EC7 Serviceability – simple calculation models

Malcolm Bolton

Scope

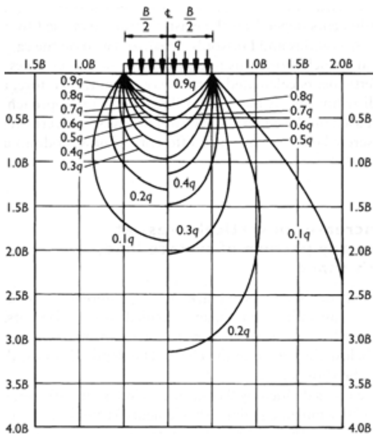
- Why specify a serviceability criterion?
- What have engineers been taught to do?
- Why is that inadequate?
- Soil non-linearity
- FE analysis
- Atkinson's equivalent-constant stiffness
- Bolton's equivalent-constant strength
- Is the EC7 framework appropriate?
- What is the way forward for EC7?

Why specify a serviceability criterion?

- Soil can deform excessively before mobilising peak strength.
- Structures crack up with small differential settlements.
- Other issues also relate to small structural movements:
  – interruption of services (e.g. opening of pipe/sewer joints)
  – malfunction of sensitive machinery (e.g. lifts)
  – poor vehicle ride quality (e.g. bridges, warehouse floors)
  – aesthetic disappointment (e.g. leaning towers?)
- Most foundation problems concern settlements, not collapse.
- Stiffness and strength are different attributes and, from the earliest days of Limit State Design, ULS and SLS have been distinguished in principle by different criteria.

What have engineers been taught to do?

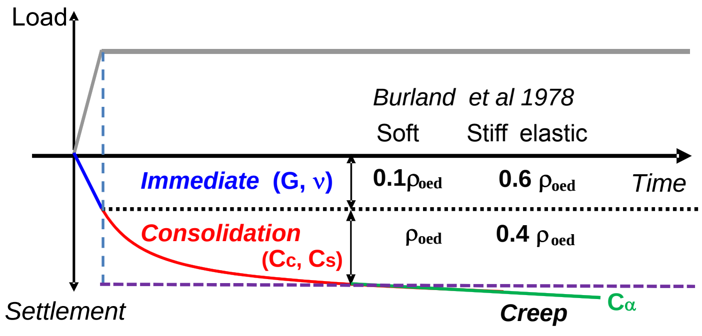
Vertical stress below pad/strip



- Identify layers Δz
- Get oedometer stiffnesses E_o
- Use elastic stress distributions to obtain vertical stresses $\delta\sigma_v$ at the centres of each layer
- Find vertical strains $\delta\varepsilon_v = \delta\sigma_v/E_o$
- Find layer compressions $\delta\rho_{oed}$
- Find $\rho_{oed} = \Sigma\delta\rho_{oed}$
- Use ρ_{oed} to estimate settlement

What have engineers been taught to do?

Process oedometer data



Components of foundation settlement in clay

What have engineers been taught to do?

Apply linear elastic displacement solutions directly.

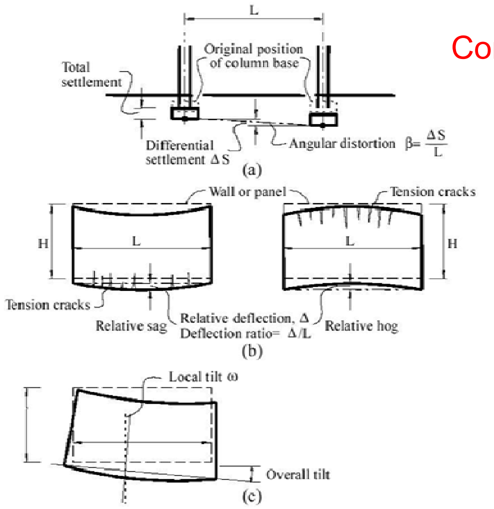
The settlement below a uniformly loaded circular area on uniform linear elastic soil is:

Uniform load: central settlement: $w_o = \frac{(1-\nu)}{G} qa$

edge settlement: $w_e = \frac{2}{\pi}\frac{(1-\nu)}{G} qa$

Rigid punch: ($q_{avg} = V/\pi a^2$) $w_r = \frac{\pi}{4}\frac{(1-\nu)}{G} q_{avg} a$

What have engineers been taught to do?



