The Use of Cone Penetration Testing for Integrated Site Characterization

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26th Vancouver Geotechnical Society Symposium
Friday, May 31, 2019

Outline

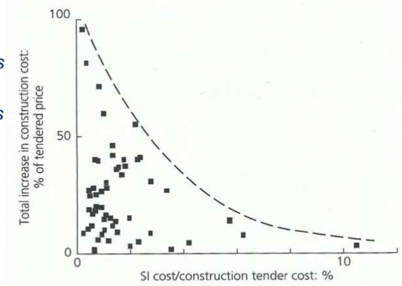
- *Importance of Site Characterization in Geotechnical Practice*
- *Approach to Integrated Site Characterization*
- *CPT Correction – Thin Layer Correction for Cone q_t Measurement*
- *CPT Operation – Variable Rate Cone Penetration Testing*
- *CPT Interpretation – Mapping Spatial Stratigraphic Correlation Structures*
- *Summary*

Importance of Site Characterization in Geotechnical Practice

(Collaborators: L. Yabusaki, P. Lucia, D. Coduto)

Our risky profession…

- *Geotechnical engineering is one of the financially riskiest engineering professions due to the inherent uncertainty associated with characterizing the subsurface.*
- *Damages incurred to the constructed project often lead to claims against geotechnical engineers, on the assertion that the "Standard of Care" was not followed.*
- *Past studies:*
  - *Clayton (1995): Synthesis of past studies:*
    - *10 highway projects - 50% excess costs due to inadequate site investigation.*
    - *28 construction projects - 76% of issues attributed to subsurface conditions.*
    - *Inverse correlation between SI cost & overrun costs.*
  - *Abdulahad et al. (2010): Review of 41 legal cases identified differing soil conditions as a primary source.*



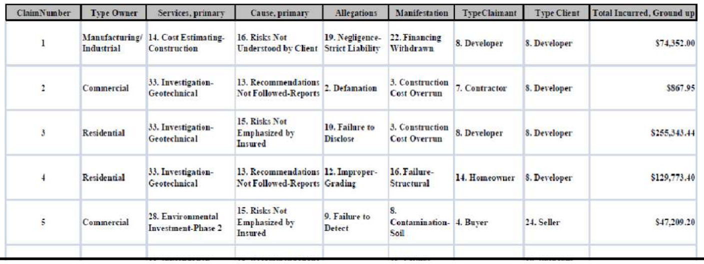
Evaluation of our responsibility…

- *Claims arises out of an assertion that the engineer has failed to meet the Standard of Care (SOC).*
- *Standard of Care, defined by Geoprofessional Business Association (GBA, formerly ASFE), is "…that level of skill and competence ordinarily and contemporaneously demonstrated by professionals of the same discipline practicing in the same locale and faced with the same or similar facts and circumstances."*
- *Statement ambiguity only compounded by the nature of geotechnical work, where decisions are based on interpretation, judgement, and past experience.*
- *Thus, it is very difficult to provide compliance to SOC.*

- *Basis of a lawsuit on negligence: "a plaintiff must prove that the defendant had a duty to the plaintiff, the defendant breached that duty by failing to conform to the required standard of conduct, the defendant's negligent conduct was the cause of the harm to the plaintiff, and the plaintiff was, in fact, harmed or damaged." (West's Encyclopedia of American Law).*
- *Negligence determined by jury following presentation of opinions by expert witnesses.*

What leads to claims against geotechnical engineers

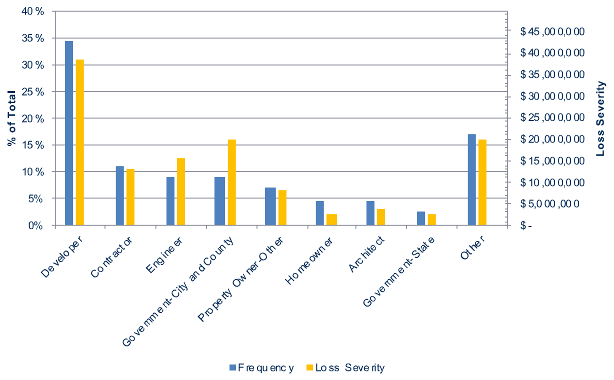
- *Terra Insurance Company, an insurer of geotechnical companies, paid out $124,151,356 for 897 claims out of 1500 filed over a period of 25 years.*
- *Terra documented attributes of each claim at time of filing.*
- *Note that "loss severity" is only money paid out by Terra and does not include lost revenue and costs of insured geotechnical firms, which can also be substantial.*



ClaimNumber	Type Owner	Services, primary	Cause, primary	Allegations	Manifestation	TypeClaimant	Type Client	Total Incurred, Ground up
1	Manufacturing/ Industrial	14. Cost Estimating-Construction	16. Risks Not Understood by Client	19. Negligence-Strict Liability	22. Financing Withdrawn	8. Developer	8. Developer	$74,352.00
2	Commercial	33. Investigation-Geotechnical	13. Recommendations Not Followed-Reports	2. Defamation	3. Construction Cost Overrun	7. Contractor	8. Developer	$867.95
3	Residential	33. Investigation-Geotechnical	15. Risks Not Emphasized by Insured	10. Failure to Disclose	3. Construction Cost Overrun	8. Developer	8. Developer	$255,343.44
4	Residential	33. Investigation-Geotechnical	13. Recommendations Not Followed-Reports	12. Improper-Grading	16. Failure-Structural	14. Homeowner	8. Developer	$129,773.40
5	Commercial	28. Environmental Investment-Phase 2	15. Risks Not Emphasized by Insured	9. Failure to Detect	8. Contamination-Soil	4. Buyer	24. Seller	$47,209.20

Claims database

Who sues geotechnical engineers?



Claims database

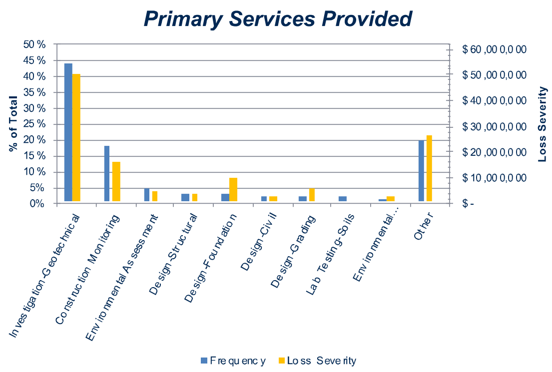
[REFERENCE]

- *Scope of work leading to a claim.*

Primary Services	***Frequency***	***% of Total***	***Loss Severity***	***% of Total***	***Cost per Claim***
Investigation-Geotechnical	393	43.81	$ 50,841,556	40.95	$ 129,367
Construction Monitoring	162	18.06	$15,939,692	12.84	$ 98,393
Environmental Assessment	39	4.35	$ 4,995,932	4.02	$ 128,100
Design-Structural	30	3.34	$ 3,359,666	2.71	$ 111,988
Design-Foundation	27	3.01	$ 9,608,188	7.74	$ 355,858
Design-Civil	23	2.56	$ 2,628,776	2.12	$ 114,294
Design-Grading	17	1.90	$ 6,269,627	5.05	$ 368,801
Lab Testing-Soils	17	1.90	$1,046,271	0.84	$ 61,545

Claims database

- ➢ Scope of work leading to a claim.



Claims database

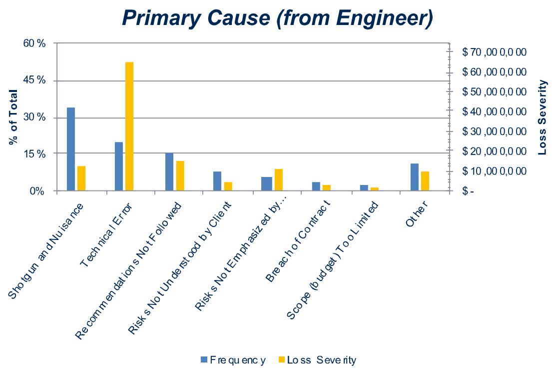
[REFERENCE]

- ➢ What engineers believe is the problem.

Primary Cause	Frequency	% of Total	Loss Severity	% of Total	Cost per Claim
Shotgun and Nuisance	307	34.23	$ 2,785,346	10.30	$ 41,646
Technical Error	176	19.62	$ 65,407,674	52.68	$ 371,634
Recommendations Not Followed	143	15.94	$ 15,063,166	12.13	$ 105,336
Risks Not Understood by Client	71	7.92	$ 4,775,202	3.85	$ 67,256
Risks Not Emphasized by Insured	55	6.13	$10,728,801	8.64	$ 195,069
Total	897	100	$ 124,151,356	100	$ 138,407

Claims database

- ➢ What engineers believe is the problem.



Claims database

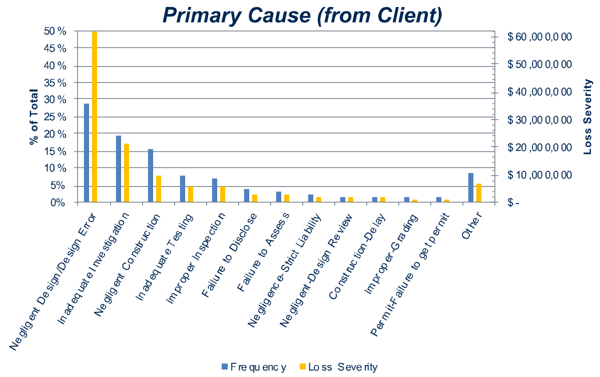
[REFERENCE]

- ➢ What clients believe is the problem.

