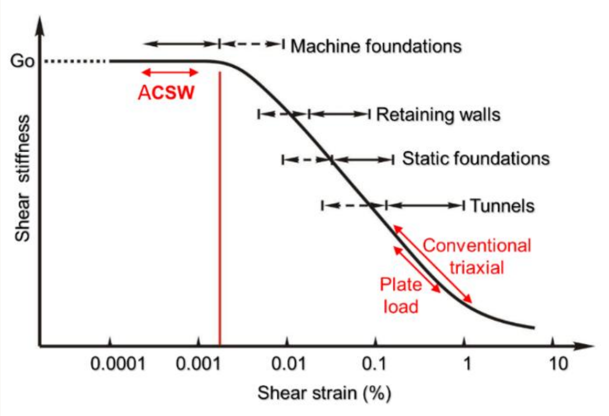
USING ACSW FOR SETTLEMENT ANALYSIS

Guidance Note SSGN005

The Problem of Stiffness Measurement for Settlement Analysis

Obtaining accurate, representative, ground stiffness values is essential for optimising design where the Serviceability Limit State (SLS) is critical. This is made particularly difficult because of the non-linear relationship between soil strain and stiffness, the impact of disturbance of soils on measured stiffness values and often unrepresentative nature of small soil samples to bulk stiffness.



For accurate prediction of ground movements, stiffness measurements should therefore be representative of the bulk in-situ ground stiffness at a known strain.

ACSW Stiffness Measurement

Traditional methods of determining ground stiffness are either cheap but inaccurate (for example empirical relationships such as with SPT N value) or accurate but expensive (for example large scale load tests or pressuremeter testing). In contrast, ACSW testing provides accurate stiffness profiles at reference small strain levels, non-intrusively, down to typical 10 to 15m depth for about the cost of a plate load test. Since 12 to 20 tests can normally be completed in an 8-hour shift, ACSW testing can be carried out rapidly and cost effectively to allow accurate whole site characterisation.

ACSW testing accurately measures a surface Rayleigh wave velocity (V_r) profile. Simple well-understood relationships are then used to convert V_r to stiffness moduli as follows:

- V_r is converted to V_s through a simple relationship with Poisson's ratio (max. 7% variation for normal range of Poisson's ratio values)
- V_s is directly related to the small-strain Shear Modulus (G_0) by the function $G = \rho . v_s^2$ (where ρ is soil density)
- G_0 can be converted to small-strain Young's Modulus (E_0) using the relationship $E=G.(2.(1+\nu))$ where ν is Poisson's ration
- The value of Poisson's Ratio will determine whether the value of E derived from G is undrained (v=0.5) or drained (ν =0.2 to 0.3).

Since stiffness is measured by ACSW at small strain levels where stiffness is constant, strain-softening functions can be applied to E_0 to give a design E value at the appropriate strain. ACSW test data is provided in an Excel format which allows the user to adjust any assumed parameters, including design strain.

Settlement Calculations

The basis for a range of increasing complex settlement analyses are set out below. However, it should be noted that the benefits of using more complex approaches have been shown to be small compared to the use of accurate and representative in-situ soil stiffness values which ACSW provides (ref. Heymann *et al*, 2017).

Routine Analysis

For simple, routine analysis suitably strain-softened ACSW stiffness data can be used directly in hand calculations adjusting for stress distribution and soil strata. Alternatively strain softened stiffness moduli can be input into conventional linear elastic software such as Oasys Pdisp. Adopting an undrained modulus will provide immediate settlements, using the drained modulus will provide total settlements.

The basis of this approach is set out in Eurocode 7 (BS EN 1997-1:2004) Part 1 Annex F.2:

> ***The total settlement of a foundation on cohesive or non-cohesive soil [s] may be evaluated using elasticity theory and an equation of the form:***
>
> $s = p \times B \times f/E_m$
>
> ***where:***
>
> ***E_m is the design value of the modulus of elasticity***
>
> ***f is the settlement coefficient***
>
> ***p is the bearing pressure, linearly distributed on the base of the foundation (foundation width B)***

A 0.1% strain is a typical moderately conservative value for foundations and ACSW data is set to this default value using the Rollins Equation (Rollins *et al* 1998):

$$\frac{G}{G_0} = \frac{1}{[1 + 16\gamma(1.2 + 10^{-20\gamma})]}$$

Where γ is shear strain

The Excel ACSW output allows the user to specify alternative strain levels, or to use other strain softening functions if these are considered more appropriate for specific design conditions.

Refined Analysis

An improved level of accuracy can be provided through the use of a step wise analysis approach. This methodology allows the non-linear stiffness behaviour of soils to be simply modelled and improves accuracy where operational strain levels are uncertain or where only light loadings are being applied and strain levels are low. In this approach the loading is incrementally applied to the soil with the strain at each stage then used to adjust stiffness values for the next load increment.