Poulos et al, 2001; Burland & Wroth 1974

Consider differential settlement

Express out-of-straightness Δ over chord length L as relative deflection Δ/L.

Link Δ/L to cracking damage.

Impose serviceability limits

e.g. 1/1000 sagging

e.g. 1/2000 hogging

depending on H/L etc.

Why is that inadequate?

- Settlement does not relate uniquely to E_o from oedometer
  - immediate settlement is a function of shear modulus G
  - primary consolidation is a function of bulk modulus K
  - G/K is a function of Poisson's ratio ν
- Soil is not linear elastic: G, K and ν vary strongly with strain
  - so stress distributions differ from Boussinesq etc.
  - and superposition does not apply
- Differential settlement Δ arises from spatial variations of both stress and soil stiffness, so it depends on deviations not on means.
- Δ/L is a function of the soil-structure stiffness ratio:

  e.g. Horikoshi K. & Randolph M.F. (1997) On the definition of raft-soil stiffness ratio for rectangular rafts, Geotechnique 47(5):1055-1062.

Soil non-linearity

- Small-strain shear modulus varies as:

$$G_0 \approx \frac{B}{(1+e)^3}(p')^{0.5}$$

where B ~ 20 000 kPa for clays, ~ 60 000 kPa for sands

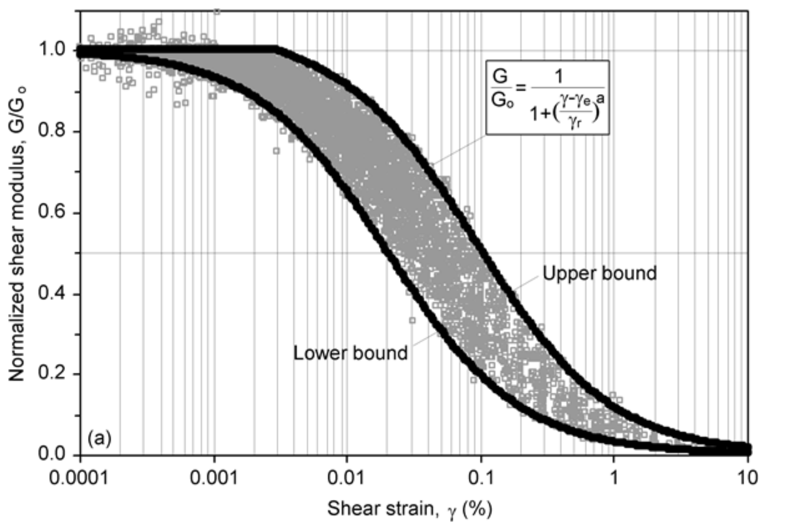
- Secant stiffness G then reduces quasi-hyperbolically:

$$\frac{G}{G_0} \approx \frac{1}{\left[1+\left(\frac{\gamma}{\gamma_{ref}}\right)^a\right]}$$

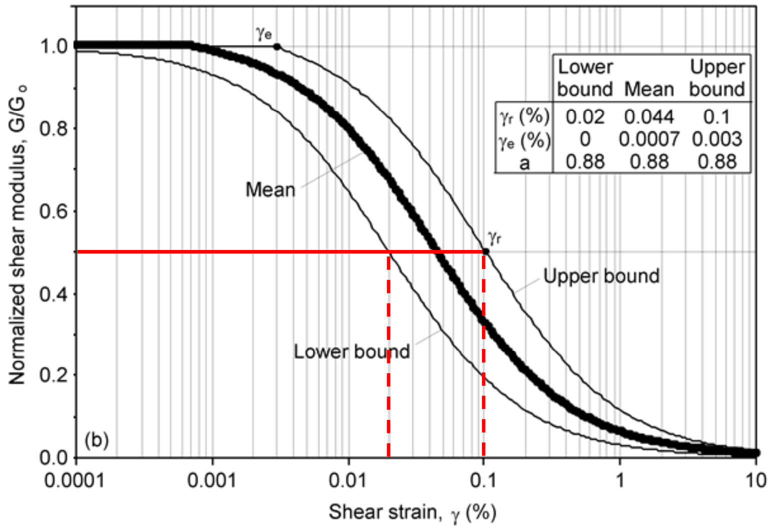
where a ≈ 0.7 for clays and $U_c^{-0.075}$ ≈ 0.8 to 1 for sands;
and $\gamma_{ref} \approx w_L\ 10^{-3}$ for clays and $f(U_c, I_D, e, p')$ for sands.

