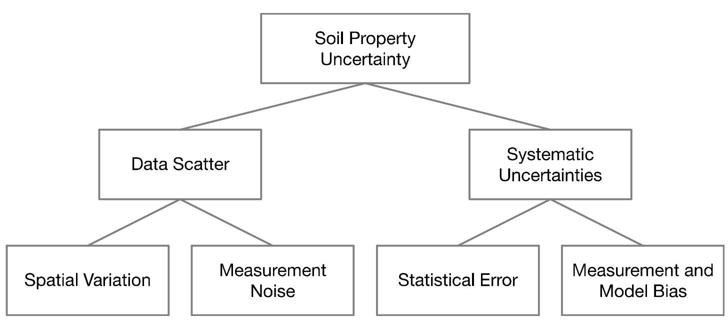


Shoreline of Honshu
N
200 km
TOKYO
Focal Depth 30 km
50 km
50 km
200 km
100 km
130 km

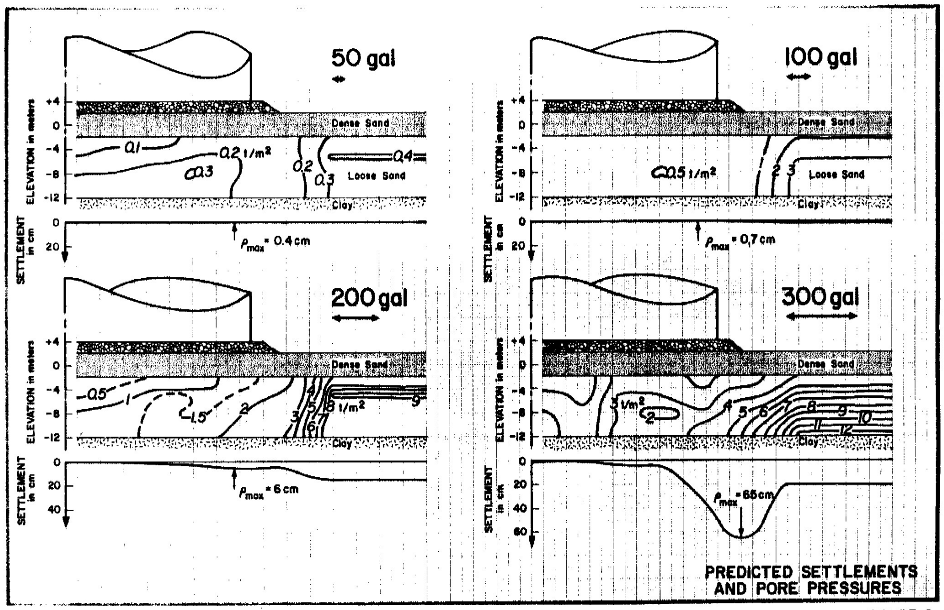


RATE OF OCCURRENCE in events/year
10^0
10^{-1}
10^{-2}
10^{-3}
10
100
1000
PEAK SURFACE ACCELERATION, cm/sec

TONEN



Soil Property Uncertainty
Data Scatter
Systematic Uncertainties
Spatial Variation
Measurement Noise
Statistical Error
Measurement and Model Bias



T.W. Lambe
Cambridge, Mass. USA

FIGURE 9

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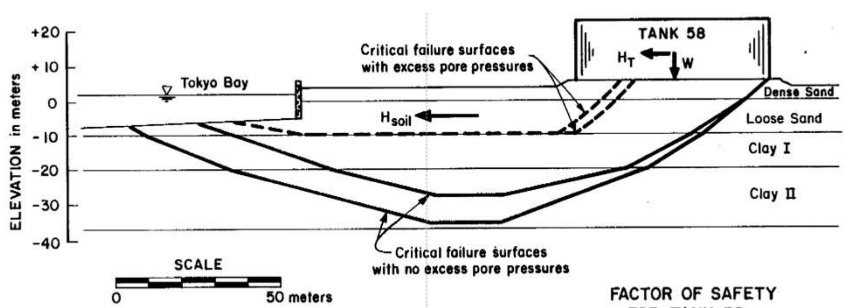
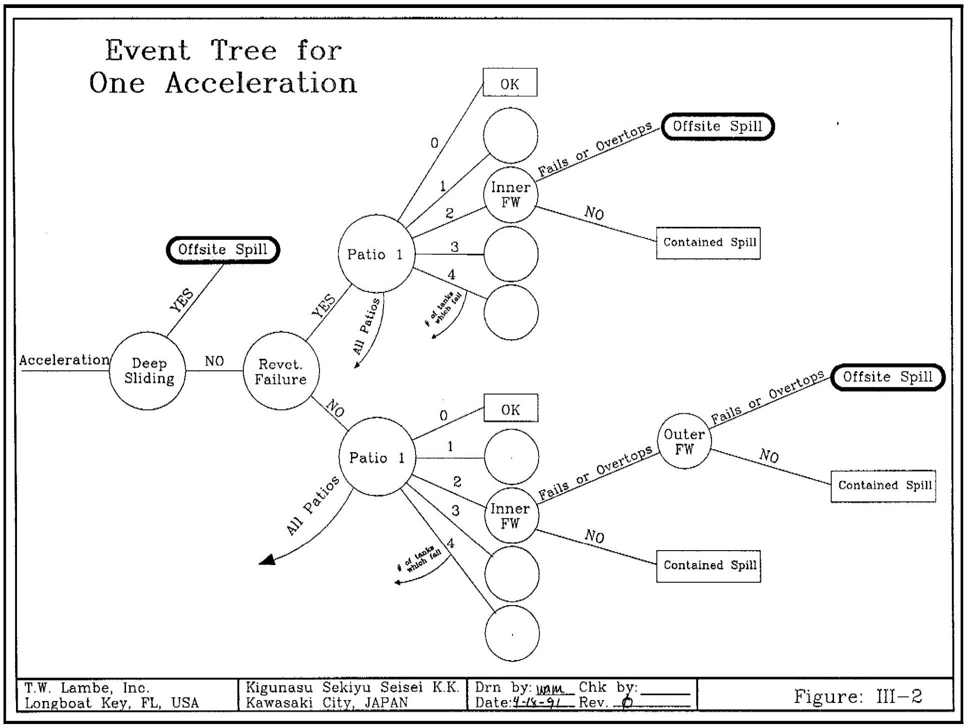


FACTOR OF SAFETY
FOR TANK 58

12



Lessons learned

WHAT WE LEARNED ABOUT JUDGMENTAL PROBABILITY :

- Dominance of epistemic uncertainties over “randomness”
- Divide and conquer — Hierarchy of soil property uncertainties
- Usefulness of reliability modeling vs. direct judgments
- Value of “slow-thinking” — deliberation and consensus

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Dam safety & WEP's

Rajendra Pachauri, the head of the U.N. Intergovernmental Panel on Climate Change (IPCC), left, and Sweden's Environmental minister Lena Ek, right, comment on the U.N. IPCC climate report, in Stockholm, Friday Sept. 27, 2013.

Scientists can now say with extreme confidence that human activity is the dominant cause of the global warming observed since the 1950s, a new report by an international scientific group said Friday. Calling man-made warming "extremely likely," the Intergovernmental Panel on Climate Change used the strongest words yet on the issue as it adopted its assessment on the state of the climate system.

– AP

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"Words of estimative probability"

Table 3. Verbal mapping scheme used in federal dam safety studies (USBR and USACE 2012a).

Descriptor	Probability
Virtually Certain	0.999
Very Likely	0.99
Likely	0.9
Neutral	0.5
Unlikely	0.1
Very Unlikely	0.01
Virtually Impossible	0.001

Table 2. Agreed upon terms describing uncertainty in IPCC reports (IPCC 2010).

Term	Probability
Virtually Certain	0.99-1.00
Very Likely	0.90-1.00
Likely	0.66-1.00
About as likely as not	0.33-0.66
Unlikely	0.00-0.33
Very Unlikely	0.00-0.10
Exceptionally unlikely	0.00-0.01

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“Words of estimative probability”

100% Certainty		
The General Area of Possibility		
93%	give or take about 6%	Almost certain
75%	give or take about 12%	Probable
50%	give or take about 10%	Chances about even
30%	give or take about 10%	Probably not
7%	give or take about 5%	Almost certainly not
0% Impossibility		

Sherman Kent(1903-1986)

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“Words of estimative probability”

100% Certainty		
The General Area of Possibility		
93%	give or take about 6%	Almost certain
75%	give or take about 12%	Probable
50%	give or take about 10%	Chances about even
30%	give or take about 10%	Probably not
7%	give or take about 5%	Almost certainly not
0% Impossibility		

Sherman Kent(1903-1986)

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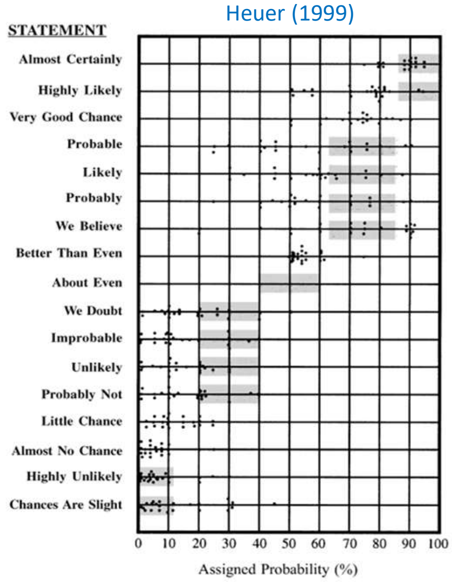
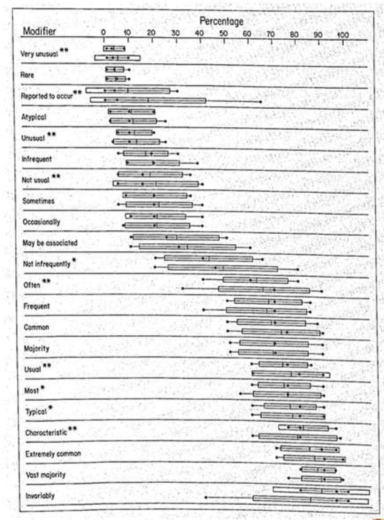
“Words of estimative probability”

Heuer (1999)

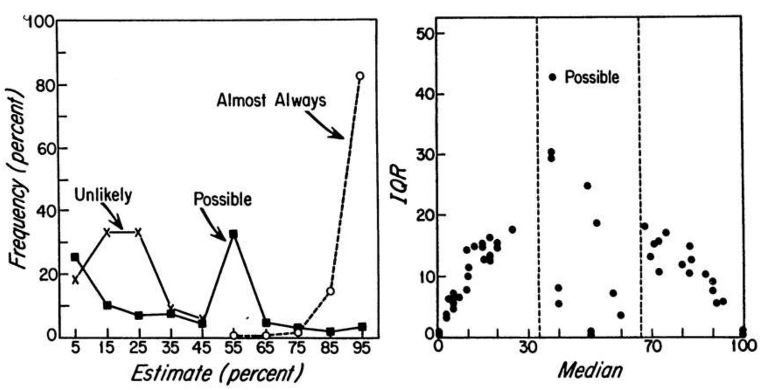


Nakao and Axelrod 1983



“Words of estimative probability”

Science Writers



Mosteller, F., and Youtz, C. (1990). “Quantifying Probabilistic Expressions.” *Statistical Science, 5* (1), 2–12.

