Presentation Overview

• Introduction
• Site investigations
  – Case study
• Modelling spatial variability of the ground
• Risk-based framework for site investigations
• Results:
  – Pad footing
  – Piles
• Conclusions
Optimising Site Investigations

• The largest element of financial and technical risk usually lies in the ground.

• Structural foundation failure can often be attributed to inadequate and/or inappropriate site investigations.

• Engineering properties of soil and rock often exhibit significant variability from one point to another (spatial variability).

• One would expect the scope of site investigations to be directly linked to the variability of the ground.

Optimising Site Investigations

• Over the last 30 years geotechnical investigation prices have been driven down.

• The scope often being governed by minimum cost and time of completion.

• Institution of Civil Engineers (UK) concluded that:

  “You pay for a site investigation whether you have one or not.”
Inadequate Site Investigations

Inadequate site investigations increase the risk of:

- Foundation failure, i.e. under-design;
- Over-design;
- Unforeseen issues in the ground that can lead to construction delays and added costs.

Case Study – University of Adelaide


- **1996**: University of Adelaide commissioned the construction of two buildings – Engineering and Science.

- Total cost of construction: $24 million
Original Site Plan

Site Geology

- Torrens Alluvium.
- More variable than Adelaide CBD.
Case Study – University of Adelaide

- Structural engineering consultant sought three tenders.
- Prices varied between 0.25% and 0.4% of $24 million budget.
- Scope varied between tenderers: max. depth of borehole drilling between 10 and 22 m.
- Successful tenderer was the most expensive proposal – selected because of its scope.

Site Investigation Scope

- 3 × deep wash-bored boreholes to 22 m;
- 6 × shallow dynamic-push boreholes to 6 m;
- 6 × CPTs to between 7 and 11 m;
- 1 × groundwater monitoring borehole;
- 9 × UU triaxial tests;
- Shrink/swell, CBR tests;
- Chemical analysis of groundwater.
Site Investigation Plan

Site Investigation Report

• Piles were recommended and the report stated that bored piles were “unlikely to be viable.”

• Recommended driven piles; driven cast-in situ with enlarged bases; or Atlas screw piles.
Building Design Modifications

- In early 1997 (after the site investigation), cost estimates revealed the project was forecast to be well over budget.

- This prompted a major review of the scope of the building.

- In early 1998, it was decided to modify the Engineering Building, the:
  - basement computer suites were removed;
  - the footprint of the building approximately 20 m to the west; and
  - building’s internal space was redefined.

Final Site Plan
Foundation Construction

• No additional site investigation was undertaken.

• Bored piles were constructed, which subsequently failed to meet the design total settlement criteria.

• Statically-driven piles (G-piles) were subsequently installed.

G-Piles
Outcome

• Additional $170,000 to the construction budget (2.4% of the construction budget for the Engineering Building);

• Delay of between 4 and 6 weeks to the construction period.

Optimising Site Investigations

• **Aim:** To provide geotechnical engineering practitioners with quantitative tools to facilitate the design of reliable site investigations.

• Facilitate meaningful conversations with clients, such as:
  
  “With an extra two boreholes, the risk of foundation failure, over-design and cost over-runs can be reduced by 10%.”

• Enables one to compare scopes of site investigations and their reliability; e.g.:
  
  “Are 6 × boreholes with 8 triaxial tests better than 4 CPTs?”
Spatial Variability

- Soils and rocks are inherently variable from one location to another.

Spatial Variability

This is due mainly to the complex and varied processes and effects which influence their formation, and include:
- sedimentation
Spatial Variability

- parent material

Spatial Variability

- weathering and erosion
Spatial Variability

• climate

Spatial Variability

• topography
Spatial Variability

- organisms

Spatial Variability

- structural defects (faults, folds, joints, fractures)
Spatial Variability

• layering (stratigraphy)

Spatial Variability

• stress history
Spatial Variability

• suction

Spatial Variability

• time.
Modelling Spatial Variability

Mathematical techniques focus on stochastic methods:
- Regression analysis
- Random field theory
- Geostatistics
- Fractal theory.