Oztoprak & Bolton (2011); Vardanaga & Bolton (2011)

Sand non-linearity: 454 tests reported by 61 authors

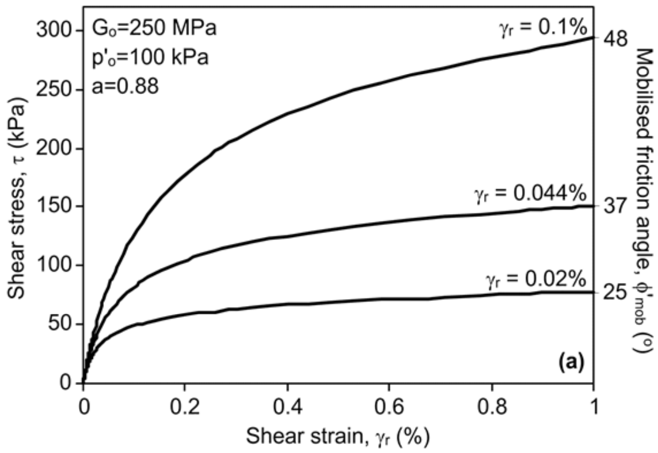


Sand: quasi-hyperbolic fit with upper and lower bounds



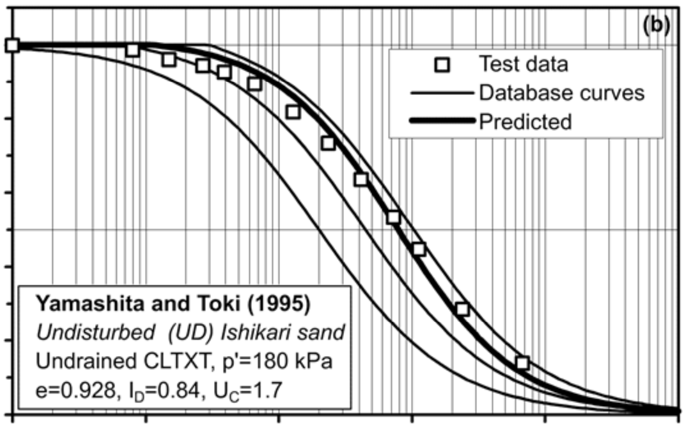
EC7 Today and Tomorrow Malcolm Bolton 11

A range of stress-strain curves for sand up to γ = 1%

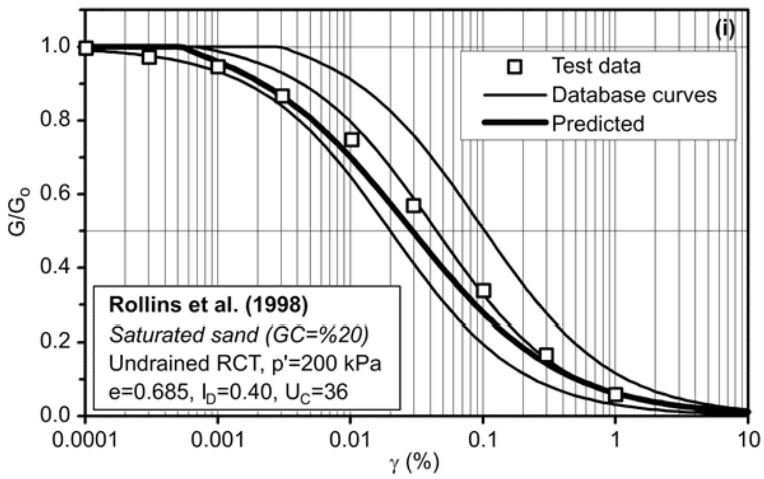


EC7 Today and Tomorrow Malcolm Bolton 12

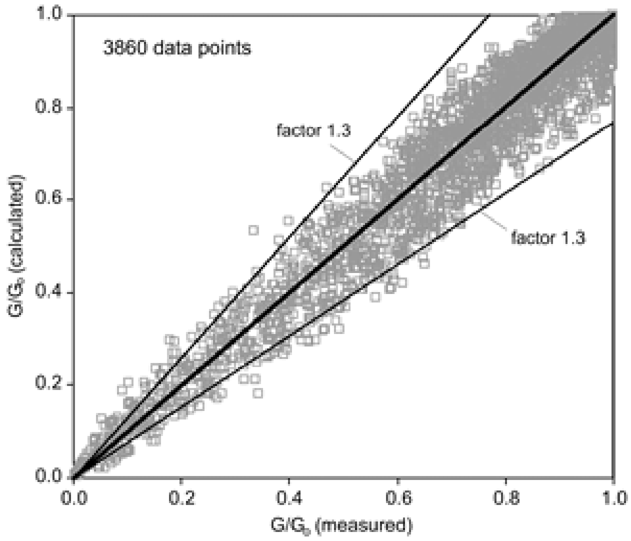
Predicting the response of a dense uniform sand