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“Words of estimative probability”

DNI 2015, Intelligence Community Directive 203, Office of the Director of National Intelligence, Washington DC, 6pp.

almost no chance	very unlikely	unlikely	roughly even chance	likely	very likely	almost certain(ly)
remote	highly improbable	improbable (improbably)	roughly even odds	probable (probably)	highly probable	nearly certain
01-05%	05-20%	20-45%	45-55%	55-80%	80-95%	95-99%

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“Words of estimative probability”

MISLEADING WORDS TO BE AVOIDED

Weasel words
A chance
Cannot discount
Cannot dismiss
Cannot rule out
Could
It’s conceivable
May
Maybe
Might
Perhaps
Possibly
Suggests
We believe that …

22

“Words of estimative probability”

Pope Francis criticises overuse of adjectives

Pope gives views on language in speech to Vatican communications team

▲ The pope took particular aim at the word ‘authentic’, especially when describing ‘authentic Christians’.
Photograph: Yara Nardi/Reuters

The Guardian, Sep 24th, 2019

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Lessons learned

WHAT WE LEARNED ABOUT WEPs :

1. WEPS ARE INADEQUATE.
2. MEAN DIFFERENT THINGS TO DIFFERENT EXPERTS.
3. MAY OBSCURE DIFFERENCES AMONG EXPERTS.
4. MEAN DIFFERENT THINGS TO THE SAME PERSON IN DIFFERENT SITUATIONS.
5. MEAN DIFFERENT THINGS TO EXPERT *VS.* STAKEHOLDER.
6. MAY TEND TO ANCHOR EXPERTS’ LATER RESPONSES.

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Lessons learned

WHAT WE LEARNED ABOUT WEPs :

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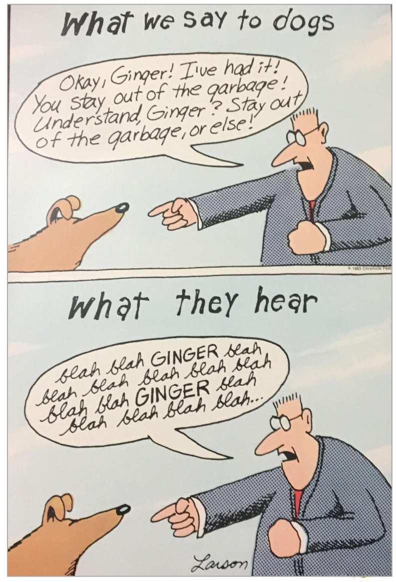

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Levee safety: Bayes' Factors

"Bayes' Rule is trivial, but it is very tidy."

—Ian Hacking (2001)

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Levee safety: Bayes' factors

CONDITION SURVEYS


(State of Maryland, DNR)

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Levee safety: Bayes' factors

DON'T FORGET, "STATISTICS ARE YOUR FRIENDS!"

$$\frac{Pr(H|data)}{Pr(\bar{H}|data)} = \frac{Pr(H)}{Pr(\bar{H})} \times \frac{Pr(data|H)}{Pr(data|\bar{H})}$$

$$Odds(H|data) = Odds(H) \times LR$$

Bayes' Factor = Weight of evidence
a/k/a Likelihood Ratio

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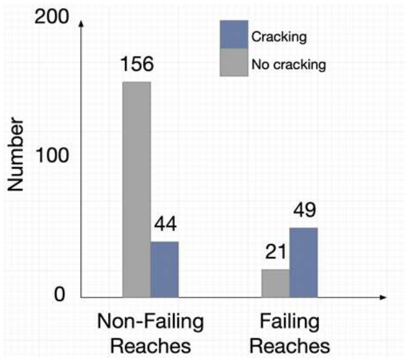
Levee safety: Bayes' factors

CONDITION SURVEYS



You've observed cracking.
What's the chance of a failing reach?

$$LR = \frac{Pr(C|F)}{Pr(C|NF)} = \frac{156/200}{21/70} = 3.2$$

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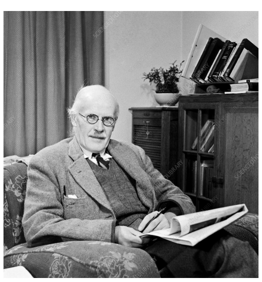
Levee safety: Bayes' factors

SIR HAROLD JEFFREYS' WEIGHT OF EVIDENCE



LR	lnLR	logLR	Weight of Evidence, K
< 1:1	< 0	< 0	Negative (supports alternative proposition)
1:1 to 3:1	0 to 1.1	0 to 0.5	Barely worth mentioning
3:1 to 10:1	1.1 to 2.3	0.5 to 1	Substantial
10:1 to 30:1	2.3 to 3.4	1 to 1.5	Strong
30:1 to 100:1	3.4 to 4.6	1.5 to 2	Very strong
>100:1	> 4.6	> 2	Decisive

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Levee safety: BAYES' FACTORS

CONDITION SURVEYS

	Failing		Non-failing		Total
	Number	Fraction	Number	Fraction	
Cracking	70	70%	200	22%	270
Settlement	40	40%	100	11%	140
Both	30	30%	50	6%	80
Total	100	100%	900	100%	1000

	P(data|F)	P(data|¬F)	LR	P(F)	P(F|data)
P(H|C)	70%	22%	3.18	0.10	0.26
P(H|S)	40%	11%	3.64	0.10	0.29
P(H|C,S)	30%	6%	5.00	0.10	0.38

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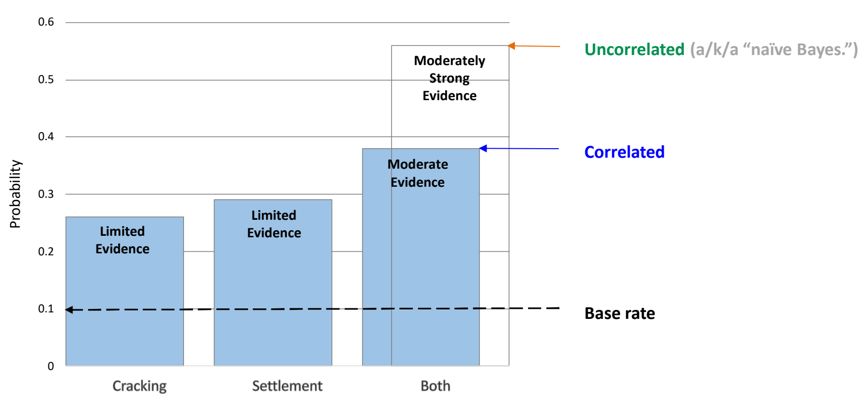
Levee safety: BAYES' FACTORS

CONDITION SURVEYS



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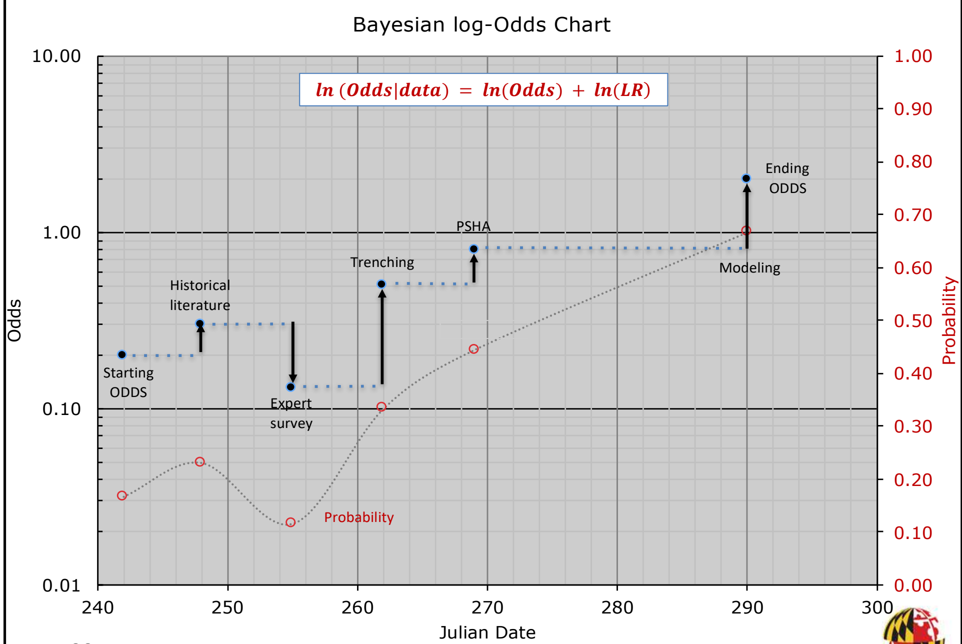

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Whitman-Casagrande scheme

WHITMAN'S (1984) REFORMULATION OF CASAGRANDE'S THINKING

	Gradient scale →	
$p=10^{-2}$	*$p=10^{-1}$*	*$p=10^{0}$*
Stiff	SHELL	Flexible
Regular	VALLEY	Irregular
Small	SETTLEMENT	Large
Flat	ABUTMENTS	Steep
Plastic	CORE	Brittle
No	ARCHING	yes

	Gradient scale →	
$p=10^{-3}$	*$p=10^{-2}$ … 10^{-1}*	*$p=10^{0}$*
Careful	SUPERVISION	Not
Satisfied	CRITERIA	Not met
Stable	SOIL	Dispersive
Low	GRADIENTS	High

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What we learned

WHAT WE LEARNED ABOUT BAYES' FACTORS :

ENTIRE WEIGHT OF EVIDENCE IN DATA OR OBSERVATIONS

INTUITIVE TO MOST ENGINEERS

CONCEPTUALLY EASY TO APPRAISE

(INCREDIBLY) STRONG INFERENCES FROM WEAK OR SPARSE DATA

FOUNDATION FOR AI-CLASSIFICATION, FORENSICS, AND MANY FIELDS

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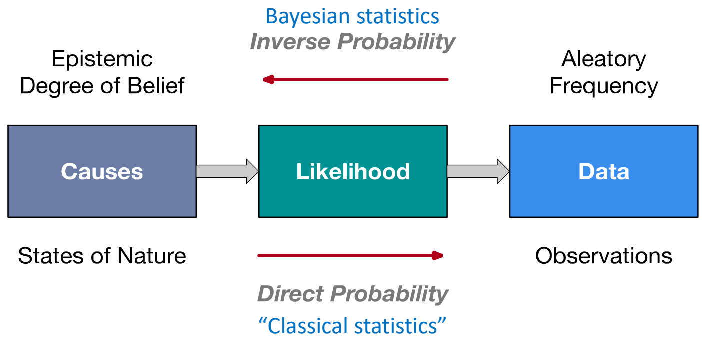
Philosophical digression

All GT's are Bayesians ±

All GT's are Bayesians ±

INVERSE PROBABILITY

THE STATISTICS YOU LEARNED IN COLLEGE IS USELESS



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All GT's are Bayesians ±

FREQUENTIST ("CLASSICAL") STATISTICS IS ABOUT RANDOMNESS IN NATURE.

- Needs lots of data to yield significant results,
- Considers repetitive events in ∞ series of trials,
- Confidence intervals AREN'T probabilities on states of nature.

GEOTECHNICAL ENGINEERING IS ABOUT EPISTEMIC UNCERTAINTY.

- Sparse data,
- Unique situations,
- Admits of probabilities on states of nature,
- Admits of subjective judgment.

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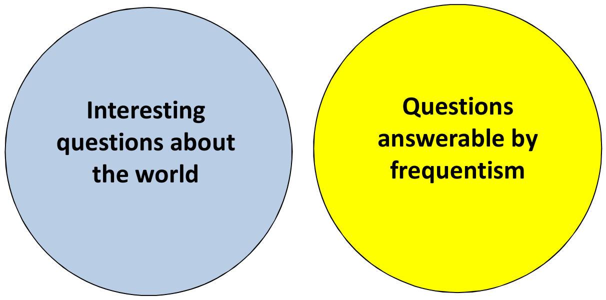
All GT's are Bayesians ±



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Experts and their opinions

Things we know about the biases of expert judgment
& about calibrating judgmental probabilities

Experts and their opinions

"WITHOUT DATA YOU'RE JUST ANOTHER PERSON WITH AN OPINION."

Edwards Deming (1900-1993)

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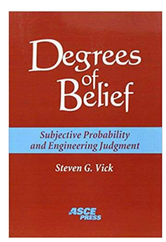
Experts and their opinions

COGNITIVE BIASES

IMPORTANT AND PERVASIVE

- Over-confidence
- Ignoring base-rates ("representativeness")
- Blindness to sample size ("representativeness")
- Anchoring on best-estimates
- Availability



Tversky, A., and D. Kahneman. "Belief in the 'law of Small Numbers'." *Psychological Bulletin* 76 (1971): 105–10.

Tversky, A., and D. Kahneman. "Judgment under Uncertainty: Heuristics and Biases." *Science* 185 (1974): 1124–31.