Allegations	Frequency	% of Total	Loss Severity	% of Total	Cost per Claim
Negligent Design/Design Error	258	28.76	$ 61,745,096	49.73	$ 239,322
Inadequate Investigation	174	19.40	$ 21,377,309	17.22	$ 122,858
Negligent Construction	138	15.38	$ 9,830,677	7.92	$ 71,236
Inadequate Testing	69	7.69	$ 6,105,029	4.92	$ 88,478
Improper Inspection	62	6.91	$ 5,507,468	4.44	$ 88,830

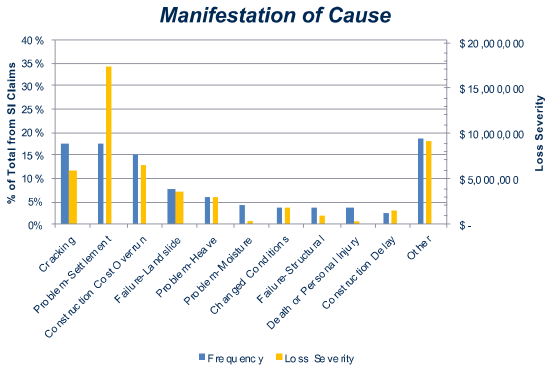
Claims database

- *What clients believe is the problem.*



Claims database

- *Manifestation of cause.*



Summary

- *About 50% of the claims stem directly from inadequate site characterization, with additional indirect contributions.*

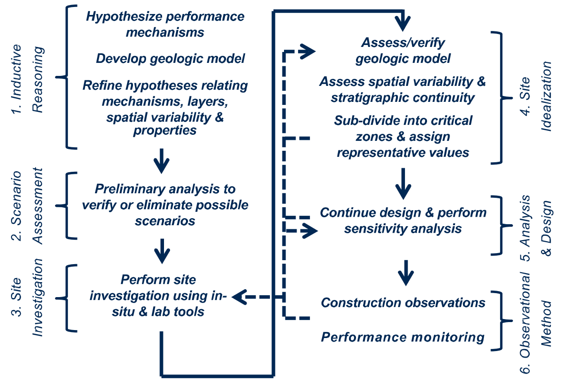
- *Geotechnical engineers can protect themselves in this 'risky business' if they can prove they followed the Standard of Care, which itself is a non-specific definition.*

- *The common deficiencies in project documentation that led to either inadequate performance or the inability to prove that the Standard of Care was followed were:*
  - *incomplete/insufficient documentation at time work was performed*
  - *lack of rigorous internal/external peer review*
  - *lack of systematic approach for site characterization process*

- *Terra Insurance (w/ GBA) has promoted Risk Management practices, and have seen risk reduced from about one claim for every $250,00 in revenue in 1969 to one claim for every $35,000,000 in revenue in 2014.*

Integrated Site Characterization Approach

Integrated site characterization approach



Stage 1: Inductive Reasoning

[REFERENCE]

- ***Hypothesize performance mechanisms:***
  - *Controlling mechanism(s) deformation or failure based*
  - *Loading conditions (e.g. static, dynamic) and duration*
  - *Length scale of deformation/failure zones for each mechanism*
- ***Develop geologic model:***
  - *Geologic (and anthropogenic) formational processes that led to current site conditions*
  - *Thickness, variability, and soil properties of each expected strata*
  - *Soft/weak zones of particular concern*
- ***Refine hypotheses relating mechanisms, layers, spatial variability, & properties:***
  - *Identify primary strata engaged in each mechanism*
  - *Compare length scale of mechanism with layer geometry and spatial variability*
  - *Assess relative importance of mapping spatial variability and refining controlling engineering property values*
  - *Identify ‘baseline’ case from on historic data and literature values*
  - *Identify property/parameter range for sensitivity studies (Note: geotechnical engineers typically underestimate…we are optimists!)*

Stage 2: Scenario Assessment

[REFERENCE]

- ***Specify assumptions that can be justified***
- ***Identify simplified analysis procedure for ‘efficient’ sensitivity study***
- ***Use (simple) idealized project cross-section(s) for analysis***
- ***Perform sensitivity studies varying critical parameters/properties to elucidate controlling factors***
- ***Determine aspects controlling performance and how reducing uncertainty in these areas improves estimation of performance***

- ***Outcomes:***
  - *Geologically-based (quantitative) hypothesis of the subsurface conditions that exist at the site (including major units, vertical and lateral variability, soil property ranges)*
  - *Detailed understanding of the likely mechanisms controlling performance*
  - *Knowledge of which conditions/parameters control the governing mechanisms*

Stage 3: Site Investigation

[REFERENCE]

- *Extent of spatial variability guides data collected*
  - *High spatial variability ➤ focus on assessing spatial variability*
  - *Low spatial variability ➤ focus on refining property measurements*
- *First verify geologic model & soils present*
- *Identify soft/weak zone of particular concern*
- *Identify and use best practices for soil characterization w/ combination of in-situ and laboratory methods*
- *Use drilling & sampling methods appropriate to required lab data*
- *Multi-stage field mobilization & modification of SI as data collected*
- *Cross-verify critical parameters/properties with multiple measurements*

- ***Outcome:***
  - *An experimental, site-specific database of conditions/parameters expected to control system performance and design*

Stage 4: Site Idealization

[REFERENCE]

- Site Idealization is explicit process from Site Investigation
- Compile & resolve differences in property/parameters estimates obtained from different methods
- **Assess & verify geologic model:**
  - Extent of primary units
  - Presence of soft/weak zones and unexpected zones
- **Assess spatial variability & geologic continuity:**
  - Connectivity of geologic units/zones
  - Presence of critical bounding geologic features
  - Thickness, variability, and soil properties of each strata
- **Sub-divide into zones & assign representative values:**
  - Sub-divide zones considering mechanism length scale
  - Define parameter property values (mean & distribution)
  - Incorporation of spatial variability into selection of representative values
- **Outcome:**
  - Well documented idealized site condition that communicates process/decision(s) for simplification & parameter selection

Stage 5: Analysis & Design

[REFERENCE]

- Repeat simple scenario analysis with updated baseline to model to determine if major changes in expected performance exist
- Increase analysis/design complexity as suited to project value/consequence
- Continue sensitivity study to identify critical conditions for design
- As necessary, return to earlier stages as necessary to increase certainty of analysis

Stage 6: Observational Method

[REFERENCE]

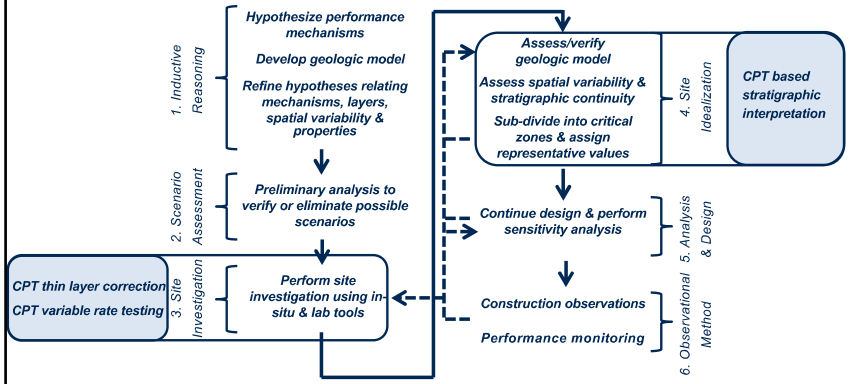
- Verify geologic model, stratigraphic units, and soil properties by detailed construction observations
- Verify adequacy of design (if possible) via construction observations
- Design long term performance monitoring system to measure long-term performance of "full scale experiment"
- Develop management and decision plan of action for decision making in advance

How may this approach differ?

- Integrated site characterization is a process that begins with the desk study and continues through construction.
- Site investigation is only one part of site characterization.
- Emphasis placed on detailed analysis prior to mobilizing for site investigation.
- Enables prioritization, efficiency, and (possibly) reduced costs in site investigation.
- Site investigation becomes verification instead of discovery.
- Site idealization is an explicit step that communicates decisions/assumptions made is selecting values for analysis/design.
- Provides framework for systematic sensitivity analysis during analysis and design.

- Multiple iteration cycles throughout site characterization process.
- Separation and transparency between hypotheses, data collected, idealized site, and analysis results.
- Provides framework for thorough documentation and peer-review.
- Archives the work undertaken proving that the standard of care was met at the time the project was performed.