- Regression analysis is too simplistic;
- Geostatistics is similar to RFT;
- Fractal theory: useful but no modelling tools are available.

Random Field Theory

- 3D extension of time series analysis.
- Applied to geotechnical engineering by Prof. Eric Vanmarcke (MIT, Princeton) in late 1970s, early 1980s.

Spatial variability is expressed by 3 parameters:
1. Mean (average);
2. Variance, Standard deviation, Coefficient of variation;
3. Scale of fluctuation.
Scale of Fluctuation

- The scale of fluctuation, $q$, is a measure of the distance over which soil properties are highly correlated.

- Small values of $q$ imply rapid fluctuations about the mean.
Scale of Fluctuation – 2D

Autocorrelation

- Unlike classical statistics, random field theory incorporates the observed behaviour that properties nearby are more related (i.e. autocorrelated), than those farther away.
Autocorrelation

- The autocovariance, $c_k$, and the autocorrelation coefficient, $\rho_k$, at lag, $k$, are defined as:

$$c_k = \text{Cov}(X_i, X_{i+k}) = E[(X_i - \bar{X})(X_{i+k} - \bar{X})] = E[X_iX_{i+k}] - \bar{X}^2$$

$$\rho_k = \frac{c_k}{c_0}$$

- It is not possible to know $c_k$ nor $\rho_k$ with any certainty, but only to estimate them from samples obtained from a population, say $X_1, X_2, ..., X_n$.

Sample Autocorrelation Coefficient

- Hence, the sample autocorrelation coefficient, at lag $k$, $r_k$, is defined as:

$$r_k = \frac{\sum_{i=1}^{n-k}(X_i - \bar{X})(X_{i+k} - \bar{X})}{\sum_{i=1}^{n}(X_i - \bar{X})^2}$$
Sample Autocorrelation Function

- The sample autocorrelation function (ACF) is the plot of \( r_k \) for lags \( k = 0, 1, 2, \ldots, K \); where \( K \) is usually, \( n / 4 \).

ACF – Small \( \theta \)
ACF – Large $\theta$

ACF – Example

- Cone penetration test (CPT) sounding is a geotechnical engineering example of a 1D random field.
ACF – Example (2)

- Keswick Clay only
- Statistical homogeneity, stationarity.

![Graph showing Cone Tip Resistance, $q_c$ (MPa) vs Depth Below Ground (mm)]

ACF – Example (3)

<table>
<thead>
<tr>
<th>Depth (mm)</th>
<th>$q_c$ (MPa)</th>
<th>$q_c$ (MPa)</th>
<th>$q_c$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1100</td>
<td>1.66</td>
<td>1.66</td>
<td>1.66</td>
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<tr>
<td>1105</td>
<td>1.72</td>
<td>1.72</td>
<td>1.72</td>
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<tr>
<td>1110</td>
<td>1.69</td>
<td>1.69</td>
<td>1.69</td>
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<tr>
<td>1115</td>
<td>1.70</td>
<td>1.70</td>
<td>1.70</td>
</tr>
<tr>
<td>1120</td>
<td>1.70</td>
<td>1.70</td>
<td>1.70</td>
</tr>
<tr>
<td>1125</td>
<td>1.77</td>
<td>1.77</td>
<td>1.77</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>5045</td>
<td>2.08</td>
<td>2.08</td>
<td>2.08</td>
</tr>
<tr>
<td>5050</td>
<td>2.02</td>
<td>2.02</td>
<td>2.02</td>
</tr>
<tr>
<td>5055</td>
<td>1.76</td>
<td>1.76</td>
<td>1.76</td>
</tr>
</tbody>
</table>

Lag 1 Shift data UP by 1 cell
Lag 2 Shift data UP by 2 cells

Quadratic Trend $r^2 = 0.719$
ACF – Example (4)

ACF – Example (5)
ACF – Example (6)

Lag 50, i.e. 250 mm

ACF – Example (7)

Autocorrelation, $r_k$
Determining $\theta$ from ACF

Scale of fluctuation, $\theta$, can be determined from the ACF by:

- Curve fitting;
- Using Bartlett’s limits.