Predicting the response of a loose widely graded sand

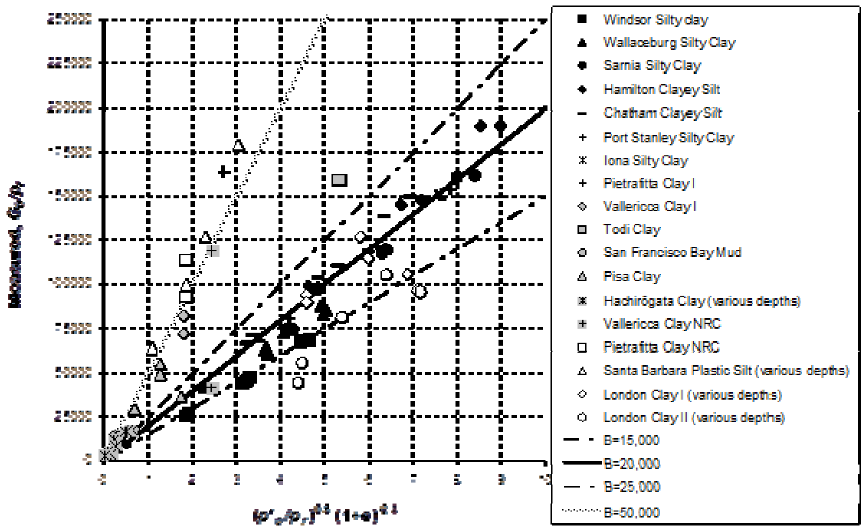


Reliability of predictions of G/G_0 for sand



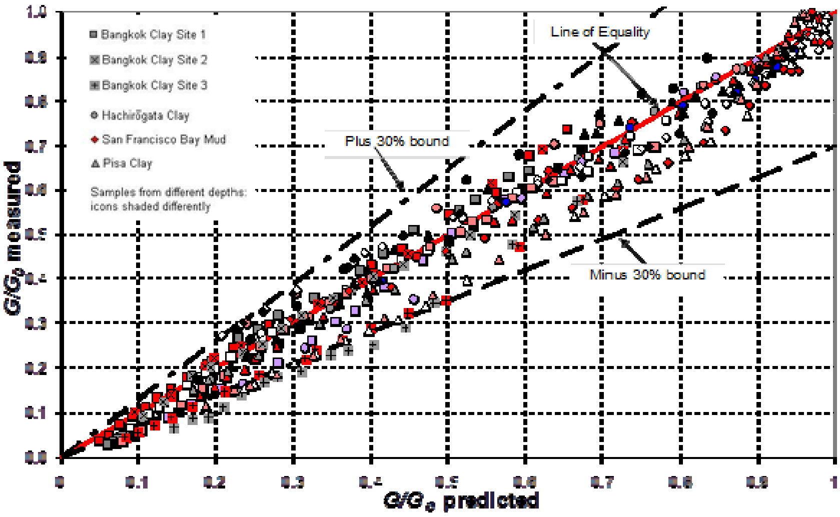
EC7 Today and Tomorrow Malcolm Bolton 15