Integrated site characterization approach



1. Inductive Reasoning
- Hypothesize performance mechanisms
- Develop geologic model
- Refine hypotheses relating mechanisms, layers, spatial variability & properties

2. Scenario Assessment
- Preliminary analysis to verify or eliminate possible scenarios

3. Site Investigation
- Perform site investigation using in-situ & lab tools
- CPT thin layer correction
- CPT variable rate testing

4. Site Idealization
- Assess/verify geologic model
- Assess spatial variability & stratigraphic continuity
- Sub-divide into critical zones & assign representative values
- CPT based stratigraphic interpretation

5. Analysis & Design
- Continue design & perform sensitivity analysis

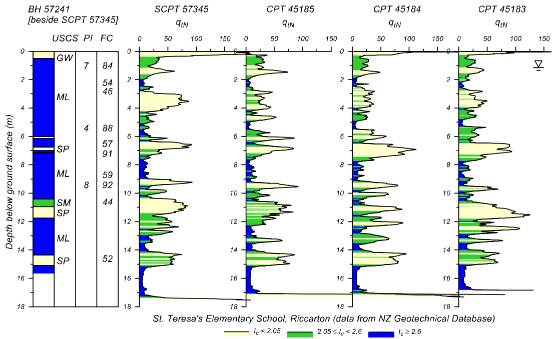
6. Observational Method
- Construction observations
- Performance monitoring

CPT Correction: Thin-Layer Correction for Cone q_t Measurement

(Collaborators: R.W. Boulanger)

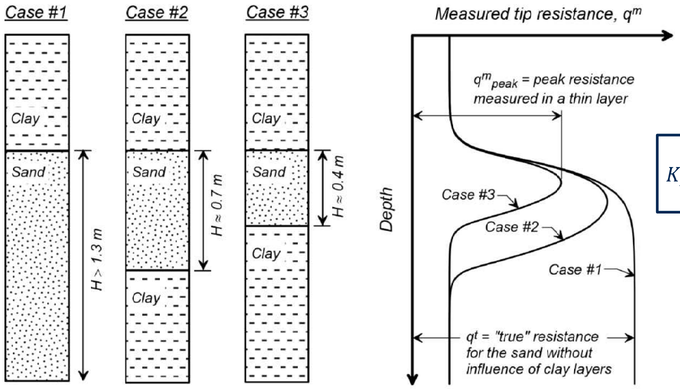
Motivation

- Soil volume engaged in CPT q_t measurement acts as averaging filter, reducing fidelity.
- Consequences in accurately characterizing thin-layers and transitions zones.
- Design & analysis challenges associated with liquefaction evaluation, slope stability, etc.



St. Teresa's Elementary School, Riccarton (data from NZ Geotechnical Database)

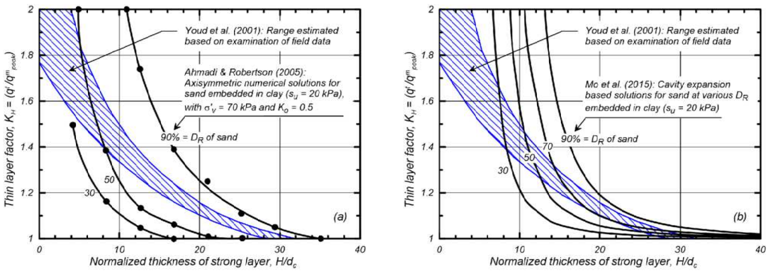
Conceptual: schematic of thin layer & transition effects



$$K_H = \frac{q^t}{q^m_{peak}}$$

Prior corrections for cone penetration in layered soil profiles

- Range of experimental and numerical based solutions have broadly similar trends, are symmetric about the thin layer, and consider influence of sand density.



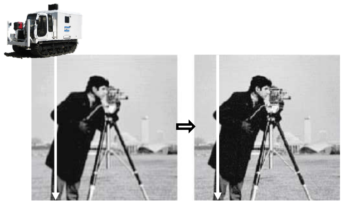
Practical limitations and research goal

- Application of thin-layer factors is relatively rare in practice because it is:
  - subjective on how to apply to any natural stratigraphy, such that results can differ significantly between individuals
  - time consuming to apply (not automated)
  - may only have a modest effect for many design/evaluation problems

- The goal was to develop a procedure that is:
  - generalized for any stratigraphy
  - objective, repeatable, & tunable
  - automatable

Inverse filtering procedure

- Inverse filtering is widely used in image and signal processing for a broad range of applications because it can help restore or improve image/measurement quality if:
  - a good model can be developed for the function that "blurred" the measurement
  - the signal-to-noise ratio in the measurement is favorable



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  - the signal-to-noise ratio in the measurement is favorable

- Application to cone penetration testing has three components:
  - Filter model for cone penetration
  - Inverse filtering solution procedure
  - Interface detection and correction procedure

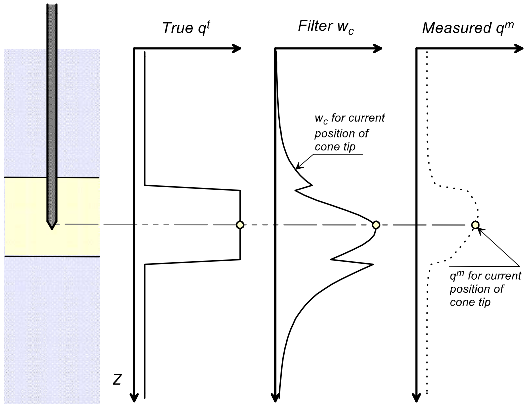
- Validation of procedure:
  - Prediction of K_H and sensing/development distances for idealized 2 and 3 layer systems.
  - Evaluation of the above results against experimental and numerical simulation data.
  - Comparisons are for validating the procedure [i.e., we don't use K_H in application].

Filter model for cone penetration

- The tip resistance measured at a point (q^m) is influenced by soils above and below the tip.
- The degree of influence depends on the soil's strength & stiffness relative to the stress imposed by the penetrating cone.
- The q^m profile is the "true" q^t profile convolved with the filter.

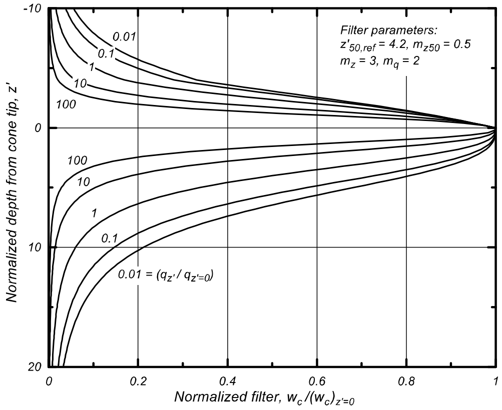
$$q^m(z) = q^t(z) * w_c(z)$$

$$q^m(z) = \int_{z_{\min}}^{z_{\max}} q^t(\tau)\, w_c(z-\tau)\, d\tau$$



Filter model for cone penetration

- Filter based on q, as a convenient proxy for strength and stiffness.
- Filter depends on
  - z' (asymmetrically)
  - $q_{z'} / q_{z'=0}$
  - $z'_{50,ref}$
- Filter developed from established trends.



Solution procedure

- A method of successive substitutions was implemented.
  - Basic equations are first rearranged as:

$$q^t = q^m + dq$$

$$q^t = q^m + \left(q^t - q^t * w_c\right)$$

  - Successive iterations applied as:

$$q^{inv}_{n+1} = q^m + \left(q^{inv}_n - q^{inv}_n * w_c\right)$$

  - Iterations continue until the error criterion is satisfied.

$$err = \frac{\sum \left| \left(q^{inv}_{n+1} - q^{inv}_n\right)_i \right|}{\sum \left| \left(q^m\right)_i \right|} < 10^{-6}$$

Solution procedure – limits on spatial frequency

- The highest spatial frequency for which q^m contains meaningful information is limited by:
  - data sampling interval
  - physical size of the cone
- Solution procedure has two steps for removing higher-than-justifiable spatial frequencies.
  - During each successive iteration, q^{inv} is smoothed (low-pass spatial filtered) by taking a moving average over a window that is the larger of either:
    - (1) three data points, or
    - (2) ceiling of the cone tip length divided by the sampling interval
  - After convergence, q^{inv} is low-pass spatial filtered using the same filter models as for cone penetration, but with $z'_{50,ref}$ equal to the cone tip length.

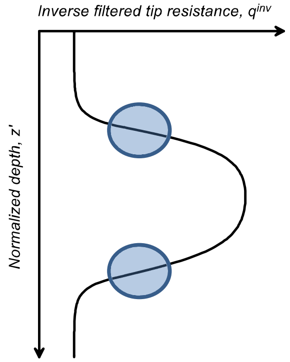
Interface detection and correction

[REFERENCE]

- Detection and correction of sharp interfaces requires a separate algorithm because:
  - a step in q^t corresponds to very high spatial frequencies
  - those frequencies are outside the limits of what can be defined by q^m or q^{inv}
- Sharp transitions (or an interface) are considered likely to exist if the rate of change in the logarithm of q^{inv} with respect to normalized depth (z')

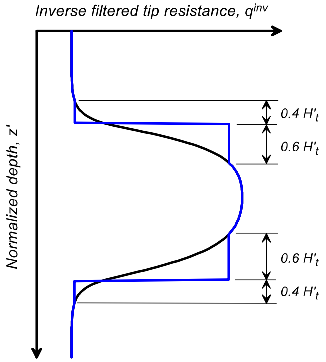
$$m_i = \frac{\ln\left(q_{i+1}^{inv}\right) - \ln\left(q_i^{inv}\right)}{z'_{i+1} - z'_i}$$

is larger than a threshold value, m_t



Interface detection and correction

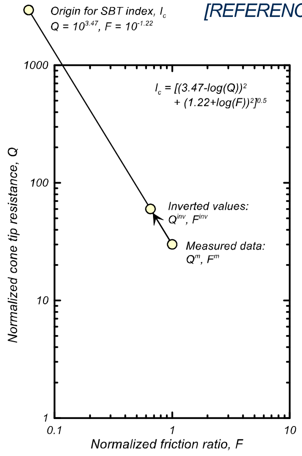
- Interface transition zones
  - identified by $m \geq m_t$ (with $m_t = 0.1$ for results shown herein)
  - subsequently includes all contiguous points with $m > m_t/5$
- Limits on transition interval thickness
  - if < $3d_c$ thick, then it is not considered an interface
  - if > $12d_c$ thick when q^{inv} is increasing, then it is truncated to 12 d_c thick
  - if > $18d_c$ thick when q^{inv} is decreasing, then it is truncated to 18 d_c thick
- q^{inv} and f_s^{inv} at top of transition zone are assigned to upper 40% if q^{inv} is increasing or upper 60% if q^{inv} is decreasing.
- q^{inv} and f_s^{inv} at bottom of transition zone assigned to the remainder of the interval.