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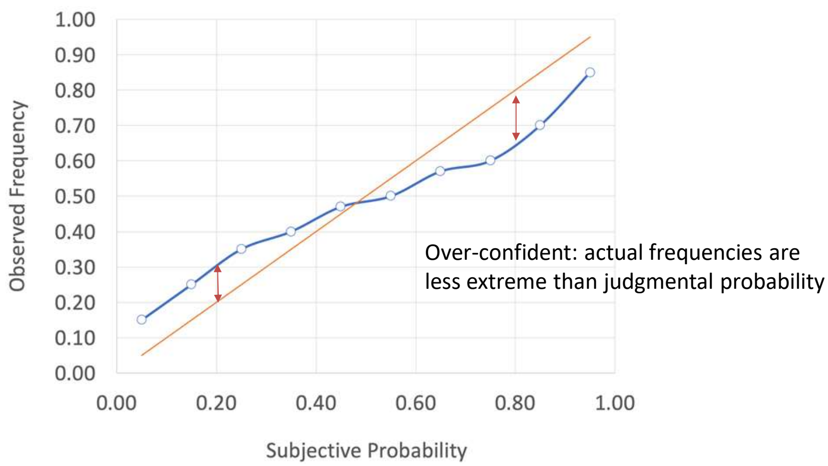
Experts and their opinions

GBB's PERSONAL CALIBRATION (*n=65*)



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Experts and their opinions

SCORING RULES

AND WEATHER FORECASTING

Left to right: Allan Murphy (chair, SC/IMSC); Glenn Brier (recipient, IMSC outstanding achievement award); and Harry Glahn (speaker, IMSC award).

$$Brier\ Score = \frac{1}{n}\sum_{i=1}^{n}(p_i - o_i)^2$$

Repetition
Feed back
Importance

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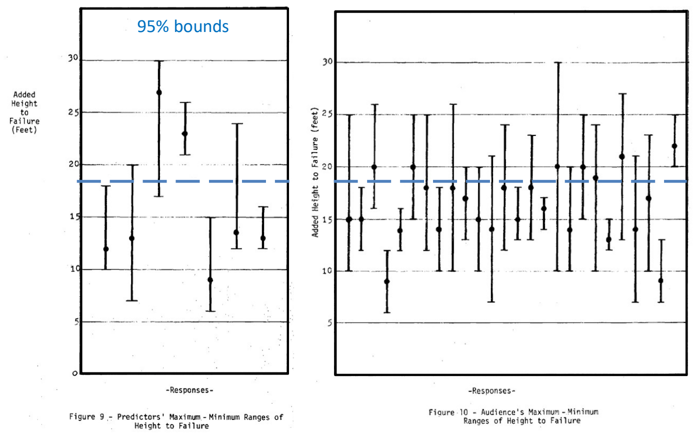
Experts and their opinions

WISDOM OF THE CROWD



From Mary-Ellen Hynes and Erik VanMarke, 1975
Replicated from Marr, 2019

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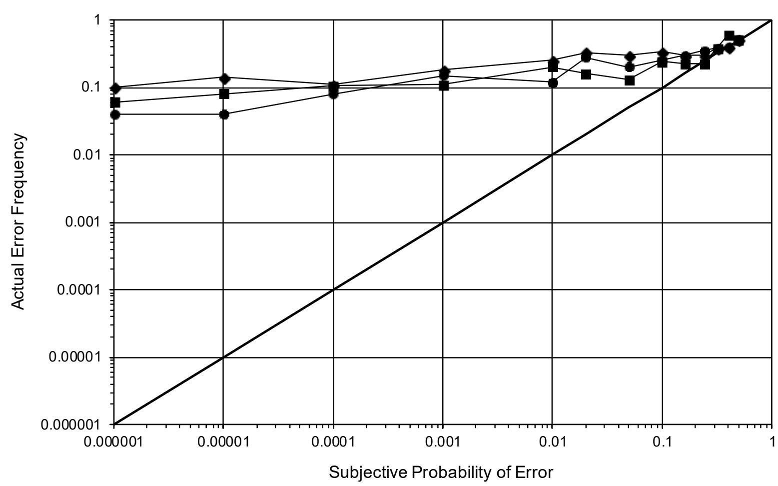
Experts and their opinions

RARE EVENTS



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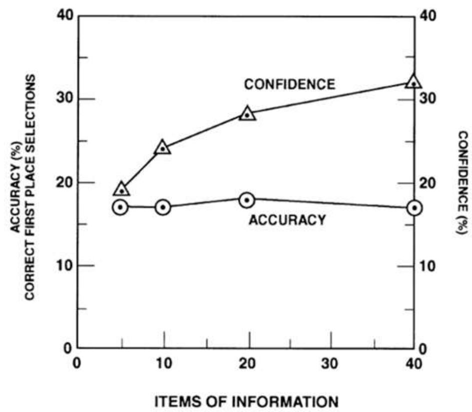
Experts and their opinions



Relationship between information, the accuracy of handicappers' prediction, and their confidence. Data from Slovic (1973); figure from Heuer (1999).

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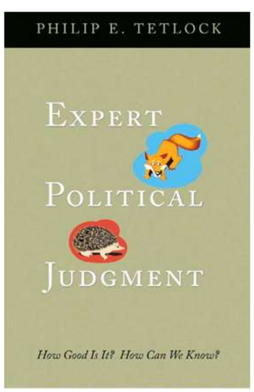
Experts and their opinions

HEDGEHOGS AND FOXES (TETLOCK 2006)



The Isaiah Berlin paradigm:

Hedgehogs are experts with a grand theory of the world.

Foxes are experts without a grand theory and ready to change their predictions based on evidence.

Foxes are better predicters than are hedgehogs.

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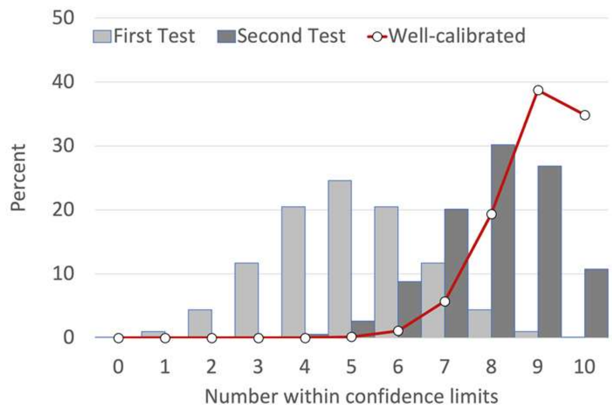
Experts and their opinions

BENEFIT OF TRAINING

Results of the training session confidence limits assessments (adapted from Hubbard 2014)



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What we learned

WHAT WE LEARNED ABOUT EXPERTS AND THEIR OPINIONS :

WE ARE ALL BIASED

OUR BIASES ARE SYSTEMATIC AND PREDICTABLE

CALIBRATION CAN BE LEARNED

RARE-EVENT PROBABILITIES SHOULD NEVER BE ELICITED

FOXES ARE BETTER PREDICTERS THAN ARE HEDGEHOGS

A GROUP OFTEN MAKES A BETTER FORECAST THAN ANY OF ITS MEMBERS

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Charting arguments

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Charting arguments

USBR-USACE APPROACH FOR DAM SAFETY RISK

PFM:	N-1	Failure Mode:	Internal erosion through the embankment (concentrated leak erosion; scour)
Initiator:	Embankment cracks or high permeability zone exists at or below the normal reservoir level		
Step-by-Step Description:	Reservoir water flows through the crack and slowly scours embankment material. The crack remains open and does not swell shut or collapse. Materials continue to erode, widening and deepening erosion pathway. The flow and erosion goes unnoticed, and when it is noticed intervention efforts fail.		
Breach:	The dam fails by gross enlargement of the erosion pathway and the reservoir is released.		

More Likely Factors	Less Likely Factors
• Seep observed at the base of the dam collected by toe drain pipe at auxiliary spillway. • Vegetation at toe near plunge pool could make it difficult to observe adverse behavior or material transport with excessive or unusual seepage. • Plastic clays could experience cracking. • Hot dry temperature creates desiccation cracking that could exacerbate existing cracking or could worsen if left untreated. • Rodent burrows could lead to defects and increased gradients. • Alluvial materials (silty sand?) in the drainage channel may have been used as embankment fill, creating a permeable u/s to d/s zone. • Small cracks could widen if they dry out due to nature of the clays. • If a concentrated leak developed and began eroding soils, there is no designed filter to	• There has been no evidence of any concentrated seepage through the embankment dam. • Cracks on embankment would be visible with little vegetation • No evidence of material transport in seepage areas • No evidence of animal burrows • No observations of sinkholes or depressions that may be indicative of subsurface cracking or erosion • There is some vegetation at the toe of the dam but no large trees or extensive root systems that could create seepage pathways. • Construction – lift thickness (8-10 inches with well documented construction would be less likely factor) • Flaw – dam was well built by SCS. Engineers were experienced with dam construction, lower risk of built-in flaw, design flaw or construction flaw.

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Charting arguments

JOHN HENRY WIGMORE (1863-1943)

(NORTHWESTERN UNIVERSITY ARCHIVE).

Wigmore, John Henry. *A treatise on the Anglo-American system of evidence in trials at common law: including the statutes and judicial decisions of all jurisdictions of the United States and Canada*. 2d ed. Boston: Little, Brown, and Company, 1923.

53

Charting arguments

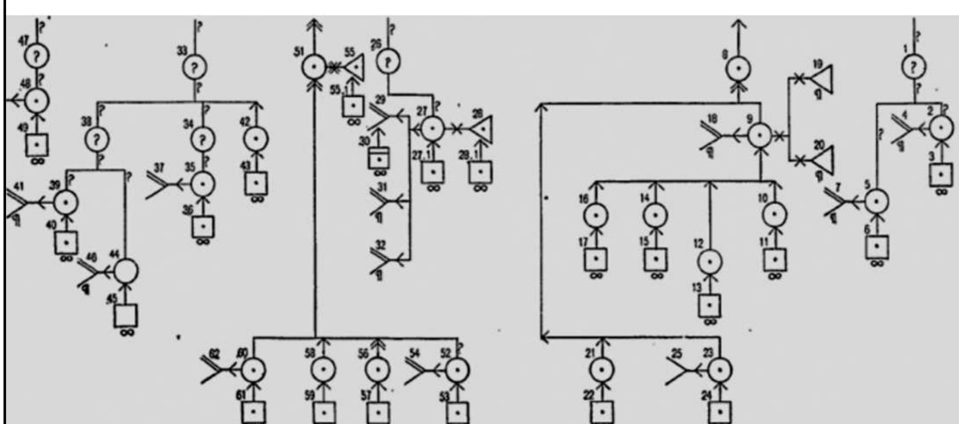

FIG. 1. Wigmore, *Chart of the Evidence in Commonwealth* v. *Umilian*. 1913. From *The Problem of Proof*.

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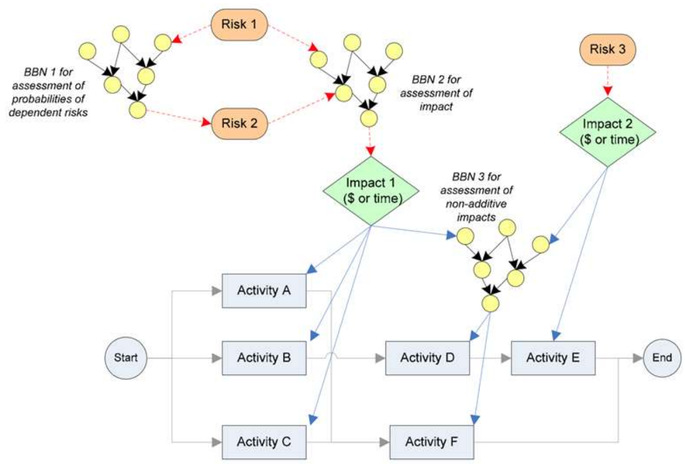
Charting arguments



Ordonez, J. (2007). "A Methodology for Project Risk Analysis Using Bayesian Belief Networks within a Monte Carlo Simulation Environment." PhD dissertation, University of Maryland, College Park.