Optimising Site Investigations

- Not possible to determine optimal site investigation for actual sites.

- It is possible, however, using virtual sites.
Optimising Site Investigations

• Simulation utilises a Monte Carlo framework.
• Results are based on thousands of simulations.
• Analyse elastic settlement → Young’s modulus, \( E \)
• Random variable, log-normal distribution
  
  - Specify: mean, COV, \( \theta \)
  - Generate random seed → Soil profile simulation

Optimising Site Investigations

• Every ‘element’ of the site is known – Complete Knowledge (CK)
Optimising Site Investigations

• Then perform a virtual site investigation.

Optimising Site Investigations

• Design footing based on specified loads and results of site investigation.
Optimising Site Investigations

- Analyse footing on complete site and assess performance (Complete Knowledge).

If $F_{SI} < F_{CK}$ then the foundation is under-designed and there are damage consequences.

13 storey collapse, Shanghai, 2009
Optimising Site Investigations

• If $F_{SI} < F_{CK}$ then the foundation is under-designed and there are damage consequences.

• If $F_{SI} > F_{CK}$ then the foundation is over-designed.

• If $F_{SI} = F_{CK}$ then the investigation provided an accurate representation of the subsurface profile.

Optimising Site Investigations

• Generate a new site and repeat thousands of times.

• Evaluate probabilities of:
  – Failure;
  – Over-design; and
  – Appropriate design.

• Numerical intensity requires a supercomputer.
Simulating Random Fields

- Local Average Subdivision (LAS) method (Fenton)
Simulating Random Fields
Simulating Random Fields

http://courses.engmath.dal.ca/rfem/

Simulating Random Fields
Pad Footing Design

PhD – Dr. Jason Goldsworthy (2006)

Research focussed on:
• a single layer, spatially variable ground profile;
• supporting a multi-storey building;
• founded on pad footings.

Pad Footing Design

Site characteristics:
• 50 x 50 m site
• 20 x 20 m building footprint
• 0.5 x 0.5 m element size
Pad Footing Design

Pad Footing Design

Small θ
Pad Footing Design

Large 0

Pad Footing Design

1 RG 1
2 RG 1
3 RG 2
4 RG 2
5 RG 3
6 RG 3
7 RG 3
8 RG 4
9 RG 5
10 RG 9
11 RG 16
12 RG 25
Case Study – Pad Footing Design

- Measurement and transformation model errors:

<table>
<thead>
<tr>
<th>Test Type</th>
<th>Measurement Bias, $e_b$</th>
<th>Random, $e_r$</th>
<th>Transformation Model, $m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPT</td>
<td>20%</td>
<td>40%</td>
<td>25%</td>
</tr>
<tr>
<td>CPT</td>
<td>15%</td>
<td>20%</td>
<td>15%</td>
</tr>
<tr>
<td>TT</td>
<td>20%</td>
<td>20%</td>
<td>0%</td>
</tr>
<tr>
<td>DMT</td>
<td>15%</td>
<td>15%</td>
<td>10%</td>
</tr>
</tbody>
</table>

Case Study – Pad Footing Design

- Costs: $C_{Total} = C_{SI} + C_{Cons} + C_{Rhb}$

- Site investigation cost ($C_{SI}$):

<table>
<thead>
<tr>
<th>Test Type</th>
<th>Cost ($ / sample location)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPT</td>
<td>$2,900^1$</td>
</tr>
<tr>
<td>CPT</td>
<td>$3,300^2$</td>
</tr>
<tr>
<td>TT</td>
<td>$2,650^3$</td>
</tr>
<tr>
<td>DMT</td>
<td>$3,600^1$</td>
</tr>
</tbody>
</table>