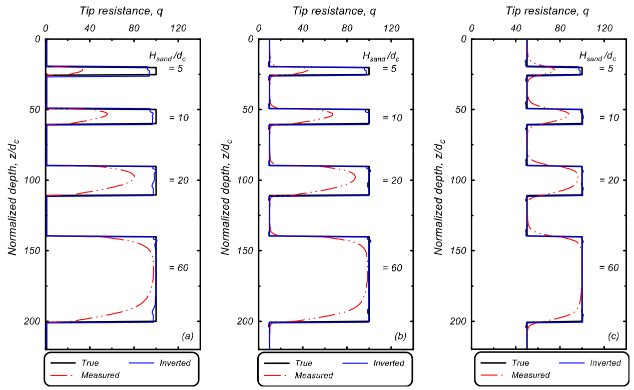
Sleeve friction…a side note

[REFERENCE]

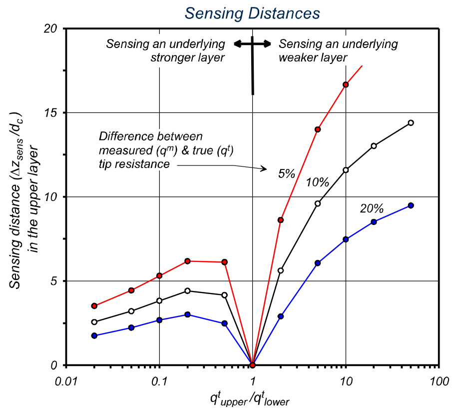
- An inverse filter for f_s would be different than the filter for q, but there is little data upon which to derive a filter model for f_s.
- Currently, it is assumed that inverse filtering of f_s and q values moves Q-F radially toward the origin of the I_c index.

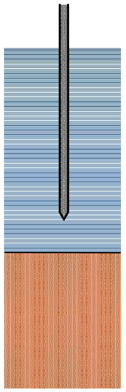


Idealized profile: q^{inv} with interface detection and correction

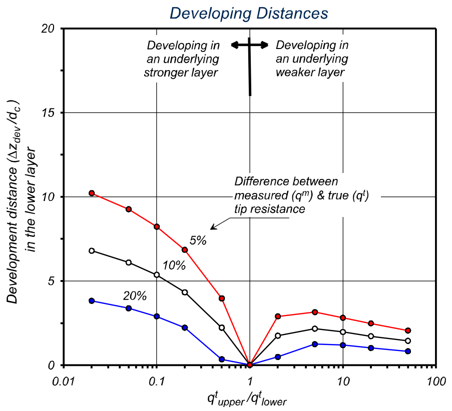


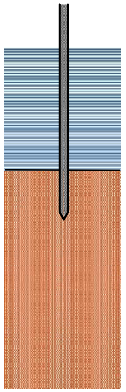
Sensing distances computed using cone filter model





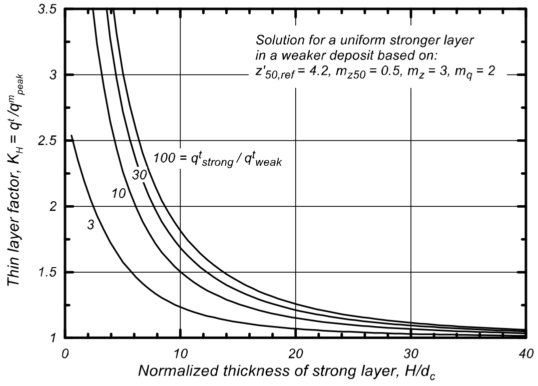
Development distances computed using cone filter model





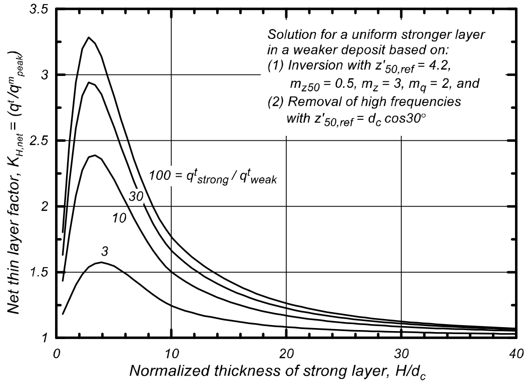
Thin layer factors from idealized profiles w/o low-pass filter steps

- K_H vs. H/d_c computed for idealized profiles
- In practice, spatial averaging and data sampling resolution limits inverse filtering for very thin layers

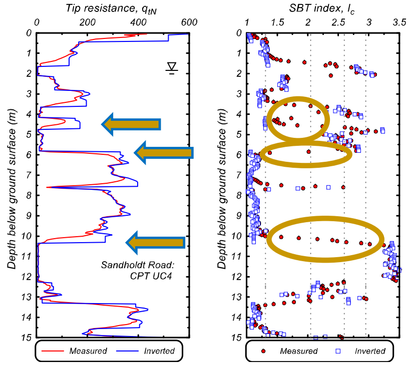


Thin layer factors from idealized profiles with low-pass filter steps

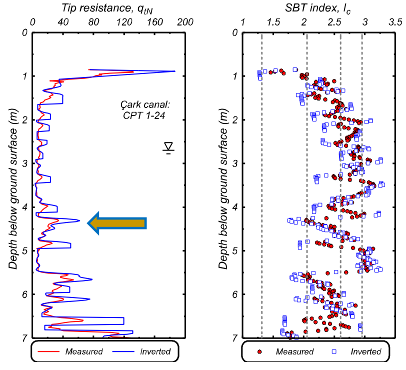
- K_H vs. H/d_c computed for idealized profiles
- Application of low-pass spatial filter
  - removes high spatial frequencies
  - reduces the amplification of q^m for $H/d_c < 4$.



Examples 1 & 2

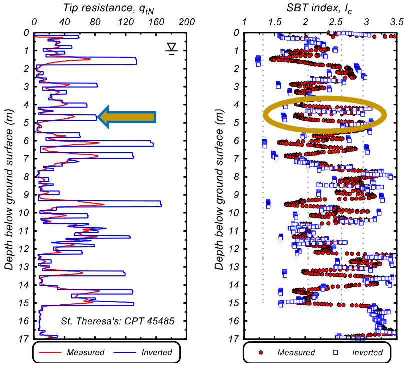


Sampling interval 50 mm

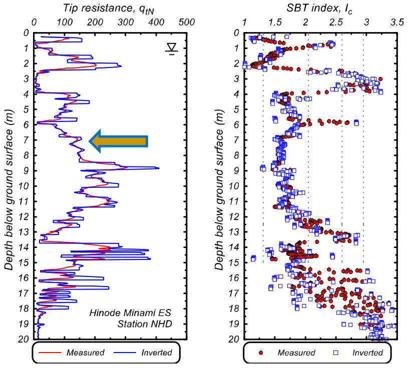


Sampling interval 20 mm

Examples 3 & 4



Sampling interval 10 mm



Sampling interval 25 mm

Summary

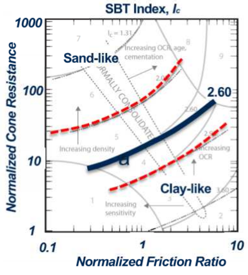
- ➢ An inverse filtering procedure was developed for estimating "true" tip resistance and sleeve friction values from measured cone penetration test data in interlayered soil profiles.
  - The procedure is intended to improve or enhance our interpretation of field measurements, while recognizing that any inverse filtering process will be neither unique nor perfect.
- ➢ The inverse filtering procedure:
  - can be applied to any stratigraphy
  - is objective, repeatable, & tunable
  - is automatable
- ➢ Acceptance of results still requires judgement through consideration of geologic depositional environment (e.g. abrupt transition vs. upward fining sequence).
- ➢ Consequence of use on subsequent performance will be problem/project specific.

CPT Operation: Variable Rate Cone Penetration Testing

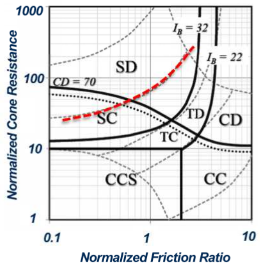
(Collaborators: R.A. Jaeger, D.A.J. Wahl, C.P. Krage,
M.F. Randolph, and R. W. Boulanger)

Motivation

- ➢ Partially drained conditions can occur during cone penetration at 2 cm/sec.
- ➢ This can produce measurements that do not align with either drained or undrained analyses.
- ➢ Results in inability, or increased uncertainty, in estimation of soil properties.