Importance of measuring G_0 to get B for a clay



EC7 Today and Tomorrow Malcolm Bolton 16

Reliability of G/G_0 predictions for nc clays



EC7 Today and Tomorrow Malcolm Bolton 17

Soil non-linearity: summary

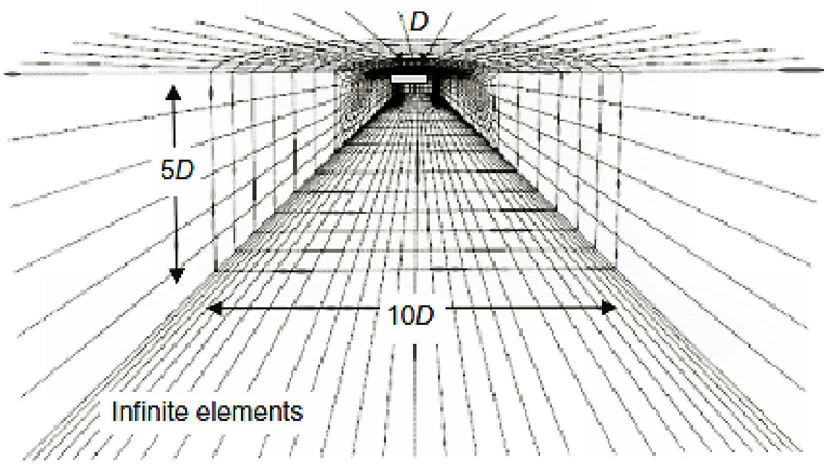
- The major uncertainty in assessing stiffness is the factor B in G_0, which can be assigned after shear wave speed measurements on site, or in the laboratory.
- Databases for sands and clays now exist, and will soon be published, which enable engineers to predict the hyperbolic shape of shear stress-strain curves.
- These databases allow a reliability-based prediction of soil stiffness as a function of stress and strain, using only routine ground investigation data.
- We have a good database for G, but not yet for K or E_0. So site-specific oedometer data will still be required. Further work is needed to distinguish immediate and long-term settlements.

EC7 Today and Tomorrow Malcolm Bolton 18

FE analysis

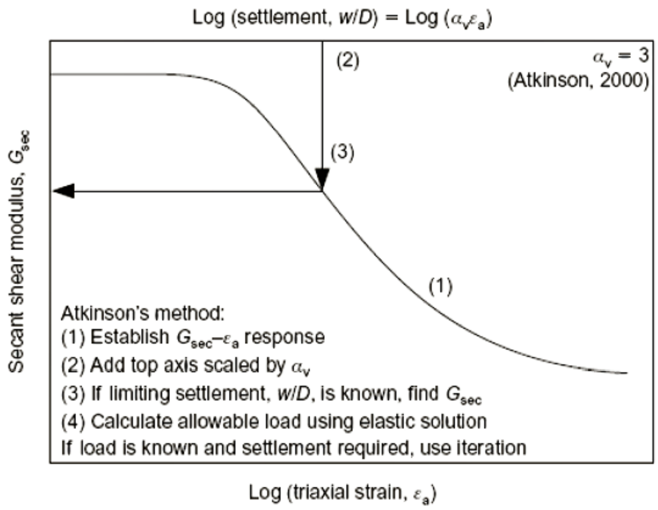
- Current practice is often to estimate an equivalent-linear stiffness, estimate a Poisson's ratio, and put these into an elastic Mohr-Coulomb framework in programs such as Plaxis or FLAC.
- This can be improved by using hyperbolic elastic stiffness for foundations at small to moderate strains, and by using Cam Clay models when working beyond plastic yielding for earthworks on soft clay.
- Project-specific FEA is the topic of the next speaker.
- But I will show that non-linear FEA can be used to validate simplified calculation procedures that may be more appropriate for design and decision-making.

Non-linear FEA to compare Atkinson's and Bolton's methods



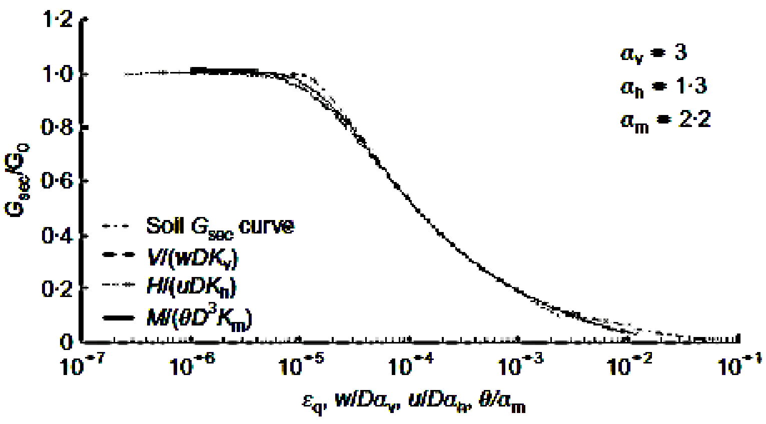
Osman, White, Britto & Bolton (2007) Simple prediction of the undrained displacement of a circular surface foundation on non-linear soil, Geotechnique 57 (9): 729-737.

