Ground Risk: why take the chance?
The application of Advanced Continuous Surface Wave data to managing ground risk

Chris Milne, Director, Ground Stiffness Surveys Limited
Continuing challenges for GI

- **Risk** – unforeseen ground conditions, services, hazardous or sensitive environments
- **Cost** – expenditure due early in project life
- **Time** – access restrictions; need for rapid results
- **Conservatism** – wider industry slow to accept new approaches
- **Lack of understanding of value of properly scoped GI (still!)** for some projects
‘New’ challenges for GI

• **Focus on SLS** – need for accurate strain softened stiffness values

• **Recognition of limitations of traditional investigation approaches for design**
  
  *e.g. SPT stiffness relationships*

• **Advances in design software** – increasing use of FEA

• **Digital data requirements**
Surface wave methods

• Testing measures **speed of surface (Rayleigh) waves** travelling through the ground over a range of frequencies

• **Profile depth based on wavelength** (velocity/frequency)

• **Known velocity relationships** between Rayleigh wave velocity ($V_r$), shear wave velocity ($V_s$) and stiffness ($G_0$) – see Tomlinson!

• **Known stiffness relationships** between $G$ & $E$ for design strain-softening

• **Obvious advantages** – rapid, economical, non-intrusive, in-situ, bulk stiffness measurement - why not commonly used?

“Surface wave testing has been ‘the next big thing’ for the last 20 years”
What is ACSW?

Advanced Continuous Surface Wave (ACSW) developed to address perceived issues with surface wave testing:

• Speed & cost
• Practicality in UK construction environment
• Standardisation as an engineering test
• Repeatability & quality control
• Flexibility & accessibility of outputs
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ACSW test setup

- Generator & test equipment operated within vehicle
- Data collection within vehicle
- Single operator vehicle lift
- Armoured shaker power cable (230v 3-phase)
- Numbered spike geophones (typical 0.6m spacing)
- Warning signs prohibiting unauthorised access to test area
- Test location as selected by client
- Shaker seated on 25mm sand bed in hand excavated approx. 400Lx400Wx50D mm excavation (if required)

See GSS Test Layout Drawing GSSDWG001
Rapid and low impact test methodology

- Robust all-weather system
- Automated by easy-to-use software
- Rapid (20 mins per test)
- Low intensity – single technician, small working area
- Not sensitive to site noise – working around other operations possible
- Low cost – about that of a PLT
- Low risk – non-intrusive, low vibration

ACSW construction testing system capable of 12 to 20 tests per shift
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C-DAS control & analysis software

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### Field user interfaces

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<table>
<thead>
<tr>
<th>VS (m/s)</th>
<th>Thickness (m)</th>
<th>Depth (m)</th>
<th>Density (kg/m³)</th>
<th>Eo (MPa)</th>
<th>ν</th>
<th>En (MPa)</th>
<th>E at 0.1% strain (MPa)</th>
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Strain level softened to: **0.1%**

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First test of night in Up 4 foot at southern end of site. Good model fit (10 layers - minimum 2m, maximum 3m thickness).
Typical ACSW field testing arrangement

Safe one person operation from modified 4WD vehicle
Site operation

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a bright new wave in geotechnics
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Dispersion curve – $V_r$ against frequency

Simple inversion – approximate average stiffness with depth

C-DAS field output

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C-DAS reporting output

<table>
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<tr>
<th>Vs (m/s)</th>
<th>Thickness (m)</th>
<th>Depth (m)</th>
<th>Density (kg/m³)</th>
<th>Go (MPa)</th>
<th>v</th>
<th>E0 (MPa)</th>
<th>E at 1% strain (MPa)</th>
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<td>0.0</td>
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Notes:
1. Vs values have been determined from advanced inversion of field dispersion data. Vs values derived by inversion rely on assumptions of soil density and Poisson’s Ratio. Where no project specific data is provided then default values of \( v = 1800 \text{ kg/m}^3 \) and \( v = 0.26 \) are assumed. Refer to above GSS report conditions for further information.
2. \( G = \rho v^2 \)
3. \( E = G (1 + v) \)
4. Softened values of stiffness are calculated using Rotllin equation:

\[
G = \frac{1}{G_0 \left[ 1 + 16\gamma \left( 1.2 + 10^{-3} \gamma \right) \right]}
\]

Rotllin et al. (1998)

Depth (m)

Edit spreadsheet output giving strain softened E

Modelled layered stiffness profile

Shear wave velocity \([Vs]\) (m/s)
ACSW risk reduction applications

Rapid, low risk, low intensity, low cost:

1. supplementary GI – e.g. sensitive, difficult to investigate or high-risk sites
2. high quality stiffness data
3. validation & control testing – e.g. ground improvement
4. hazard assessment – e.g. shaft investigations
5. Rayleigh wave investigation – e.g. HS2

Easy to understand immediate on-site outputs for targeted investigation
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**Supplementary GI:** Ground profile comparisons

Boundaries indicated in simple inversion data

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Grass over TOPSOIL of dark brown sandy slightly gravelly organic SILT. Sand is fine to coarse, Gravel is fine to coarse sub-rounded to rounded of quartzite and quartz.</td>
</tr>
<tr>
<td>0.35</td>
<td>Orangeish brown silty gravelly fine to medium SAND. Gravel is fine to coarse, sub-rounded to rounded of quartzite and quartz.</td>
</tr>
<tr>
<td>0.35</td>
<td>Medium dense brown sandy sub-rounded to rounded fine to coarse GRAVEL and COBBLES of quartzite and quartz.</td>
</tr>
<tr>
<td>1.80</td>
<td>Very loose to loose reddish brown silty fine SAND</td>
</tr>
<tr>
<td>1.90</td>
<td>Stiff to very stiff reddish brown slightly sandy slightly gravelly CLAY. Sand is fine, Gravel is fine to medium, rarely course of sub-angular to sub-rounded mudstone, blue grey siltstone, quartz and quartzite.</td>
</tr>
</tbody>
</table>
Increasing near surface stiffness with increasing depth of Oxford Clay cutting

Stiff MG and granular Alluvium over very soft Clay and Peat
Supplementary GI: problematic ground

How to investigate intrusively?

2nd Forth Crossing Approach Embankment
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Stiffness data: ACSW vs High Pressure Dilatometer

HPD $G_{ur}$ data points

Simple inversion

Advanced inversion

HPD $G_i$ data points

Stiffness data: ACSW vs High Pressure Dilatometer

HPD $G_{ur}$ data points

Simple inversion

Advanced inversion

HPD $G_i$ data points
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Conservative empirical relationships between CPT & SPT & stiffness

Stiffness data: Settlement analysis case study - 1

Stiffness data:
Settlement analysis case study - 2
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Validation & control testing:

*ground improvement*

3D modelling of backfilled workings

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Hazard assessment: Shaft investigations
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Evaluating impacts of design mitigations

Consistency of approach: C-DAS used for modelling & field data evaluation

Rayleigh wave investigation: High Speed Rail modelling & mitigation design

Modelling using derived BH Vs profiles (direct import)
Discussion

• ACSW can offer a rapid, cost-effective means for geotechnical risk reduction

• ACSW is another tool in the GI armoury – it doesn't replace the need for a comprehensive GI and other techniques may sometimes be more appropriate

• As with all testing, ACSW needs to be undertaken and reviewed by a competent professional in the light of all available geotechnical data

• Research and development is ongoing – expect to see more published ACSW applications

“A significant advancement in development of a non-intrusive in situ testing that has the potential to change Site Investigation work”

2018 Ground Engineering Award Judges