55

What we learned

WHAT WE'VE LEARNED ABOUT CHARTING ARGUMENTS :

DECOMPOSING AN INFERENCE INCREASES CLARITY

SIMPLER ELICITATIONS ARE EASIER THAN COMPLEX ONES

INFLUENCE DIAGRAMS AND CHARTS HELP (BUT TAKE TIME AND EFFORT)

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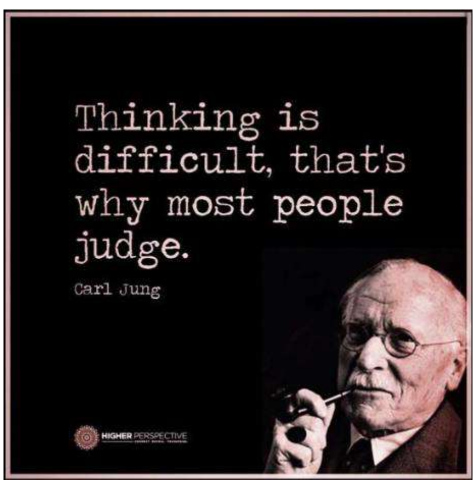
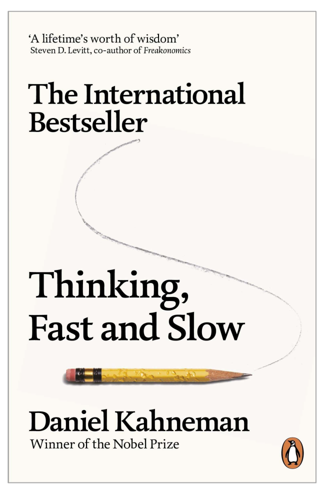
Protocols of expert elicitation

Process is important

Protocols of expert elicitation





Protocols of expert elicitation

JUST ASK THE EXPERT …

“ While this method is surely the most common, it is equally surely the worst. […] Considerable thought must be given to the manner in which probabilities are elicited. ”

— Roger Cooke (1991)

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Protocols of expert elicitation

BETTING APPROACH

THE BRETT KAVANAUGH NOMINATION

One-point assessment of my subjective probability a week before the Senate vote.

Here’s is what I calculated:

Q1: Would I bet on confirmation *vs.* a 50:50 bet on a coin … yes ∴ $p \geq 1/2$.

Q2: Would I bet on confirmation *vs.* not rolling a 6 with a die … no ∴ $p \leq 1/6$.

Q3: Would I bet on confirmation *vs.* not drawing a Spade with cards … yes ∴ $p \leq 3/4$.

Q4: Would I bet on confirmation *vs.* not rolling a (5,6) with a die … maybe ∴ $p \geq 2/3$.

I’m not sure that I can refine the probability more than that, so let’s say that in favor of the confirmation, $0.66 \leq p \leq 0.75$.

In the end, the confirmation was successful. Was my subjective probability “wrong”? No, I would have made those bets with actual money.

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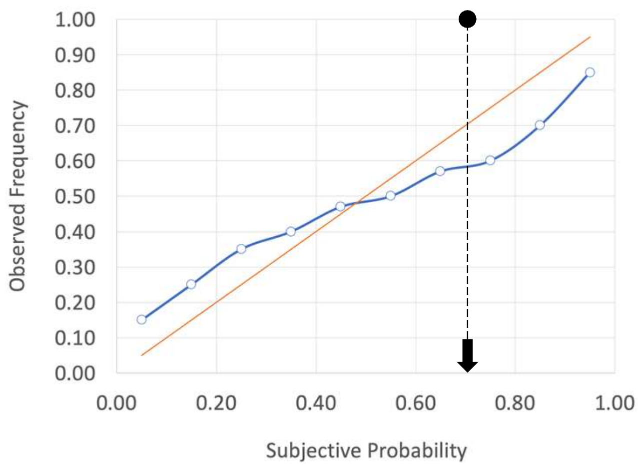
Experts and their opinions

GBB's PERSONAL CALIBRATION



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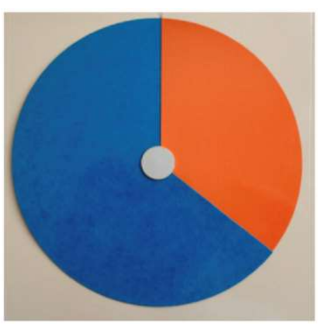
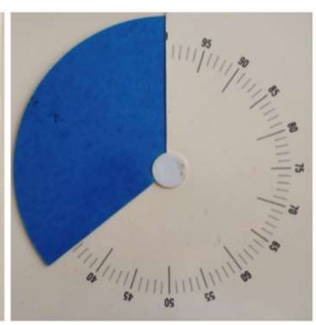
Protocols of expert elicitation



FRONT



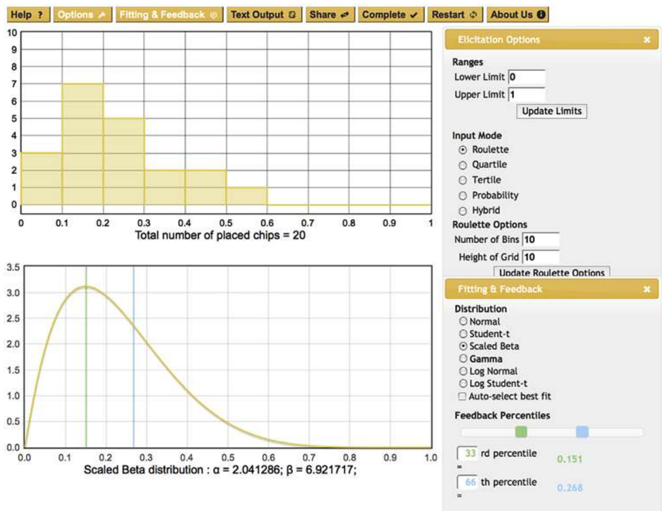
BACK

Decision Focus, Inc.

Spetzler, C. S., and von Holstein, C.-A. S. S. (1975). "Probability Encoding in Decision Analysis." *Management Science*, *22* (3), 340–358.

62

Protocols of expert elicitation



Morris, D. E., Oakley, J. E., and Crowe, J. A. (2014). "A web-based tool for eliciting probability distributions from experts." *Environmental Modelling & Software, 52*, 1–4.

Protocols of expert elicitation

GROUP PROBABILITIES

1. BAYESIAN LIKELIHOOD (PETER MORRIS' APPROACH)
2. WEIGHTED SUM (ROBIN COOKE'S 'CLASSICAL' APPROACH)
3. GROUP CONSENSUS (UNIVERSITY OF SHEFFIELD APPROACH)

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Protocols of expert elicitation

WHAT WE LEARNED ABOUT FORMAL PROTOCOLS :

1. BETTING APPROACH IS ESSENTIAL
2. HOW YOU ASK QUESTIONS IS IMPORTANT
3. KEEP IT SIMPLE
4. CONSENSUS DISCUSSION IS VITAL

65

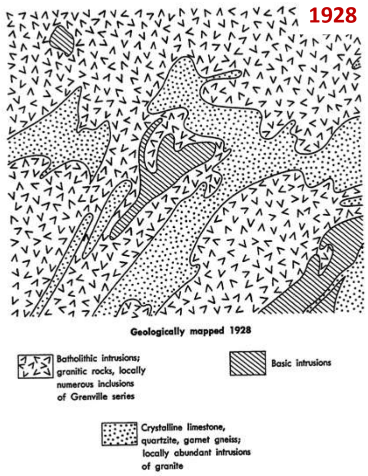
Geology and models

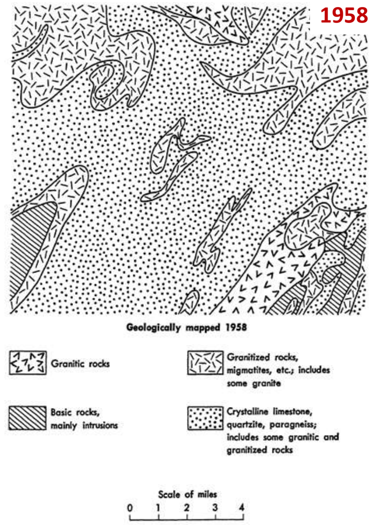
Data don't speak for themselves

Geology and models

Harrison, J.M. “Nature and Significance of Geological Maps.” In *The Fabric of Geology*, edited by C.C. Albritton, 225–32. Boston: Addison-Wesley, 1963.

EXPLANATIONS (HYPOTHESES)





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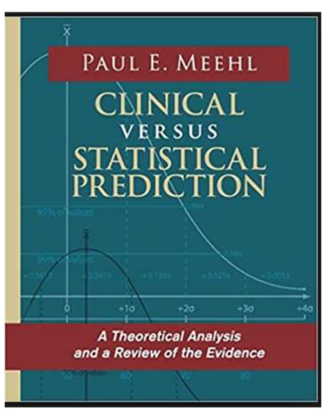
Geology and models

RELIABILITY APPROACH GENERALLY OUTPERFORMS DIRECT PROBABILITY



(1954)


The Robust Beauty of Improper Linear Models in Decision Making

ROBYN M. DAWES University of Oregon

(1979)

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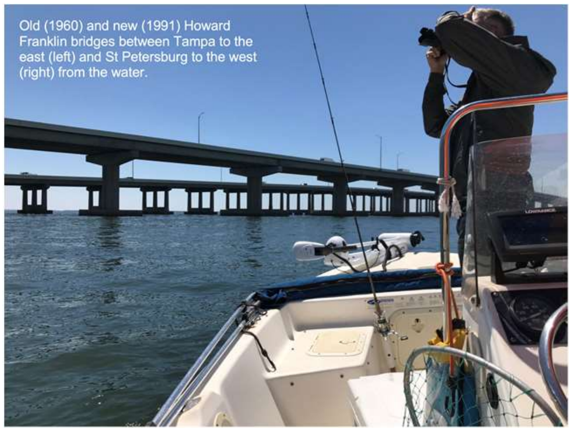
Geology and models



Baecher, GB, McGillivray, RT, and Waits, TM (2020). "Unraveling foundation uncertainty: how statistical analytics helps control design-build and planning risk," *Geostrata,* ASCE GeoInstitute, Reston.

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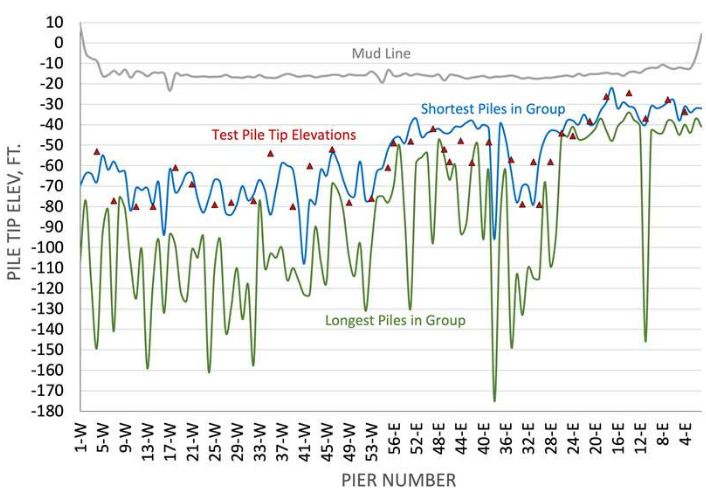
Geology and models



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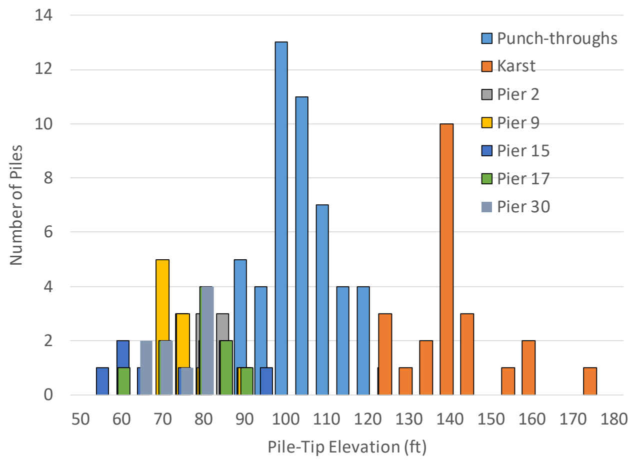
Geology and models