Atkinson's equivalent-constant stiffness: vertical response



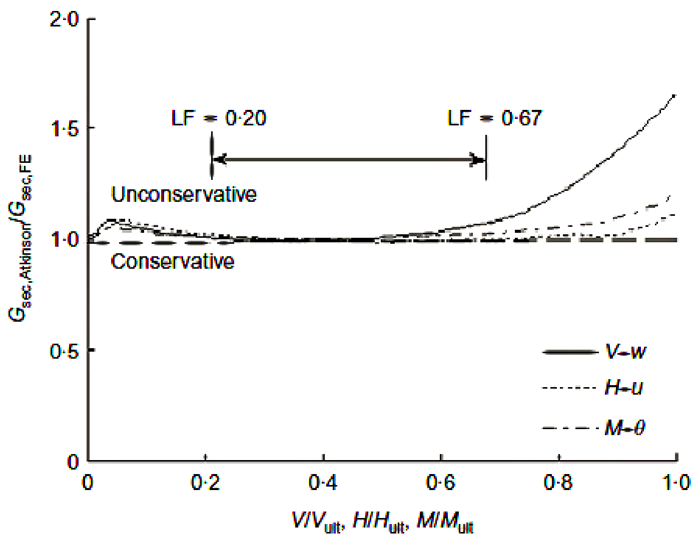
Atkinson J.H. (2000) Non-linear soil stiffness in routine design, Geotechnique 50 (5): 487 –508

α-scaling for a footing under V or H or M loading



Osman et al (2007) show that different α-values are required for each different loading case

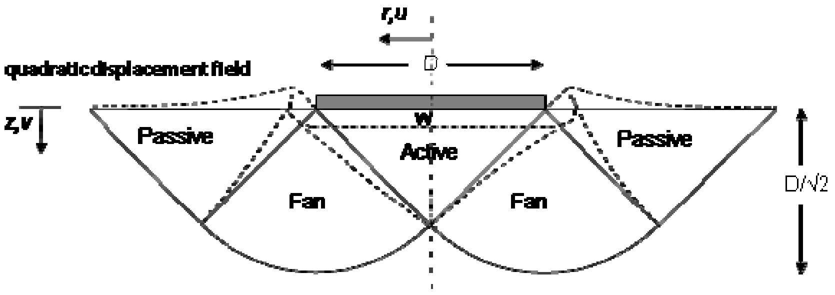
Accuracy of equivalent-constant stiffness approach



Osman & Bolton's equivalent-constant strength

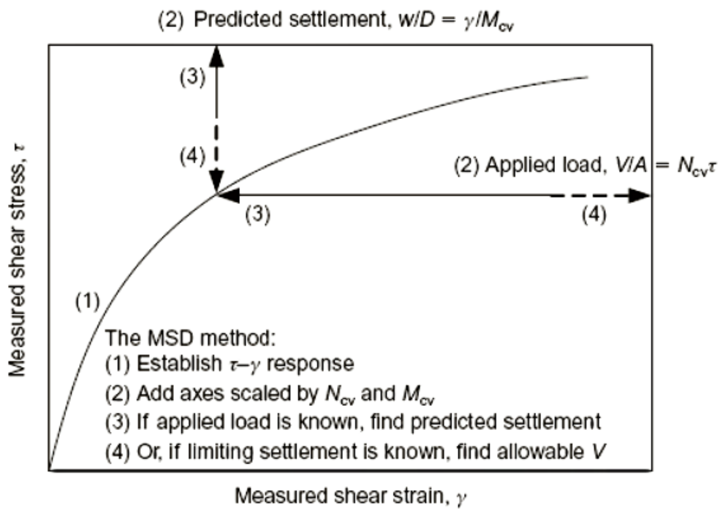
- Mobilizable Strength Design (MSD) has been applied to a wide variety of displacement calculations: for retaining walls, braced excavations, tunnel construction, shallow foundations, and piles.
- In each case, the raw stress-strain data, or an equivalent predicted hyperbolic curve, is used directly by relating shear strain to a normalized structural displacement and by relating shear stress in the soil to a boundary stress.
- The rigid circular foundation was first solved in Osman A.S. & Bolton M.D. (2005) Plasticity based method for predicting undrained settlement of shallow foundations on clay, Geotechnique 55 (6): 435–447.