1: Based on one sample every 1.5 m;  
2: Based on one sample every 0.5 m;  
3: Based 2 tests per borehole.
Case Study – Pad Footing Design

• Construction cost ($C_{Cons}$):
  – $11,650 \text{ m}^2$
  – Foundation cost = 1.8% × $C_{Cons}$

• Rehabilitation cost ($C_{R hb}$):

<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
<th>Cost ($ / m^2 / storey)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minor</td>
<td>Patching, repainting &amp; minor plumbing repairs</td>
<td>$410</td>
</tr>
<tr>
<td>Major</td>
<td>Significant patching, structural retrofitting, major plumbing repairs &amp; foundation underpinning</td>
<td>$2,035 + $1,730 / m^2 footing</td>
</tr>
</tbody>
</table>

Pad Footing Design

• Rehabilitation cost ($C_{R hb}$):
Pad Footing Design – Results

![Graph showing comparison between different methods (SPT, CPT, TT, DMT) for construction and rehabilitation costs]
Pad Footing Design – Results

![Graph showing Site Investigation Cost as Percentage of Construction Cost]

- Site Investigation Cost as Percentage of Construction Cost
- Total Cost - $ million
- CPT
- SPT
- DMT
- TT
Pile Design

PhD – Michael Crisp (Current)

Research focussed on:
• multi-layer, complex, spatially variable ground profiles;
• supporting a multi-storey building;
• founded on piles.

Complex Multi-layered Sites
Complex Multi-layered Sites

Generate:
- **Multiple soil layers** with each incorporating spatial variability

Layer boundaries that are:
- Horizontal;
- Inclined;
- Undulating;
- Ragged;
- Intermixed.

Complex Multi-layered Sites – Lenses
Complex Multi-layered Sites – Intermixed

Complex Multi-layered Sites – Single
Single Layer – Anisotropic variability

Pile Design – Initial Results
## Reduction Methods

<table>
<thead>
<tr>
<th>Reduction Method</th>
<th>Relationship</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard Arithmetic Average (SA)</td>
<td>( \frac{1}{n} \sum_{i=1}^{n} x_i )</td>
</tr>
<tr>
<td>Harmonic Average (HA)</td>
<td>( \frac{1}{n} \left( \sum_{i=1}^{n} \frac{1}{x_i} \right)^{-1} )</td>
</tr>
<tr>
<td>Geometric Average (GA)</td>
<td>( \left( \prod_{i=1}^{n} x_i \right)^{\frac{1}{n}} )</td>
</tr>
<tr>
<td>Minimum</td>
<td>( \min(x) )</td>
</tr>
<tr>
<td>1st Quartile</td>
<td>( \frac{1}{4} (n + 1)^{th \ value} )</td>
</tr>
<tr>
<td>Inverse Distance</td>
<td>( \sum_{i=1}^{n} \frac{S_i}{S_{total}} x_i )</td>
</tr>
<tr>
<td>Inverse Distance Squared</td>
<td>( \sum_{i=1}^{n} \frac{S_i^2}{S_{total}} x_i )</td>
</tr>
</tbody>
</table>

## Pile Design – Initial Results (2)

![Graphs showing Total Cost vs Investigation Effort, DMT, COV: 0.80 with various lines and markers representing different conditions.](image)

No. piles: 25, area: 400 m², No. Fores: 5, sef: 8, cor: 30, axis: 1, E: 45.0 MPa, test: dmt, bldepth: 20 m
Pile Design – Initial Results (3)

Pile Design – Initial Results (4)
Conclusions

Based on the examination of pad footings:

• The extent of a site investigation has a significant impact on the total cost of a foundation design.

• The optimal site investigation expenditure is a function of the variability of the soil.

• A modest increase in site investigation expenditure, leads to a reduction in the total cost of the design by up to 170 times.

• Site investigation expenditure should be closer to 0.5% of the construction cost.
Conclusions (2)

- These results are based on a simple and single ground profile and therefore should be seen as a minimum.
- The examination of complex, multi-layered profiles will reveal more practical outcomes.