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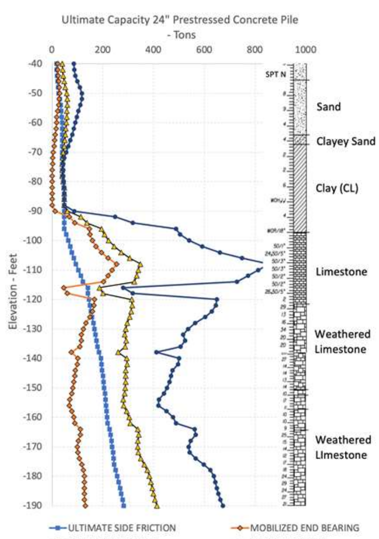
Geology and models



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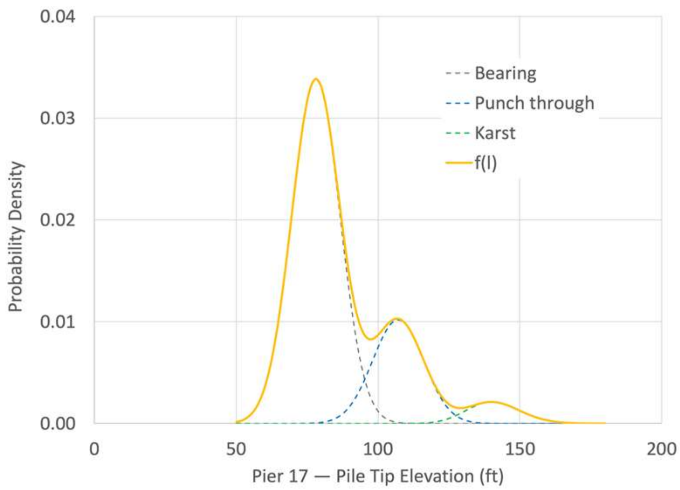
Geology and models

PHYSICS-BASED MODEL WITH JUDGMENTAL PARAMETERS



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What we learned

WHAT WE LEARNED ABOUT GEOLOGICAL JUDGMENT

GEOLOGICAL DATA DON'T SPEAK FOR THEMSELVES

GEOLOGICAL CONCEPT DRIVES INTERPRETATION

EFFECTIVE TO USE ENGINEERING JUDGMENT TO ASSIGN PARAMETERS TO MODEL

74

Don't forget, "statistics are your friends!"

It was easier as an "occult art"

75

What we've learned …

WHAT WE LEARNED ABOUT PUTTING NUMBERS ON GT JUDGMENT

1. YOU CAN'T IGNORE QUANTIFYING ENGINEERING JUDGMENT (IT'S POOR PRACTICE)
2. TAKE ELICITATION SERIOUSLY (ANYONE CAN MAKE UP CRAZY NUMBERS)
3. CAN'T JUST "ASK AN EXPERT" (YOU'LL GET A SILLY ANSWER)
4. ELICITATION IS A PROCESS (PEOPLE DON'T KNOW THEIR PROBABILITIES)
5. COGNITIVE BIASES ARE REAL (IGNORE THEM AT YOUR PERIL)
6. CALIBRATION CAN BE LEARNED (BUT IT TAKES TIME AND BELIEF)
7. IT'S USUALLY BETTER TO HAVE A MODEL (AND TO ELICIT ITS PARAMETERS)

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The End.
USACE Big Bend Dam, 14 June 2011 flood
Slide
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Geotechnical Stability of Waste Fills – Lessons Learned and Continuing Challenges

The 2018 Terzaghi Lecture

By Dr. Rudolph Bonaparte

2019 Buchanan Lecture Program
Texas A&M University

Geotechnical Stability of Waste Fills – Lessons Learned and Continuing Challenges
(54th ASCE Karl Terzaghi Lecture)

Rudolph Bonaparte Ph.D., P.E., D.GE., NAE, F.ASCE
Chairman and Senior Principal
Geosyntec Consultants, Inc.
and
Professor of the Practice
School of Civil and Environmental Engineering
Georgia Institute of Technology

Geosyntec consultants

October 18th, 2019

Organization of Lecture

1. Where Did We Start
   - *(early 1980s to mid 1990s)*
2. What Did We Learn
   - *(by mid 1990s)*
3. Continuing Challenges
   - *(2010 to present)*
4. Observations and Recommendations

2

Thousands of Waste Fills in the U.S., and Many Thousand More Around the World

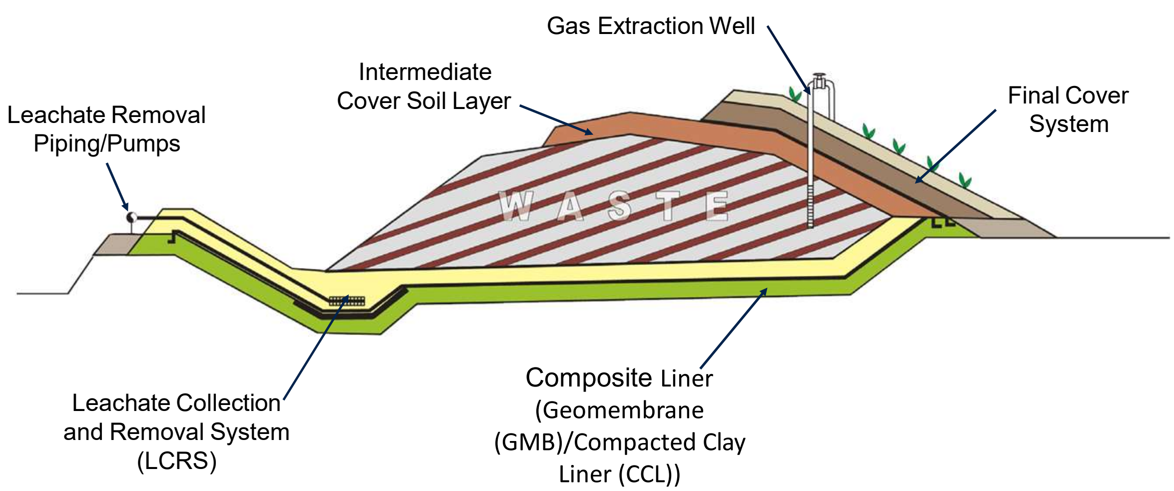
- ~2,000 active municipal solid waste (MSW) landfills
- ~10,000 closed MSW landfills
- ~1,000s of:
  - *Industrial waste impoundments and by-product landfills*
  - *Mine tailings impoundments*
  - *Coal combustion residual (CCR) impoundments and landfills*
  - *RCRA and TSCA hazardous waste (HW) landfills*
  - *Low-level radioactive waste and mixed waste (LLRW) facilities*
- Globally, there are many times the number of waste fills as in the U.S. (but focus today is on the U.S.)


OII Superfund Site Monterey Park, CA

Unstable Waste Fills Pose Risks to Lives, Property, and the Environment

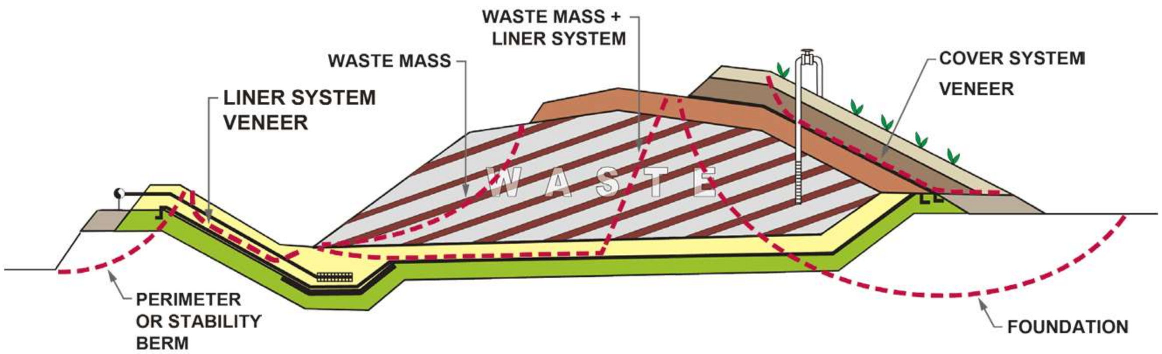
3

Typical Layout of Modern Lined Solid Waste Fill



4

Geotechnical Stability Failure Modes



Geotechnical design engineers must be cognizant of multiple potential static and seismic failure modes that can exist at each stage of waste fill development.

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Where We Started
(early 1980s to mid 1990s)

Where We Started (35 to 20 years ago)

Waste Fill Failures Drew the Scrutiny of Owners, Regulators, and Geotechnical Engineers

- Global MSW Landfill, NJ (1984)
- Kettleman Hills HW Landfill, CA (1988)
- Crossroads MSW Landfill, ME (1989)
- Chiquita Canyon, CA (1994)
- Keller Canyon Landfill, CA (1994)
- Rumpke MSW Landfill, OH (1996)
- Mahoning MSW Landfill, PA (1996)

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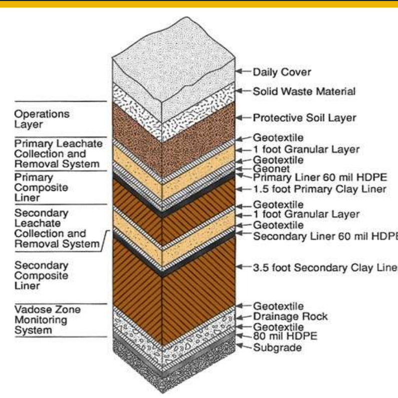
Kettleman Hills HW Landfill Unit B-19, California (1988)

Waste Mass and Liner System Interface Failure

References: Mitchell et al. (1990, 1993); Seed et al. (1990); Geosyntec (1991); Byrne et al. (1992); Stark et al. (1994); Filz et al. (2001)

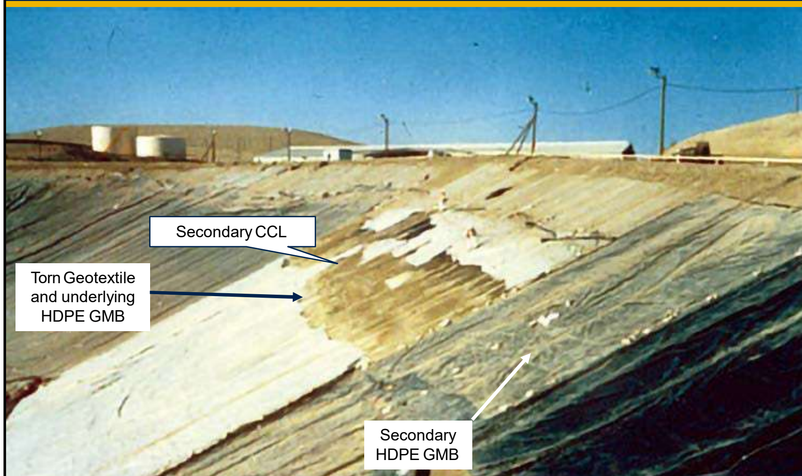


In early 1988, a year after filling began, and with the waste fill in an interim configuration with a height of 90 feet, 580,000 CY of waste moved ~ 14 feet downward and ~ 35 feet laterally over several hours

8

Kettleman Hills HW Landfill Unit B-19, California (1988)

Waste Mass and Liner System Interface Failure



Analyses and physical modeling also showed that 3-D effects were important given the waste fill geometry, and that the failure mechanism involved progressive loss of interface strength (peak to residual)

- Forensic investigation revealed a translational sliding mechanism along liner-system interfaces
- Slippage was observed to be at the interface between the secondary HDPE GMB and underlying CCL; post-failure testing of this interface produced undrained residual interface strengths of about 500 psf
- Residual interface friction angles of less than 10° were measured along geosynthetic-geosynthetic interfaces