Robertson 2009



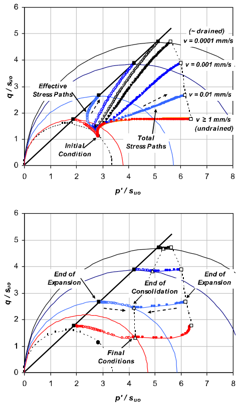
Robertson 2016

Practical limitations and research goal

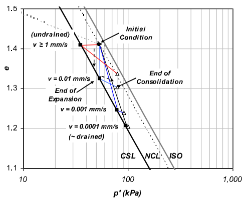
- ➢ Consideration of partially drained conditions, including adjustment of testing procedures, often not considered in practice due to:
  - inability to identify when partially drained conditions may exist
  - lack of appreciation of consequences on soil property estimation
  - insufficient guidance on how to change CPT operations to control drainage conditions during penetration

- ➢ The goal was to develop an approach to:
  - rapidly, in near real-time, identify when partially drained conditions are present
  - provide framework for mapping effect of penetration rate on CPT measurements
  - develop practical guide to adjust testing conditions during a CPT sounding

Drainage conditions during cone penetration in clay

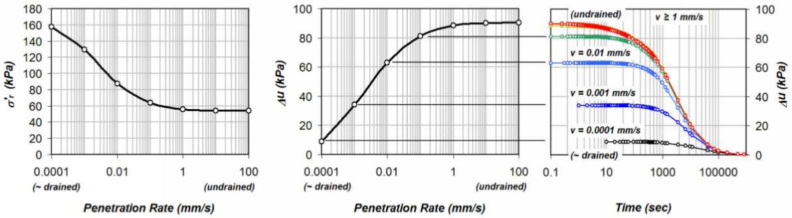


- ➢ Cavity expansion (CE) analysis using MCC calibrated to NC kaolin (Silva et al. 2006) captures the fundamental changes in loading path as the drainage condition during penetration is varied.
  - Undrained penetration ~ CAUC tx
  - Drained penetration ~ CADC tx
  - Equilibration during dissipation



Drainage conditions during cone penetration in clay

- ➢ Cone q_t is proportional to CE σ'_r and σ_r.
- ➢ Undrained penetration occurs above 1 mm/s.
- ➢ Changes in Δu and σ'_r broadly occur over the same range.
- ➢ Δu mobilized during cone penetration corresponds to initial Δu value during dissipation.
- ➢ All dissipation tests steadily decay with time, and would produce the same t_{50} value for estimation of c_h.



Normalized framework for cone penetration

Normalized Velocity:

$$V = \frac{v\,d}{c_h}$$

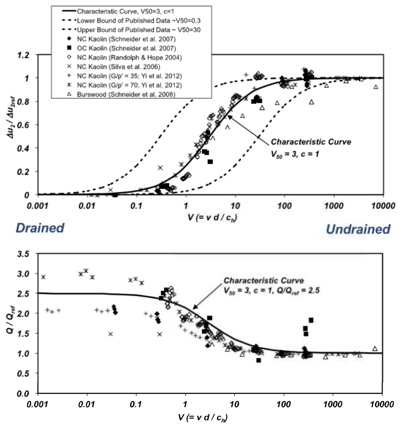
Characteristic curves:

$$\frac{\Delta u_2}{\Delta u_{2ref}} \approx 1 - \frac{1}{1+\left(V/V_{50}\right)^c}$$

$$\frac{Q}{Q_{ref}} \approx 1 + \left(\frac{Q_{drained}/Q_{ref} - 1}{1+\left(V/V_{50}\right)^c}\right)$$

Experimental agreement with:

- $V_{50} = 3$
- $c = 1$
- $Q_{drained}/Q_{ref}$ = 2.5 (unique for NC kaolin)



Normalized framework for cone penetration

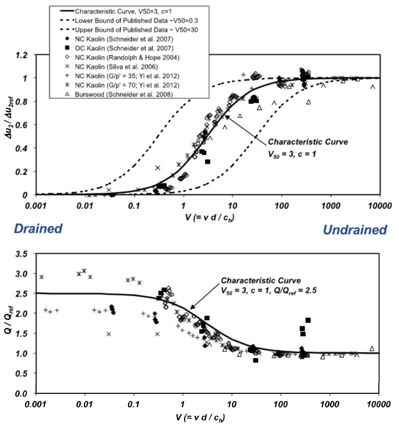
[REFERENCE]

Observations of trends:

- ➢ Undrained conditions at ($\Delta u_2/\Delta u_{2ref} > 0.9$) at $V > 30$
- ➢ Drained conditions at ($\Delta u_2/\Delta u_{2ref} < 0.05$) at $V < 0.3$

Calibration values generally range from:

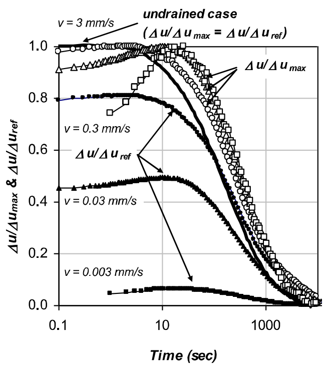
- ➢ V_{50} = 0.3 to 8
- ➢ c = 0.5 to 1.5



Influence of partial consolidation on dissipation test

- ➢ Dissipation curves from experimental data are more complex due to local pore pressure re-distribution and simultaneous partial consolidation.
- ➢ The correct normalization would be to use $\Delta u/\Delta u_{ref}$, but this value is not known in practice.
- ➢ Convention is to normalize by $\Delta u/\Delta u_{max}$, which produces shifts in dissipation curves to longer time periods and introduces an error in estimation of t_{50}.

NC Kaolin in Centrifuge CPT
Schneider et al. (2007)

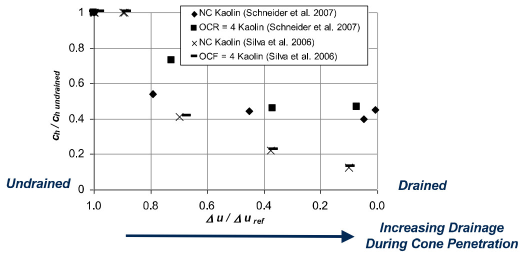


Influence of partial consolidation on dissipation test

- Teh and Houlsby (1991) solution for dissipation following undrained penetration.

General Form $T^* = \frac{c_h t}{r^2 \sqrt{I_r}}$ 50% Consol. $T^*_{50} = \frac{c_h t_{50}}{r^2 \sqrt{I_r}} = 0.245$

- Overestimation of t_{50} results in calculation of a lower c_h value.



Developed correction for dissipation test

- Correction developed with reformulation of Teh and Houlsby (1991) undrained solution to correct for partial dissipation during penetration.

$$T = \frac{c_h t}{d^2} \qquad U = \frac{\Delta u}{\Delta u_{ref}} \approx \frac{1}{1 + \left(T / T_{50}\right)^b}$$

- An estimate of the initial maximum (initial) pore pressure, U_0 (= $\Delta u_2 / \Delta u_{2ref}$), for a given V, corresponds to the notional time factor of:

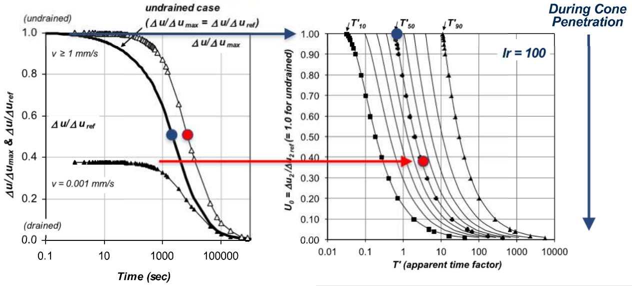
$$T_0 = T_{50}\left(\frac{1}{U_0} - 1\right)^{1/b}$$

- This produces an apparent time factor (T') to achieve a given percent of excess pore pressure dissipation from an initial normalized pore pressure, U_0.

$$T' = T_{50}\left(\frac{1}{(1-f)U_0} - 1\right)^{1/b} - T_0$$

Developed correction for dissipation test

- Dissipation after undrained penetration at $U_0 = 1$.
- T' increases with increasing dissipation during penetration.
- Example: T' at ~60% excess pore pressure during cone penetration.
  - ● undrained penetration (U = 0%), $U_0 = 1.0$, $T'_{50} = 0.61$
  - ● partial consolidation (U = ~60%), U_0 = ~0.4, $T'_{50} = 3.5$



Developed correction for dissipation test

- Implications on test interpretation can be explored with substitutions:

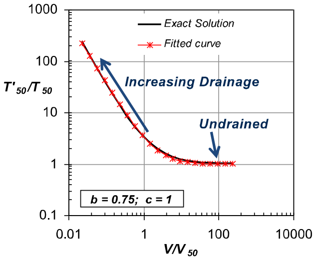
$$U_0 = \frac{\Delta u_2}{\Delta u_{2ref}} \approx 1 - \frac{1}{1 + \left(V / V_{50}\right)^c} \qquad T' = T_{50}\left(\frac{1}{(1-f)U_0} - 1\right)^{1/b} - T_0$$

- The relationship can be approximated by:

$$T'_{50} = \frac{t_{50} c_h}{d^2} = 0.06125\sqrt{Ir}\left(1 + \frac{1}{g\left(V / V_{50}\right)^k}\right)$$

w/ $V_{50} = 3$, $g = 0.43$, $k = 1.20$

(for $b = 0.75$ and $c = 1$)



- As T'_{50}/T_{50} increases V is reduced and partial dissipation occurs during penetration.