Advanced analysis

Where the settlement problem is complex, or the highest level of accuracy is required, then Finite element methods may be appropriate. Certain FE software provide small strain models with inbuilt softening functions (i.e. PLAXIS) which permit the direct input of small strain G_0 stiffness values. In this case the soil stiffnesses across the FE mesh are determined based on individual element strains permitting the accurate modelling ground stiffness around rigid structure boundaries.

Other parameters

Whilst ACSW testing data can be used for accurate assessment of immediate, consolidation and total settlements other information may be required for settlement analysis, for which additional investigation data may be required.

There is no reliable method for estimation of creep, which is highly dependent on individual soil types. For organic soils in particular creep movements may be significant. Appropriate adjustments such as a factor on total settlements are required to allow for long term creep.

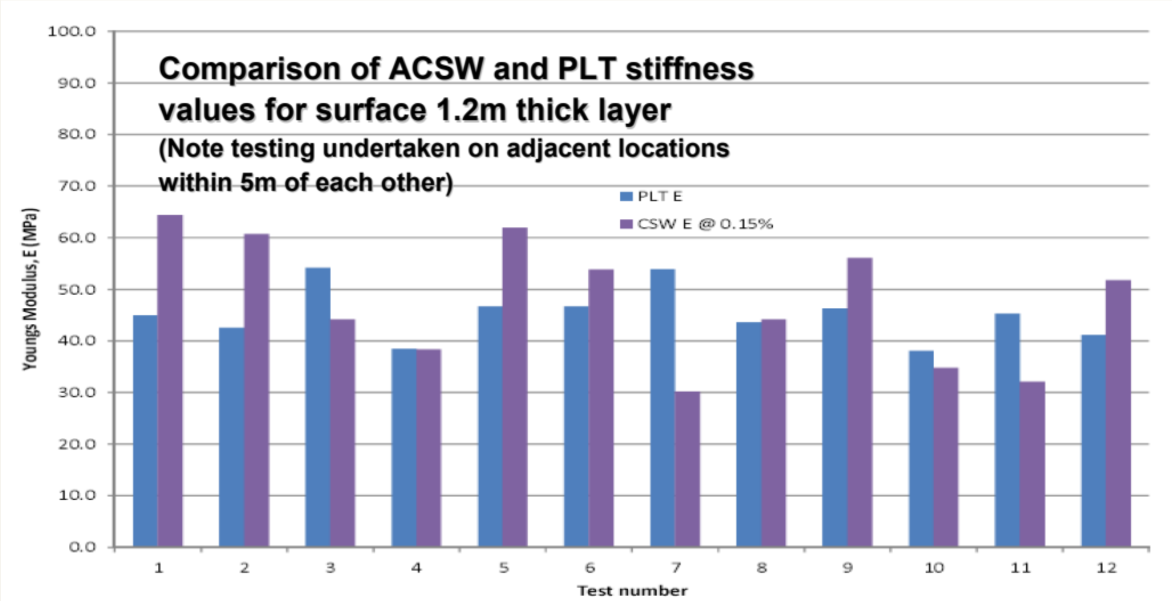
The rate of settlements is dependent on drainage. Consequently, whilst the rate of settlement may be near immediate for most granular deposits, for cohesive material it may be a significant design consideration.

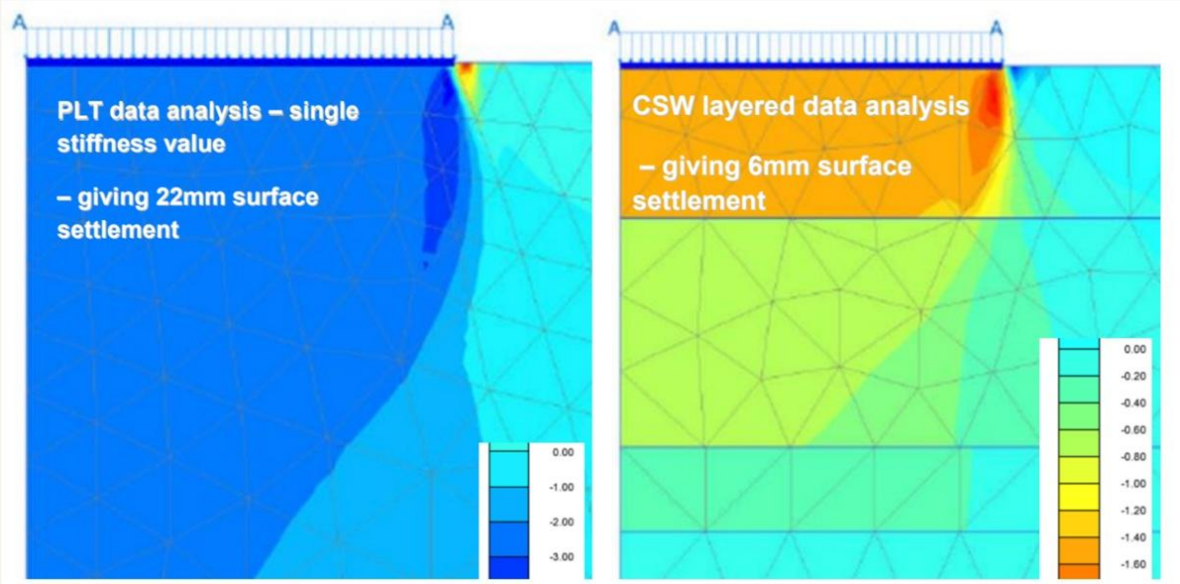
Certain geomaterials can also exhibit collapse settlement behaviour for which special consideration is required.