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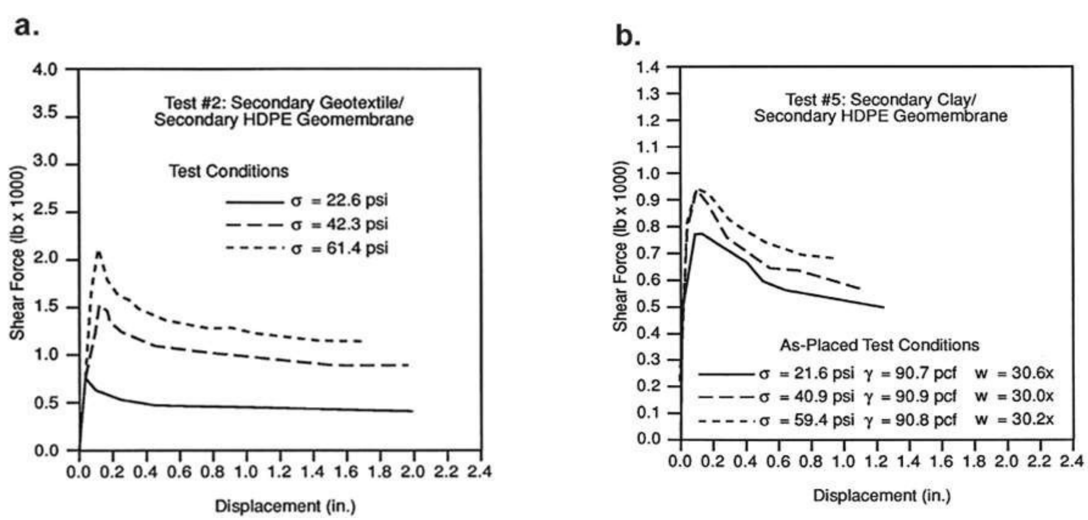
Kettleman Hills HW Landfill Unit B-19, California (1988)

Waste Mass and Liner System Interface Failure



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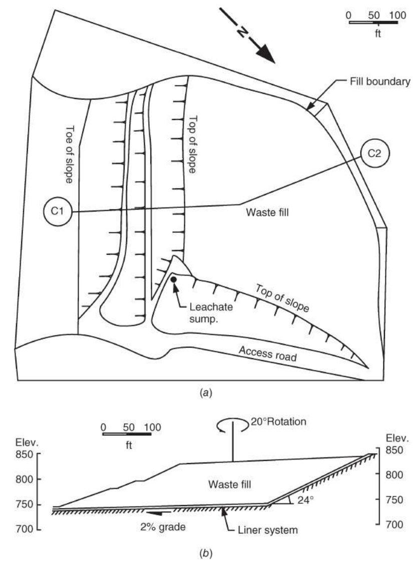
Kettleman Hills HW Landfill Unit B-19, California (1988)

Lessons Learned



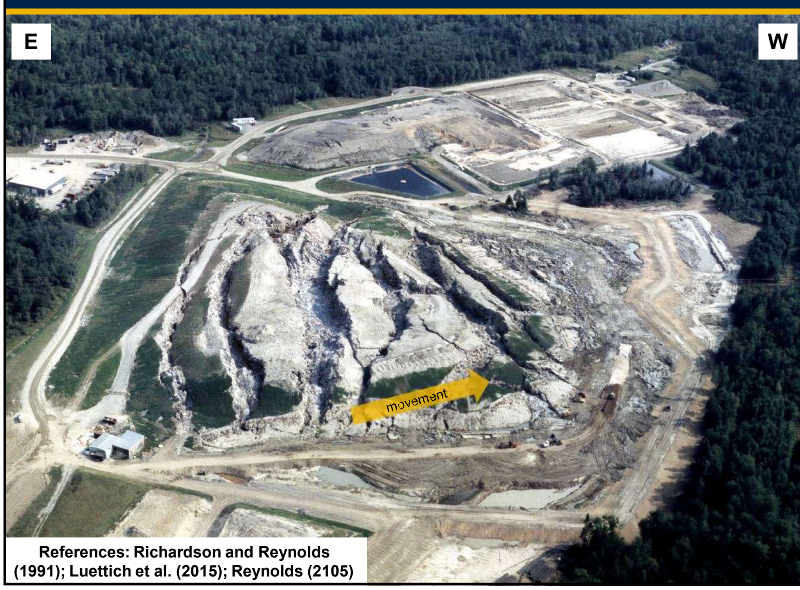
- Many liner system interfaces are weak and exhibit pronounced shear softening, with residual strengths much lower than peak strengths
- Liner system construction and waste placement operations by themselves can induce movements that mobilize post-peak interface conditions within the liner system; the potential for progressive failure must be considered in design
- Waste mass stability evaluations need to address all interim waste filling configurations ("all development phases")
- GMB/CCL interface strengths are sensitive to their compaction, moisture, and shearing conditions

Conundrum - CCL compaction conditions that favor low permeability and intimate GMB/CCL contact also favor low interface shear strength

1

Crossroads MSW Landfill, Maine (1989)

Waste Mass and Foundation Soil Failure



References: Richardson and Reynolds (1991); Luettich et al. (2015); Reynolds (2105)

- 8- acre landfill with foundation consisting of sensitive (S_t ~ 5 to 10) glaciomarine clay-silt layer with OC crust and ~ NC at depth (20 feet) (Presumpscot Fm)
- Clay-silt layer served as in-situ hydraulic barrier – there was no constructed liner or LCRS
- With the waste height at 70 feet, and after a period of heavy rain, a rapid (~ minute) retrogressive slide occurred involving 650,000 CY of MSW
- Sliding surface was in the glaciomarine layer at depths below the overconsolidated crust; waste blocks "floated" up to 160 feet to the west on remolded foundation soil

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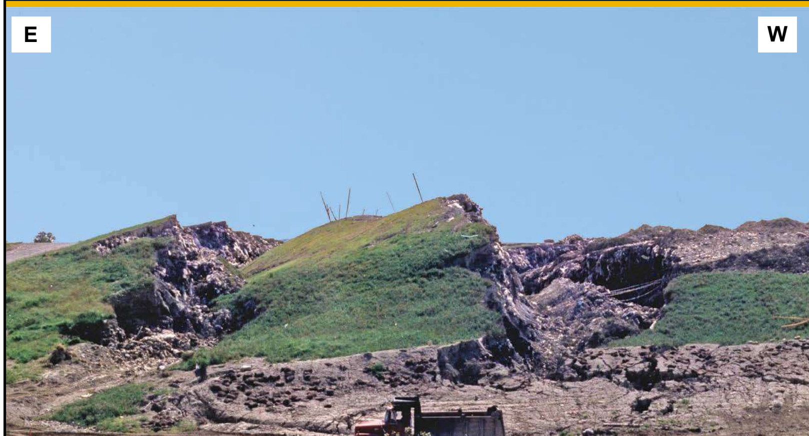
Crossroads MSW Landfill, Maine (1989)

Waste Mass and Foundation Soil Failure



The forensic investigation showed that the degree of consolidation of the foundation soil under the staged waste loading was poorly understood, soil strengths and waste unit weights were significantly underestimated (25-30% each), and liquid levels in the fill were not characterized.

- Several months prior to failure, engineers performed "updated" stability analyses that produced FS ≈ 1.0
- Foundation movements from inclinometers of 1.5 mm/month were assessed as "high, but acceptable"
- Site operations continued and stabilizing toe berms were constructed – but not on the <u>west</u> side
- The slide was trigged when a 6-foot deep excavation was made into the stiff soil crust all along the <u>western</u> toe of the cell for construction of a new landfill cell – this led to over-stressing and an initial localized failure of the sensitive foundation soil at the toe, and then the rapid retrogressive slide

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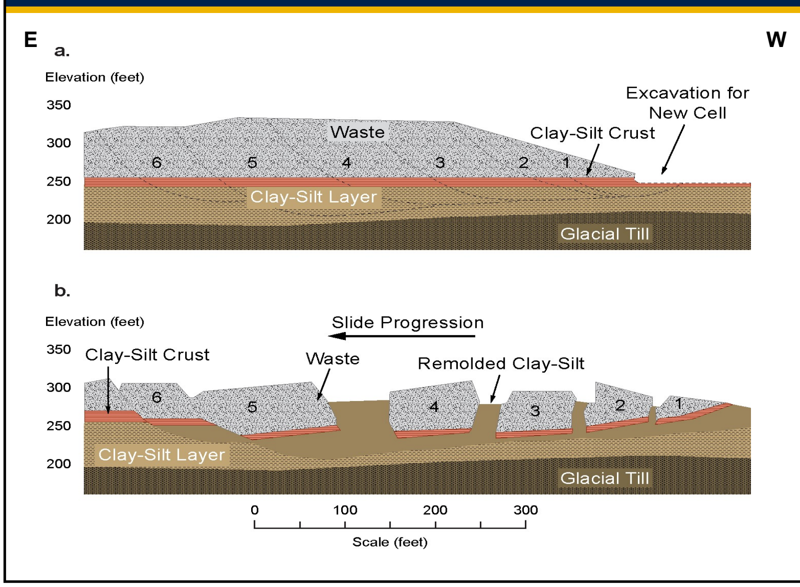
Crossroads MSW Landfill, Maine (1989)

Lessons Learned



- Both waste and foundation soil shear strengths and unit weights must be adequately characterized; recognize that waste self weight is by far the largest contributor to foundation loads for most waste fill structures
- A clear understanding of the liquid levels and pore pressure conditions in the waste fill are critical to the satisfactory assessment of waste fill stability
- Each significant construction and/or operational change in the field should be evaluated prior to implementing the change (in this case, excavation at toe triggered the slide)

For soft soil sites, the rate of waste filling may need to be limited by the rate of foundation soil consolidation and strength gain – this is a classical staged geotechnical construction condition that must be thoroughly understood

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Rumpke MSW Landfill, Ohio (1996)

Waste Mass and Foundation Soil Failure

References: Geosyntec (1996,1997), Hendron and Schmucker (1997); Evans and Stark (1997); Stark et al. (2000a,b); Chug et al. (2007)

- Starting in 1940s, waste was placed in ravines on the Rumpke property, directly onto **clayey, colluvial/residual soils that formed a mantle over bedrock** – landfilling continued until 1996, to **grades exceeding permitted design grades**
- A week prior to failure tension cracks were observed at the top of the landfill
- The morning of the slide, the toe of the landfill began to move as did the tension cracks at the crest
- After several hours of gradually increasing creep rates, the slope failed retrogressively, starting at the toe, over a timeframe of about 5 minutes
- In that short time, 1.5-million CY of material slid hundreds of feet into a deep adjacent excavation

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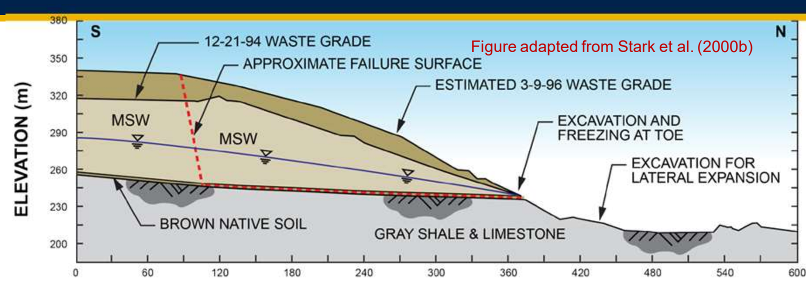
Rumpke MSW Landfill, Ohio (1996)

Waste Mass and Foundation Soil Failure



- Forensic investigation showed that the slip surface extended at a near vertical angle from the landfill crest, through the waste, to the native soil, where it followed the bedding of the soil layer
- Leachate levels in the waste mass prior to failure were later estimated to be substantial (~ 20-30 feet)
- Post-failure shear testing of the colluvial soil produced fully-softened and residual friction angles in the range of 20° and 8°, respectively; computed average friction angle at failure is about 12°
- Due to delays in opening the lateral expansion, the landfill top deck had been overfilled by 30 to 40 feet in the 18 months prior to failure; and the average slope was steepened from 3H:1V to 2.6H:1V; an analysis of the stability of the overfilled geometry was not conducted
- An excavation at the toe for an access road and freezing conditions that impeded leachate toe drainage (by creating an ice dam) may have contributed to initial triggering of the slide