Conditions when partial consolidation exists during penetration

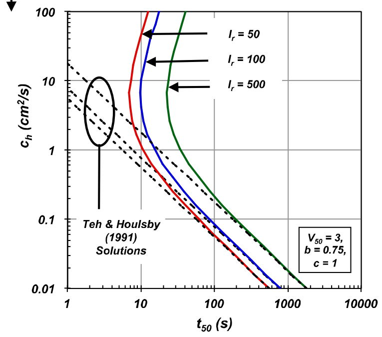
- Simplified equation for conventional piezocone testing reduces to:

$$t_{50} = \frac{\sqrt{Ir}}{c_h}\left[78 + 0.25 c_h^{\,1.2}\right]$$

(10 cm² area, v = 20 mm/s, $V_{50} = 3$, $b = 0.75$, $c = 1$)

- Partial consolidation during penetration affects c_h interpretation when measured t_{50} < 75 seconds.
- When t_{50} > 50 seconds the original solution by Teh and Houlsby (1991) is within 20%.

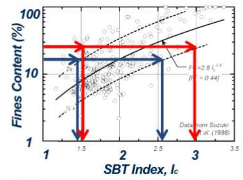
(for 15 cm² cone multiply by 1.5)



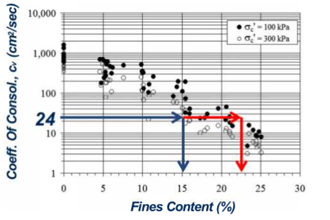
Conditions when partial consolidation exists during penetration

- Consider:
  - Lower bound condition with > 90% drained
  - $V = 0.3$
  - $v = 2$ cm/sec, $d = 3.6$ cm (10 cm^2 cone)

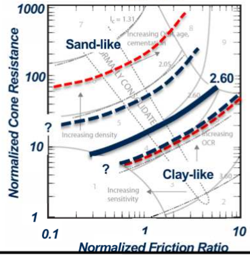
➔ $c_h \approx 24$ cm^2/sec



(Suzuki et al. 1998)



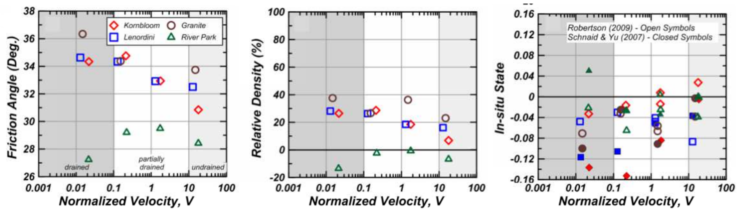
(Bandini et al. 2011)



(Robertson 2009)

Effect of partial consolidation conditions on estimated soil properties

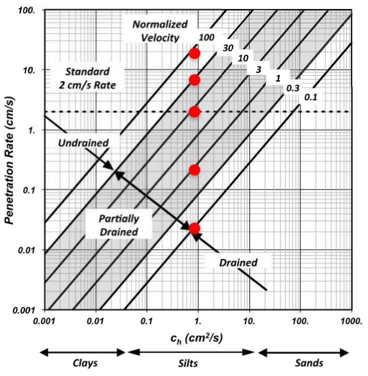
- Application of CPT data correlations to estimate engineering properties presumes that drainage conditions are consistent.
- However, estimated properties can vary substantially as drainage conditions are varied.
- Effect will vary and depends on initial soil state:
  - Loose of critical (NC) soils will generate $+\Delta u$, resulting in $Q_{drained} > Q_{undrained}$
  - Dense of critical soils can generate $-\Delta u$, resulting in $Q_{undrained} < Q_{drained}$



Selection of Penetration Rate

- Normalized velocity framework allows for control of drainage conditions through varying penetration rate.
- Recommended practice:

1. Perform 2 cm/s profile with pore pressure dissipation tests at rod breaks.
2. Determine t_{50} and estimate c_h.
3. Compute normalized velocity & plot.
4. Determine feasibility of obtaining drained or undrained cone measurements.
5. Identify penetration rates for variable rate testing in next depth interval or subsequent sounding.



(Divide Penetration Rate by 1.22 for 15 cm^2 cone.)

Summary

- The normalized velocity framework and modification of Teh and Houlsby (1991) pore pressure dissipation solution has provided a tractable approach to identify and control partial drainage conditions during cone penetration testing.
- Partial drainage conditions are present when t_{50} from a dissipation test is less than ~75 seconds.
  - These conditions may be present in intermediate (transitional, tailings, etc.) soils with I_c values between 1.5 and 3.0.
- Use of the modified Teh and Houlsby solution is appropriate when $t_{50} < 75$ sec. in order to not overestimate c_h.
- Application of empirically correlations to estimate engineering properties that presume drained or undrained conditions may be significantly over- or under- estimated when using CPT data obtained during partially drained cone penetration conditions.
- Application of the normalized velocity framework with short penetration tests at rod breaks enables rapid identification of partially drained conditions and opportunities to adjust the penetration rate to achieve the desired undrained or drained penetration conditions.

CPT Interpretation: Mapping Spatial Stratigraphic Correlation Structures

(Collaborators: C.P. Krage, D.J. DeGroot)

Motivation

- Site investigations collect statistically sparse data, usually less than 0.001% of the soil volume engaged in a project.
- Extensive engineering judgement is often exercised to ‘interpret’ subsurface conditions, producing a result that cannot necessarily be replicated by others.
- Geotechnical engineers are inherently optimistic regarding material uniformity and layer continuity (e.g. Duncan 2003), often insufficiently appreciating the extent of variability present.

- There is a need to develop a more systematic, rigorous approach to characterize subsurface conditions, leveraging geologic interpretation and the application of geostatistics. This would ideally increase the objectivity and repeatability of:
  - identification of layers and their continuity (connectivity)
  - justification and selection additional soundings/borings
  - comparison of measurements obtained with different methods/tools
  - selection of representative values for engineering analysis and design

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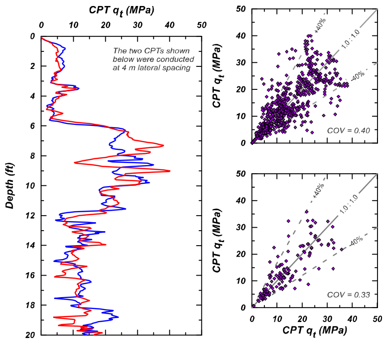
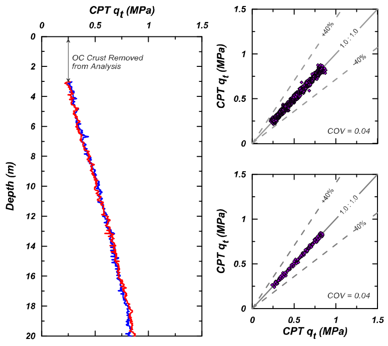
Motivation



Alluvial Deposit

North Haiwee Reservoir, CA

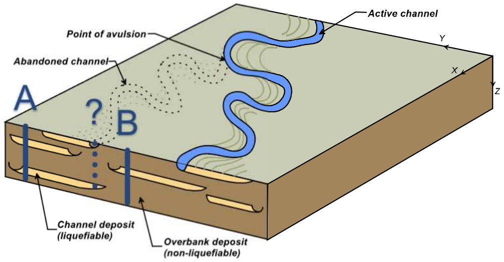


Marine Deposit

Onsoy, Norway

Motivation for geostatistical approach

- The role of geostatistics is to extend what is known from the geologic setting and from site investigation data to provide insights regarding both site conditions and the expected system performance at unsampled locations.
- Traditional site investigation approaches may not capture the connectivity/continuity of certain deposits (i.e. loose channel fill), and judgement is often employed to assess connectivity.

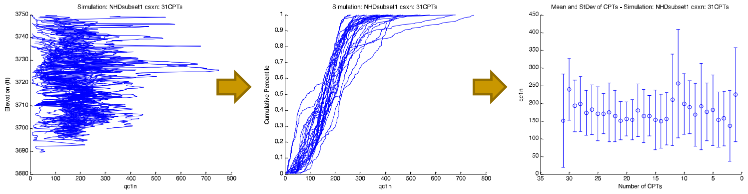


Nichols (2009)

Approaches to modeling spatial variability

[REFERENCE]

- Properties and stratigraphy of subsurface soils can be characterized using a random field approach.
  - Inherent soil variability - μ, σ, PDF, COV
- Properties and stratigraphy of subsurface soils can be characterized assuming that they exist is a spatial structure that can be captured statistically.
  - Geostatistical methods can infer spatial structure based on a given property/measurement (e.g. q_{c1N}, I_c, s_u) to differentiate between soil types (e.g. sand, clay).



Spatial correlation methods

[REFERENCE]

- In spatial correlation methods an exponential structural model most common.

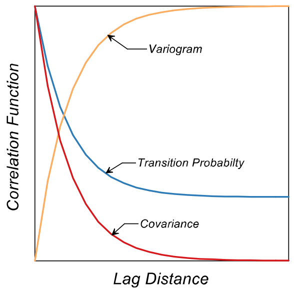
$$\rho(h) = \exp(-\frac{2h}{\theta})$$

$$\gamma(h) = 1 - \exp(-\frac{3h}{a})$$

$$t(h) = (1 - \mathrm{p}) \exp\left(-\frac{h}{L}\right) + p$$

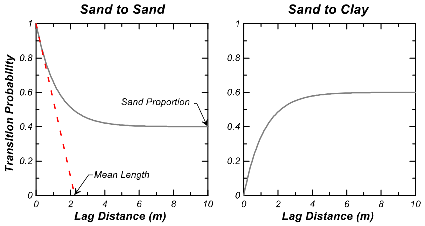
- Correlation length is the measure of statistical correlation.