Case Studies

1. <u>High Bay Development, Yorkshire</u>

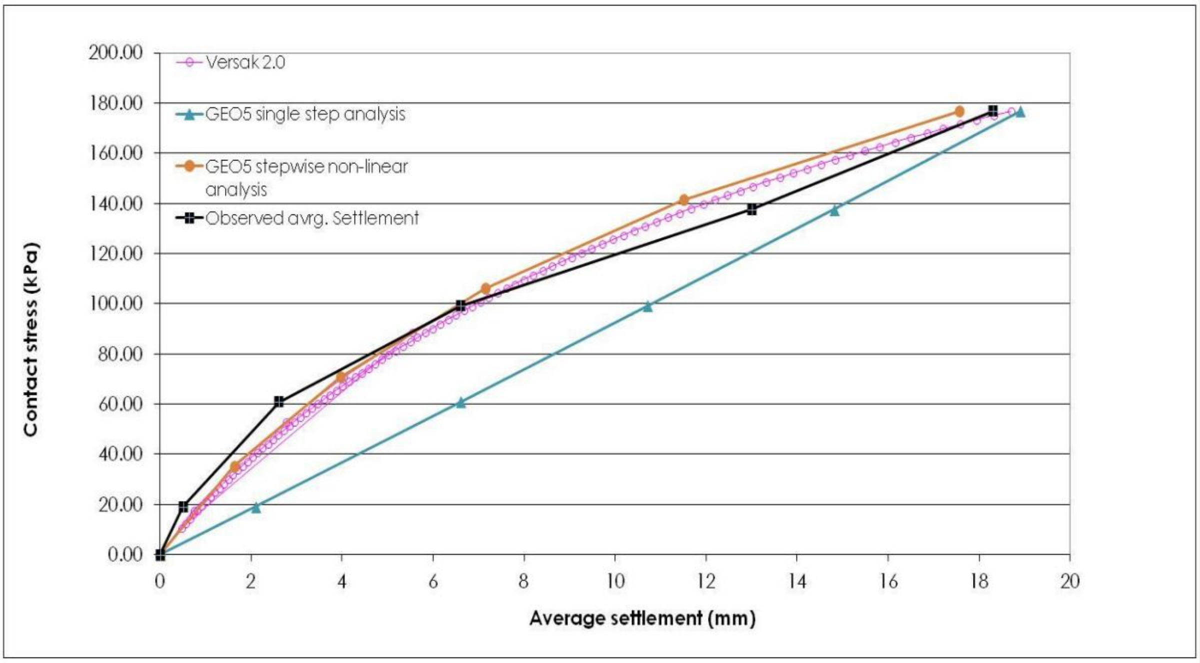
CSW testing was undertaken at the locations of twelve Plate Load Tests (PLT's) being undertaken to inform the design of settlement sensitive high bay warehouse foundations. Comparison of ACSW test results for the surface 1.2m of soil with the results of PLT's showed good agreement (see figure below). However, the results of PLAXIS analysis using the PLT data (giving stiffness down to approximately 1.2m) compared with the layered ACSW stiffness profile extending to depths of 10m gave significant reductions in displacement for this settlement sensitive structure (see figure below).





2. A5 Pont Melin Rûg

ACSW testing conducted at the site of a large-scale load test used for the design of a recently constructed road bridge demonstrated that highly accurate settlement predications can be made using ACSW data without the need for intrusive testing (ref. Heymann *et al,* 2017). Whilst iterative step-wise analysis closely models the staged load settlement curve (*see figure below*), even the simple strain softened linear elastic calculation provides a very good prediction of final total settlement.



References

- **BS EN 1997-1:2004 Eurocode &: Geotechnical Design – Part 1 General rules**
- **Heymann, G. (2007) Ground stiffness measurement by the continuous surface wave test. *Journal of the South African Institution of Civil Engineering*. Vol.49, No.1, p25-31.**
- **Heymann, G, Rigby-Jones J and C. A. Milne C. A. (2017) The application of Continuous Surface Wave testing for settlement analysis with reference to a full-scale load test for a bridge at Pont Melin Rûg, Wales *Journal of the South African Institution of Civil Engineering***
- **Rollins, K M, Evans, M D, Diehl, N B and Daily, W D III (1998) Shear modulus and damping relationships for gravels. ASCE, *Journal of Geotechnical and Geoenvironmental Engineering*, 124(5):396–405.**