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Rumpke MSW Landfill, Ohio (1996)

Lessons Learned

- Foundation conditions for old-unlined waste fills must be thoroughly understood if additional filling, excavation, or expansion of the fill is planned
- Strain incompatibility between MSW (ductile) and colluvial soil (brittle) can lead to uneven development of shear resistances, localized strain softening (post-peak shear strength), and progressive failure
- Leachate buildup in old unlined waste fills can reduce slope stability factors of safety and contribute to the development of unstable slope conditions; they need to be defined
- Operational activities (e.g., filling above the permitted heights and slopes) may reduce slope stability

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What Did We Learn (by mid 1990s)

Lessons Learned by the Mid 1990s (nearly 25 years ago)

1. **Don't forget fundamental soil mechanics**
2. **Waste materials have geotechnical properties that must be characterized**
3. **Liquid and gas conditions in the fill are important**
4. **Soil and geosynthetic interfaces must be characterized**
5. **Mobilized strength compatibility is often an issue**
   - waste (*often ductile*)
   - geosynthetic interfaces (*often brittle and strain softening*)
   - foundations (*sensitive, brittle, strain softening, undrained, and/or liquefiable*)
6. **Progressive failure mechanisms must often be considered**
7. **Time-dependent staged loading effects must be addressed at soft soil sites**
8. **Numerous interim waste configurations often require assessment**
9. **Operating conditions in the field often deviate from the original design**
10. **Approach expansions on top of old unlined fills with caution**
11. **Surface cracking and toe bulging may be signs of incipient failure**
12. **Communications between engineers and operators are critical**

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Continuing Challenges (fast forward to 2010 to present)

"So, Why do We Keep Having These Waste Fill Failures?"

Waste Fill Stability Failures Have Continued to Occur on a Regular Basis (more than one per year on average)

- Matlock Bend MSW Landfill, TN (2010)
- Confidential MSW Landfill, Eastern U.S. (2011)
- Confidential MSW Landfill, Southern U.S. (2012)
- Big Run MSW Landfill, KY (2013)
- Chrin Brothers MSW Landfill, PA (2013)
- Tri-Cities MSW Landfill, VA (2015)
- Confidential MSW Landfill, Northeastern U.S. (2017)
- Confidential MSW Landfill, GA (2018)
- Confidential MSW Landfill, SC (2018)
- Confidential MSW Landfill, GA (2019)

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Recent Waste Fill Failures in Developing Countries Have Led to Hundreds of Deaths

Recent Mine Tailings and CCR Waste Fill Failures

Confidential MSW Landfill Failure, Eastern U.S. (2011)

Waste Mass and Intermediate Cover Soil Interface Failure

Reference: Unpublished Root Cause Analysis (RCA) Report (2012) [Tom Ramsey, L
de Melo, Bob Bachus, David Espinoza, Ranjiv Gupta, and Chunling Li (Geosynte

- At the time of the failure in September 2011, waste filling had recently been completed in a landfill expansion being built over the 190-foot tall slope of a previously filled landfill cell (veneer geometry)
- This was a very wet landfill:
  - leachate recirculation at the site had been in the range of 5 to 10 million gallons per year for many years
  - high levels of stormwater infiltration were allowed (flat top deck, permeable daily cover)
  - dewatered sewage sludge was being accepted for disposal

Failure occurred in the expansion area (waste veneer) in a matter of minutes and involved ~ 160,000 CY of waste that flowed ~ 500 feet beyond the limit of liner system and retrogressed more than 100 feet behind the crest

Confidential MSW Landfill Failure, Eastern U.S. (2011)

Waste Mass and Intermediate Cover Soil Interface Failure

- Post-failure investigation showed that the slip surface was at the interface between the expansion area waste and underlying intermediate cover soil layer
- CPT_U testing (20 soundings) around the perimeter of the failed area showed high piezometric levels in the expansion waste mass
- On-site observations the day after the slide revealed:
  - leachate pools and gas vents within the failure area
  - clear evidence of leachate overland flow in and around the 500-foot off-site waste runout

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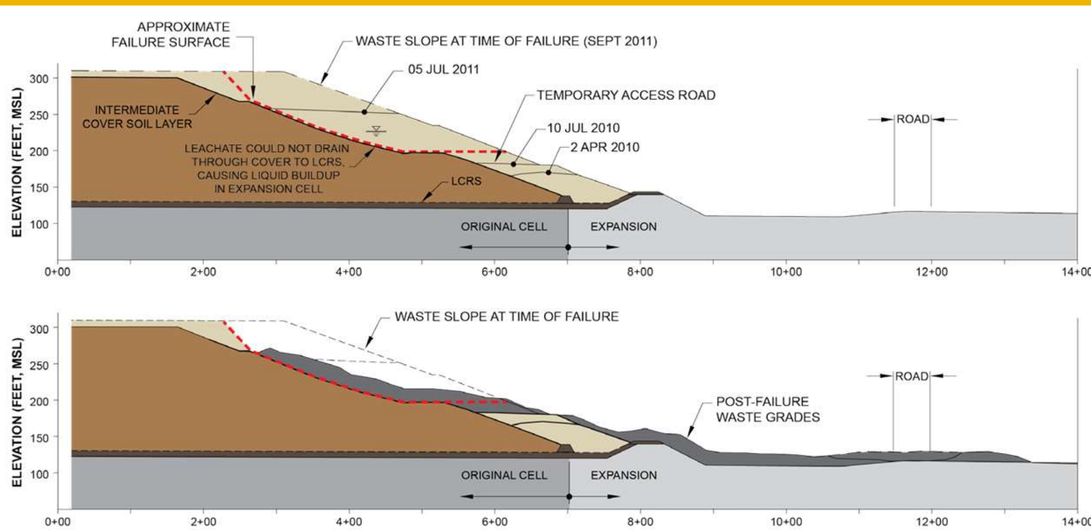
Confidential MSW Landfill Failure, Eastern U.S. (2011)

Waste Mass and Intermediate Cover Soil Interface Failure



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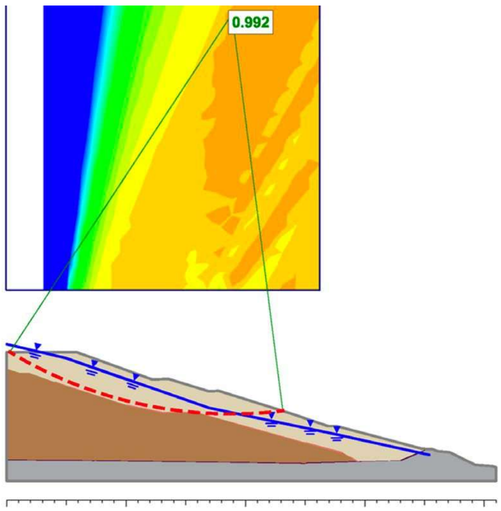
Confidential MSW Landfill Failure, Eastern U.S. (2011)

Waste Mass and Intermediate Cover Soil Interface Failure



- Slope stability analyses were conducted using the CPT_U-derived piezometric levels and the observed failure surface
- **Slope stability back-analyses** resulted in a drained waste friction angle of 26° (100 psf cohesion assumed) for FS=1.0
- **Direct shear tests on an MSW/sludge (75%/25%) sample from the site**, performed at Arizona State University, resulted in drained secant friction angles of 24° and 20°, respectively, at 10 and 20 psi normal stresses
- These calculated and measured MSW strengths are lower than those for "typical" MSW (e.g., Kavazanjian et al., 1995) revealing the effects of the sludge and possibly decomposition on waste strength

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Confidential MSW Landfill Failure, Eastern U.S. (2011)

Lessons Learned

- **Excessive leachate recirculation** and stormwater infiltration can lead to the buildup of elevated liquid levels and pore pressures in the waste
- **Vertical expansions** that involve the placement of new waste over old need to account for the interface conditions
  - in this case, a low-permeability intermediate cover impeded leachate percolation from the expansion area to the LCRS, contributing to leachate buildup
  - either the cover needed to be removed or breached, or a new LCRS placed on top of it
- **Gas collection efficiency** can be greatly reduced in excessively wet landfills, both through operational problems such as the flooding or of gas wells, and by the reduction of MSW gas permeability at increasing levels of waste saturation
- **The effects of sludge** on the strength (↓), permeability (↓), and degree of saturation (↑) of the waste mass must be accounted for in design

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Confidential MSW Landfill, Southern U.S. (2012)
Waste Mass and Foundation Failure

Reference: Unpublished RCA Report (2012) [Beth Gross and Rodolfo Sancio (Geosyntec)]

- Landfill cell was constructed in ~ 60-foot deep excavation into over-consolidated native fat clay (CH)
- Excavation:
  - occurred in 1996 to obtain borrow soil for ongoing site operations
  - liner system construction did not begin until 2007
  - for a decade, stormwater was allowed to pond in the cell bottom
- Waste filling occurred over two+ years, from mid 2007 to early 2009, creating a slope 95 feet high inclined at 4H:1V
- Liner system:
  - CCL overlain by geotextile and sand LCRS
  - not a factor in the failure

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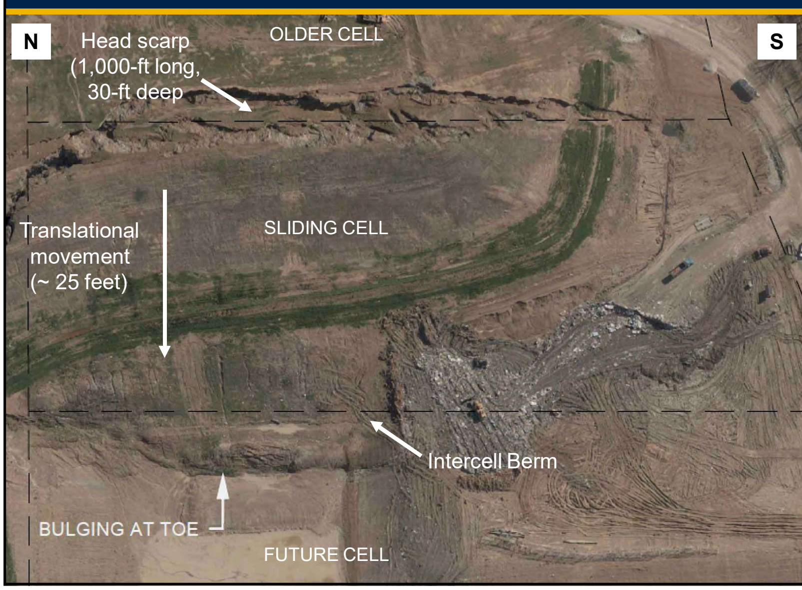
Confidential MSW Landfill, Southern U.S. (2012)
Waste Mass and Foundation Failure



- The first signs of a problem occurred three months prior to the failure when north-south oriented cracks developed at the eventual location of the slide head scarp
- Owner/operator filled the cracks, but they reopened with time, typically after rain events
- The slide involved translational movement of ~ 700,000 CY of waste and soil a distance of 25 feet
- **Forensic investigation concluded that failure mechanism involved shallow translational movement in the native clay beneath the bottom of the liner**

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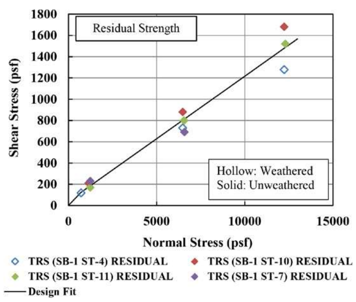
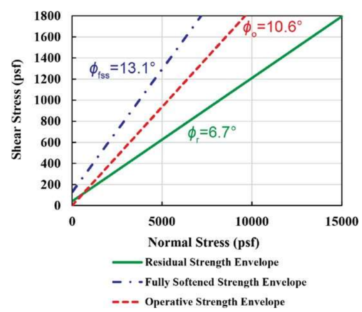
Confidential MSW Landfill, Southern U.S. (2012)