Spatial Range	Scale of Fluctuation	Autocorrelation Distance	Mean Length
a	θ = 2a/3	a/3	L = a/3



Spatial correlation modeling using transition probability

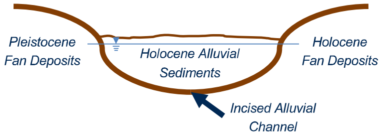
- Transition probability geostatistics describes the probability of transition between categories as a function of distance between points (Carle 1999).
- Categories can be defined based on soil type (i.e. sand or clay), soil property (i.e. q_{c1N} range), or a performance mechanism (i.e. liquefiable/non-liquefiable).



- Different transition probability models can be assigned for each orthogonal direction (x, y, z) based on field data and geologic understanding.
- Multiple realizations can be produced using kriging conditioned on the measured data.

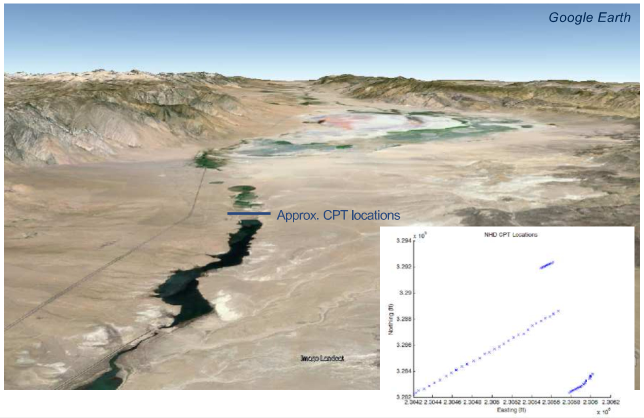
Project case history

- Long linear infrastructure to be constructed perpendicular to wide alluvial valley on eastern side of Sierra Nevada mountain range.
- Project need was to identify liquefaction susceptible layers, assess potential deformation, and, if necessary, identify zones requirement ground improvement.



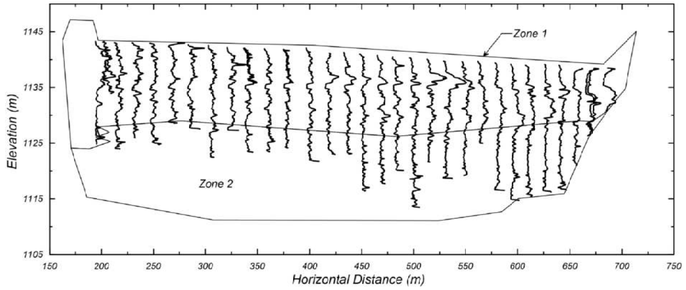
- Design EQ:
  - M=7.75
  - 84th% PGA=0.85 g
  - CSR=0.4-0.6

Project case history



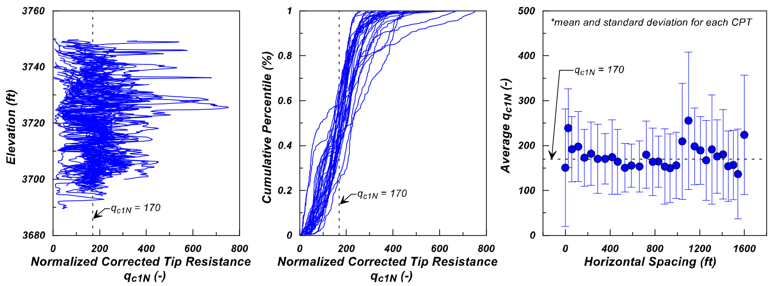
2D site investigation data

- Geologic dating determined subdivision into upper and lower alluvium zones.
- 39 CPTs across the main cross-section of the proposed dam alignment encountered primarily clean sands in the upper alluvium with 98% having $I_c < 2.6$.



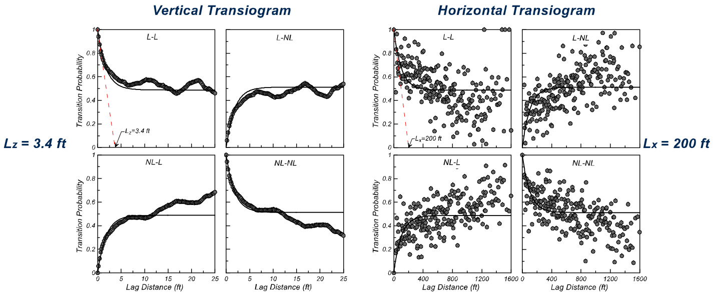
Aggregated site data

- Aggregation of the 31 CPT sounding data was achieved using stress normalized q_t.
- Based on seismic loading and Boulanger and Idriss (2015) a threshold of $q_{c1N} = 170$ was selected to categorically bin data into 'liquefiable' and 'non-liquefiable'.



Calibration of transiogram

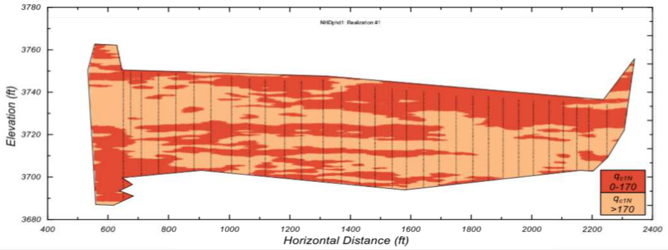
- Calibration in the vertical direction was straight forward due to extensive data obtained at close (5 cm) spacings.
- Vertical calibration was used as basis to define the sill (relative bulk portions of L & NL).
- Horizontal calibration was more variable, and the data spacing was much larger.



Geostatistical realization: Single simulation based on 31 CPT soundings

- A 2-Category statistical realization of site where all 31 CPTs soundings were used to condition the realization highlights the following:
  - each realization is exactly correct (conditioned) at sounding locations
  - the values in between soundings are unique to each realization and estimated based on the correlation function and kriging

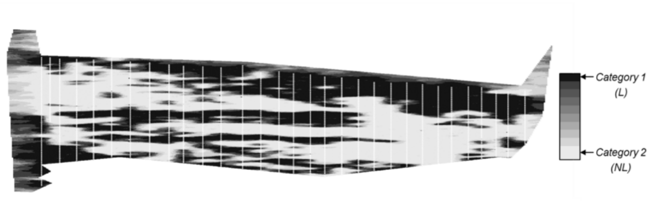
2 Category w/ q_{c1N} = 170 threshold



Geostatistical realization: 10 simulations based on 31 CPT soundings

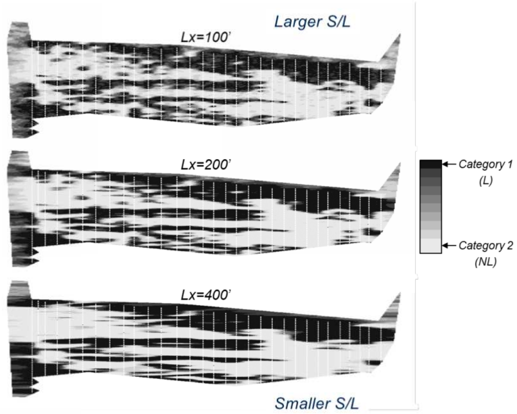
- Heat maps by averaging of 10 realizations highlights:
  - zones of certainty (Black = L & White = NL)
  - uncertainty (Gray)

2 Category w/ q_{c1N} = 170 threshold



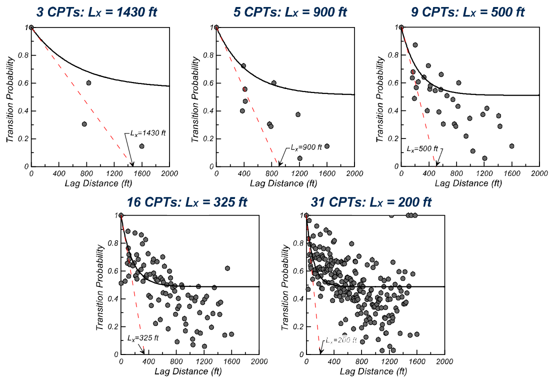
Simulation sensitivity: varying of horizontal mean length (Lx)

- Simulation sensitivity in L_X examined while keeping L_Z constant and using 31 conditioning CPTs.
- L_X adjusted based on possible calibration range from variogram.
- This results in changing S/L ratio while maintaining CPT spacing (S) for conditioning locations.
- Evident that larger S/L values result in greater uncertainty (gray) in performance and continuity of layers.