Deformation mechanism in Osman & Bolton (2005)



NB: no slip discontinuities, finite strains in Prandtl zone, zero elsewhere – matches "correct" bearing capacity within 3%

Mobilizable Strength Design (MSD)



Settlement of a shallow foundation of diameter D

- Vertical net bearing stress q requires the mobilization of an average shear stress within the mechanism:

  $\tau_{mob} = q / N_c = q / 5.9$
- Average shear strain within deformation mechanism:

  $\gamma_{mob} = M_c \, w/D = 1.35 \, w/D$
- Representative depth for shear stress-strain behaviour:

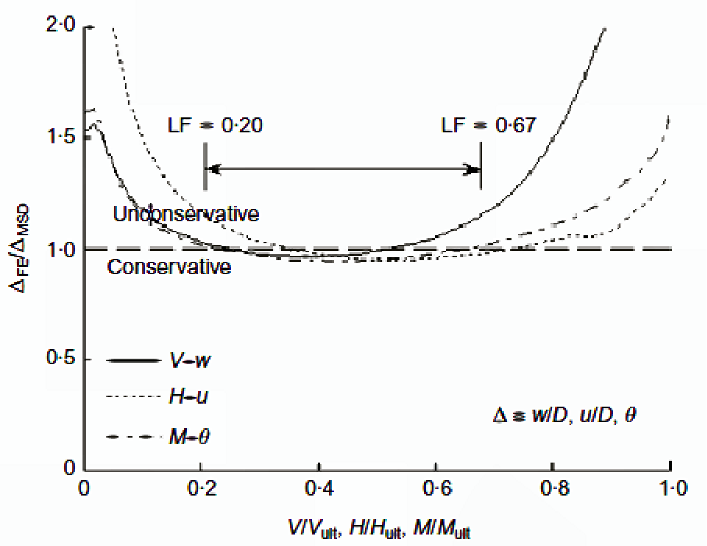
  $z_{rep} = 0.3D$
- If the representative soil test data fits:

  $\tau_{mob} = f(\gamma_{mob})$

  then the foundation load test data is taken to fit:

  $(q/5.9) = f(1.35 \, w/D)$

Accuracy of Bolton's equivalent-constant strength



Making use of non-linear soil data

- The new databases of non-linear soil behaviour allow the engineer to predict stress-strain curves based on routine ground investigation data. The measurement of any one stiffness-related quantity, such as G_0, reduces error.
- Either Atkinson-style equivalent-constant stiffness, or Bolton-style equivalent-constant strength can give reasonable estimates of the immediate displacement of a circular foundation under simple loading conditions.
- Non-linear FEA can always be used to harvest simplified solutions of this sort, leaving the designer with formulae that are as simple to apply as a bearing capacity equation, but which enable control of displacements.

Is the EC framework appropriate?

- Reliability-based assessments of soil non-linear stiffness, and predictions of ground movements in a wide variety of applications, will soon be widely available.
- This predictive power will be matched by a wider use of sensor technology to monitor movements during the construction and service life of infrastructure of all types.
- The current placing of a partial factor of unity on all elements of an SLS prediction now appears irrational.
- The EC7 focus on ULS, with arbitrary partial factors on soil strength and applied loads, and the conflation of SLS issues within ULS safety factors, now looks out-dated.
- Much more soil-structure interaction needs to be encouraged amongst EC committees!

What is the way forward for EC7?

- Eurocodes must make proper reference to publications and databases, and should be written so that engineers can take advantage of new information.
- An updated and improved EC7 should leave the existing partial factor approach untouched, so that National Appendices can continue to refer to it as they attempt to reconstruct local safety factors equivalent to their own national practice in the last half of the twentieth century.
- In stead, new material be should written to facilitate an objective approach to design, focusing initially on the prediction and control of ground movements and structural strains, and the assurance of serviceability.

The possible gains

- Beginning with a proper serviceability check promises a single design calculation that could satisfy both SLS and ULS criteria in one step, in many applications. This will simplify the design process.
- Accidental loads that will be permitted to damage a structure could be added in an extra ULS check.
- The aspiration of an objective assessment of reliability can be delivered through databases of soil deformability and the monitoring of construction displacements. EC7 could develop this as a template for all other Eurocodes.
- Since many existing partial factors are really factors of ignorance, their objectification should reduce material costs as well as offering reliability, thereby cutting waste.

My own aspiration is deliver on some of this agenda in the 52nd Rankine Lecture to be delivered precisely one year hence on Wednesday 21st March, with the provisional title “Performance-based design in geotechnical engineering”. Please come to that also!

Thank you.