Waste Mass and Foundation Failure





Geometry	Shear Strength Envelope (psf)	Elevation of Failure Plane	R_u	*FS*
Post-Failure	Residual	330	0.14	1.0
Pre-Failure	Operative	330	0.14	1.0

- Decade-long open excavation with ponded water allowed water to infiltrate the native clay through through desiccation cracks and slickensides, and by soil suction due to unloading – this led to swelling and softening of the clay and fully-softened shear strength conditions
- Stresses induced by the waste loading were sufficient to induce shear deformations in the native clay leading to progressive strength loss and ultimately failure

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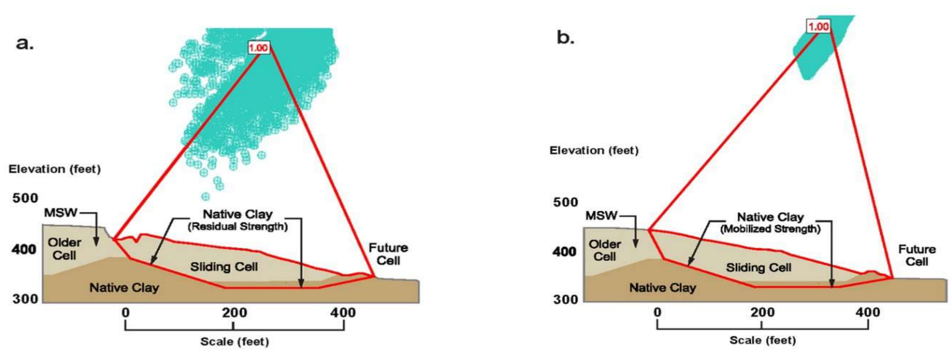
Confidential MSW Landfill, Southern U.S. (2012)

Lessons Learned



Geotechnical fundamentals matter: in this case, the OC plastic clay swelled and softened due to unloading and access to water, resulting in fully-softened shear strength conditions, followed by progressive failure under the waste loading

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Confidential MSW Landfill, Northeast U.S. (2017)
Waste Mass Failure

Reference: Unpublished RCA Report [David Bonnett and Youngmin Cho (Geosyntec) and Craig Benson (UVA)]

- In February 2017, a 15+ acre waste slope failure occurred, resulting in a worker fatality
- In the weeks leading up to the failure, surface cracking, slope bulging, leachate seeps, and gas venting were all observed; at the time of the failure, the owner was evaluating the cause(s) of these issues and attempting to install gas wells in the area to relieve pressure
- The slope failure occurred over about 10 minutes, starting with the bursting of the bulging landfill face which triggered the larger slide, releasing 220,000 CY of waste that **flowed several hundred feet** beyond the limit of the liner system

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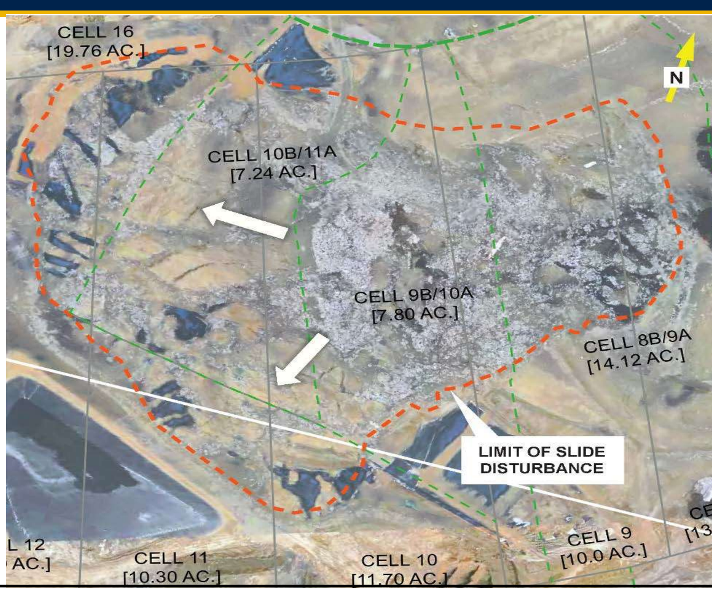
Confidential MSW Landfill, Northeast U.S. (2017)
Waste Mass Failure



- The area where the failure occurred involved an expansion of a new waste cell against the intermediate slope cover of an older portion of the landfill (again, veneer configuration)
- Intermediate cover for the original landfill consisted of cuttings from O&G drilling operations blended with lime, resulting in a relatively hard, smooth, and impermeable layer upon which waste was placed (again, no removal/breaching or overlying LCRS)
- In addition to MSW, the landfill accepted a variety of special wastes, including sludge described as low shear strength waste (LSSW)

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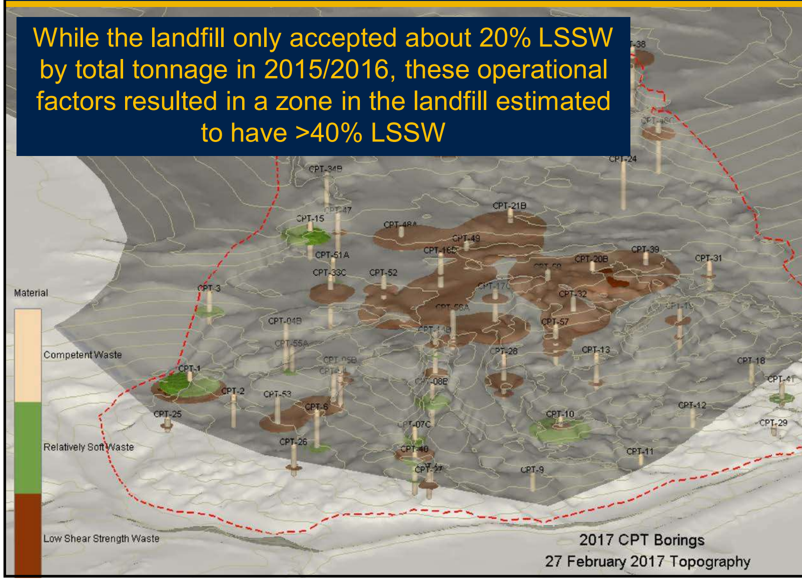
Confidential MSW Landfill, Northeast U.S. (2017)

Waste Mass Failure

While the landfill only accepted about 20% LSSW by total tonnage in 2015/2016, these operational factors resulted in a zone in the landfill estimated to have >40% LSSW



- The operations plan for the landfill required LSSW to be placed 100 feet back from the landfill edge of slope, to prevent leachate seeps and to maintain stability (a good idea)
- The setback limited the cell area in which LSSW could be placed and the amount of MSW available for mixing with the LSSW
  - the cell had a 90º wedge front face
  - the available MSW was being used up to form the setback zones
- This resulted in interior zones in the cell (brown) with high proportions of LSSW (an unintended consequence) and ultimately a weak zone through which shearing occurred

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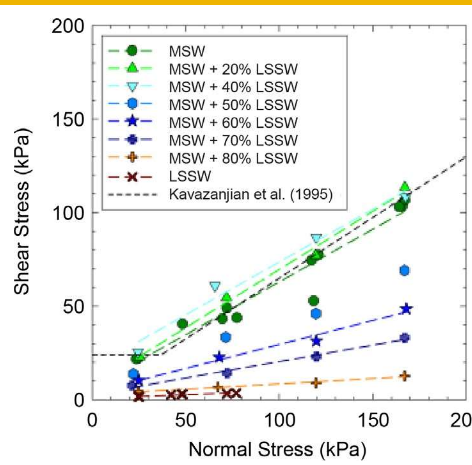
Confidential MSW Landfill, Northeast U.S. (2017)

Waste Mass Failure



Testing was conducted by Chris Bareither and Joseph Scalia at Colorado State University using Craig Benson's shear box

- Representative specimens of MSW and LSSW were obtained from bucket auger and sonic core samples retrieved from the slide area
- Direct shear testing was conducted at CSU on test specimens of MSW, LSSW, and mixtures of MSW + LSSW
- Test results showed that MSW/LSSW mixtures became substantially weaker at LSSW mass fractions above about 40%

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Confidential MSW Landfill, Northeast U.S. (2017)

Lessons Learned

- **Special (non-MSW) wastes** can create operational problems - procedures developed to mitigate the problems can have unintended consequences
- Special wastes if **placed at too high a mass fraction**, and if not thoroughly mixed with MSW or other stronger waste, will create weak zones that adversely affect waste fill stability
- Low permeability zones in the waste (e.g., from special wastes or intermediate cover soil layers) trap liquids and gases in the waste fill causing fluid pressures to become elevated

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Observations and Recommendations in Light of Continuing Challenges

We are Re-learning Many of the Lessons First Learned 25 Years Ago – Why?

1. **Don't forget fundamental soil mechanics**
2. **Waste materials have geotechnical properties that must be characterized**
3. **Liquid and gas conditions in the fill are important**
4. **Soil and geosynthetic interfaces must be characterized**
5. **Mobilized strength compatibility is often an issue**
   - waste (*often ductile*)
   - geosynthetic interfaces (*often brittle and strain softening*)
   - foundations (s*ensitive, brittle, strain softening, undrained, and/or liquefiable*)
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10. **Approach expansions on top of old unlined fills with caution**
11. **Surface cracking and toe bulging may be signs of incipient failure**
12. **Communications between engineers and operators are critical**

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Recent Lessons Learned and Recommendations

1. **Aggressive leachate recirculation can saturate waste and cause high piezometric levels**
2. **Gas well collection efficiency is substantially diminished in very wet landfills**
3. **High moisture content landfills can lead to elevated temperatures in some cases**
4. **Co-disposal of sludges and special wastes can lead to stability and other problems**
5. **Vertical expansion configurations and materials have contributed to waste fill failures**

Recirculation Landfills:
- Recirculation rates need to be moderated
- Landfill internal drainage features should be enhanced
- A proper water balance should be maintained in the waste fill (requires monitoring)

Sludges and Special Wastes:
- Detailed *special waste acceptance plans (SWAPs)* should be developed for each special waste stream
- SWAPs should address potential impacts to leachate and gas generation rates, waste properties, slope stability, and operations
- Unintended consequences of special operating procedures must be carefully considered
- A higher level of operating vigilance is needed - observational approach

Vertical Expansions:
- The intermediate cover interface must be carefully engineered for stability and permeability
  - in some cases, the cover should be removed, or at least breached
  - in others, a new LCRS should be installed on top of the cover
- The effects of the vertical expansion on leachate and gas movements in the waste fill should be carefully assessed

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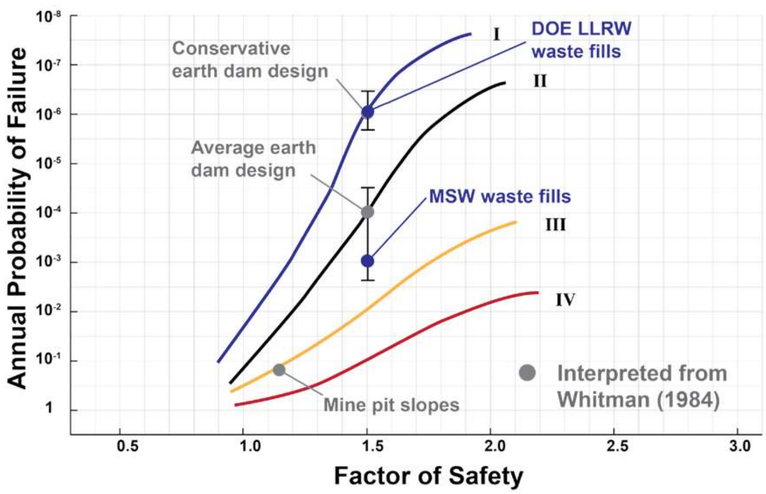
Observations and Recommendations:
State-of-the Practice



Estimated Annual Probabilities of Failure – Earth Dams and MSW Landfills

Silva, Lambe, and Marr (2008) - "Probability and Risk of Slope Failure."

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Thank You

Geosyntec consultants

Professor Karl Terzaghi

Texas A&M Foundation

Spencer J. Buchanan '26 Chair in Civil Engineering

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