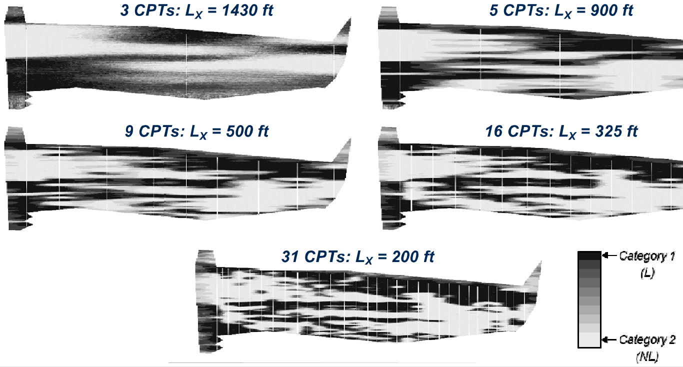
Simulation sensitivity: varying of number of CPTs

- Variograms calibrated using different number of CPTs, producing different L_x, L_y, and sill values.
  - 3 CPTs: L_x = 1430 ft
  - 5 CPTs: L_x = 900 ft
  - 9 CPTs: L_x = 500 ft
  - 16 CPTs: L_x = 325 ft
  - 31 CPTs: L_x = 200 ft



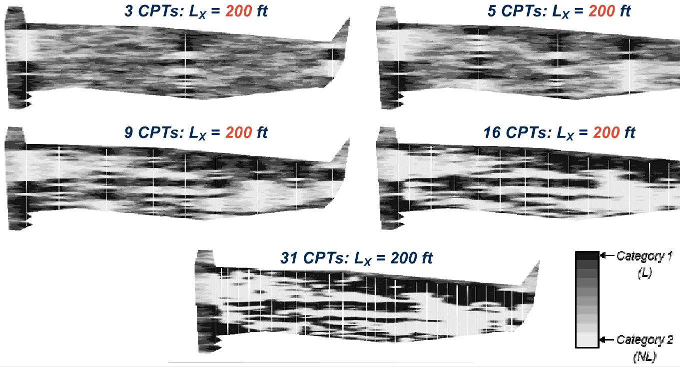
Simulation sensitivity: varying # CPTs

- Heatmaps (10 realizations) show reduced definition w/ increased L_X and CPT reduced conditioning.



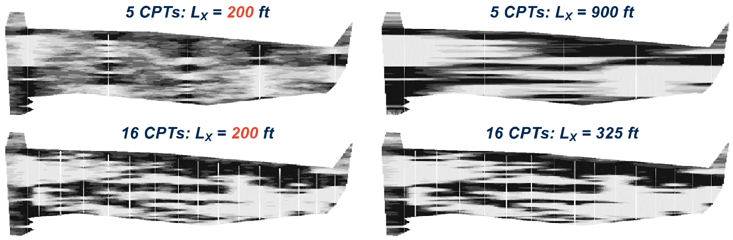
Simulation sensitivity: varying # CPTs but holding L_X = 200’

- Impact of # of conditioning locations on certainty in number & continuity of layers demonstrated by increasing # CPTs and maintaining L_X = 200’ (31 CPTs calibration).



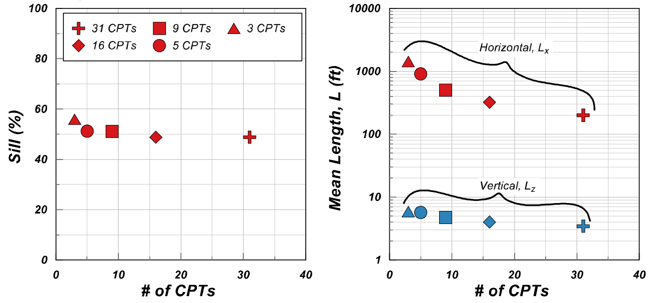
Simulation sensitivity: varying # CPTs but holding L_X = 200’

- Impact of # of conditioning locations on certainty in number & continuity of layers demonstrated by increasing # CPTs and maintaining L_X = 200’ (31 CPTs calibration).
- For example, interpretation of 5 CPTs without additional data gives us larger, incorrect L_X value (900 ft), resulting in false confidence in layer continuity relative to the actual L_X value of 200 ft.



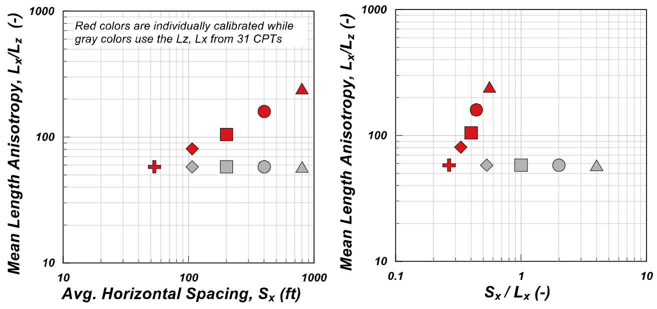
Simulation sensitivity: stability of calibrated parameters

- Estimation of bulk portions (sill) of L & NL stabilizes at 5 to 9 CPTs.
- The mean length is overpredicted with fewer CPTs, reducing at a decreasing rate.
- Practically, this implies that mean length is overestimated with an insufficient number of CPT soundings.



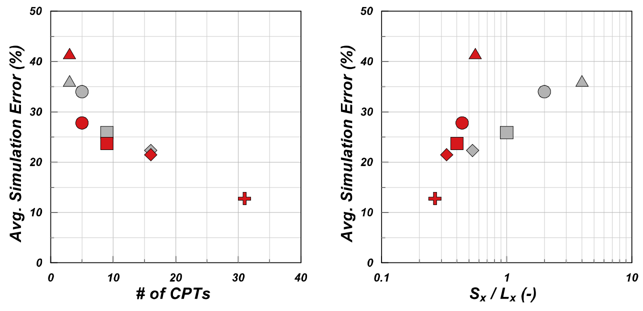
Simulation sensitivity: stability of calibrated parameters

- The stratigraphic anisotropy ratio, L_X/L_Z, decreases as the sounding spacing, S_X, decreases due to more CPT soundings.
- A reasonable estimate of the mean length requires CPTs that are spaced at 0.25x the mean length, L_X.



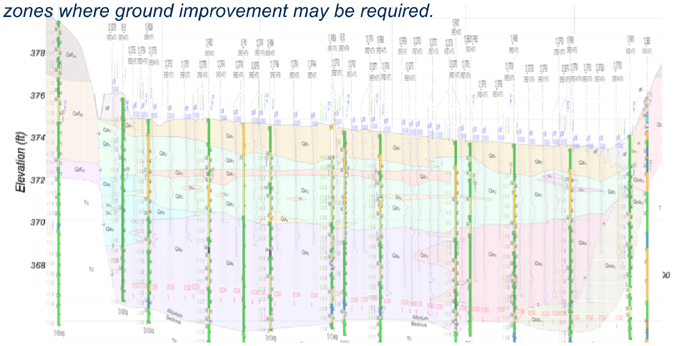
Simulation sensitivity: errors in simulations with calibrated parameters

- The error can be assessed by evaluating the variability between multiple simulations.
- Expectedly the error decreases as the number of CPTs increases.
- More generally, the error decreases as the normalized sounding spacing, S_X/L_X, decreases.



Comparison of geostatistical analysis with geologic mapping

- Strong consistency between blind development of geologic map and geostatistical modeling.
- Geostatistical application for L/NL engineering application enables rapid identification of zones where ground improvement may be required.



Summary

- Modeling using transitional probability statistics provides a structure where simulations can be calibrated and conditioned on site specific data (e.g. CPTs). The approach can also incorporate 'soft' geologic interpretation data to evaluate different site scenarios (not explicitly shown).
- Multiple simulations can be used to generate heatmaps and identify zones where greater uncertainty exists, possibly providing direction for additional investigations.
- The calibrated mean length decreases as the CPT spacing decreases, and CPT spacings at 0.25x of the actual mean length is necessary. Therefore, an initial estimate of the mean length based on the geologic depositional processes can be useful when planning CPT sounding layouts as part of the site investigation program.
- Engineering 'optimism' of the horizontal continuity can be false, with greater variability actually present.
- The application of geostatistics to map soil type, soil engineering properties, or a performance mechanism allows the engineer to explore the spatial component of several different aspects of the engineering analysis and design process.

References

- Boulanger, R.W. and DeJong, J.T. "Inverse filtering procedure to correct cone penetration data for thin-layer and transition effects", CPT '18 Conference, June 21-22, 2018, 19 pp.
- Yabusaki, L. "A History of Claims and Recommended Risk Management Practices for Site Investigation in Geotechnical Engineering", M.S.C.E. Project Report, June 2015, 36 pp.
- DeJong, J.T. and Randolph, M.F. "Influence of Partial Consolidation during Cone Penetration on Estimated Soil Behavior Type and Pore Pressure Dissipation Measurements" ASCE Journal of Geotechnical and Geoenvironmental Engineering, 2012, Vol. 138, No. 7, pp. 777-788, DOI: 10.1061/(ASCE)GT.1943-5606.0000646.
- DeJong, J.T., Jaeger, R.A., Boulanger, R.W., Randolph, M.F., Wahl, D.A.J. "Variable Penetration Rate Cone Testing for Characterization of Intermediate Soils", 4th International Site Characterization Conference, (Keynote Paper), 2012, 25-42.
- Krage, C.P. and DeJong, J.T. "Influence of Drainage Conditions during Cone Penetration on the Estimation of Engineering Properties and Liquefaction Potential of Silty and Sandy Soils", ASCE J. Geotechnical and Geoenvironmental Engineering, 2016, https://doi.org/10.1061/(ASCE)GT.1943-5606.0001543.
- Krage, C. P., DeJong, J. T., and Boulanger, R. W. "Identification of geologic depositional variations using CPT-based conditional probability mapping." Proceedings, 5th International Conference on Geotechnical and Geophysical Site Characterization, Gold Coast, Australia, September 5-9, 2016.
- Krage, C.P. Investigation of Sample Quality and Spatial Variability for Intermediate Soils, Ph.D. Dissertation, University of California, Davis, 2018, 247 pp.

Questions?

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