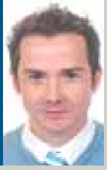
Some practical applications of CSW testing in South Africa



Fernando Pequenino
Geotechnical Manager
SMEC South Africa Geotechnical
fernando.pequenino@smec.com

Frans van der Merwe
Geotechnical Engineer
SMEC South Africa Geotechnical
frans.vandermerwe@smec.com

INTRODUCTION

This article discusses the increased use and applicability of the Continuous Surface Wave (CSW) test by using three recently completed projects as examples – a major bridge over the Jukskei River in Gauteng, extensions to the engineering building at Stellenbosch University, and the rehabilitation of a dolomite subsidence on the R21 freeway. These examples prove the value of the test in supplementing information on ground conditions gathered from other investigative methods, in deriving design parameters where no other test method is possible, and as a tool used for quality assurance purposes on a major construction project. In one of the examples significant cost savings of over R2 million were achieved through well-executed geotechnical investigations where particular reliance was placed on the CSW test.

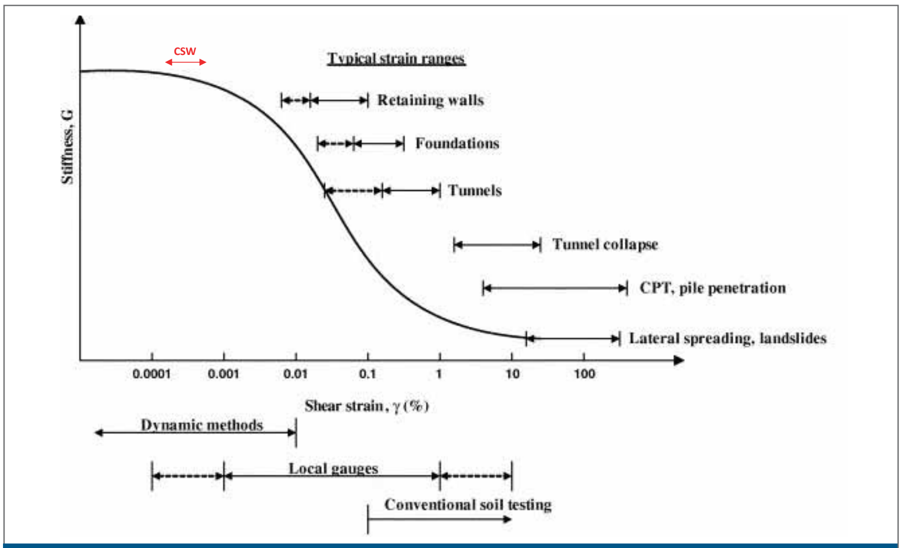


Figure 1: Strain dependency on stiffness (as adopted from Mair 1993; Rigby-Jones 2011; Basset *et al* 2005)

Jukskei Bridge at Steyn City, Gauteng

Client Steyn City Developments/Bigen Africa
Consultants Bigen Africa (main consultants), Vela VKE/SMEC SA (bridge and geotechnical engineers)
Contractor Stefanutti Stocks
Project value (bridge) R55 million

OVERVIEW

Globally, over the past 30 years or so, the role of geophysical methods in characterising sites and materials has been increasing steadily (Stokoe *et al* 2004). Two of these techniques used locally are geophysical methods for dolomite investigations, and the CSW test. This article focuses on the latter which has found applicability in a range of typical geotechnical problems.

CSW is a geophysical exploration technique which is used to evaluate the subsurface stiffness by means of a mechanical vibrator and receivers (or geophones) which are placed in linear array. The test involves measuring Rayleigh Wave velocities as they propagate through the soil mass. The velocities measured by the geophones are then converted, by an experienced analyst, to a corresponding stiffness profile with depth at the position of the test. Depending on the size of the shaker used and the specific ground profile, the CSW is generally limited to measuring the very near surface profile (typically to depths of 6–12 m). For a detailed discussion on the stress waves and CSW the reader is referred to work done by Stokoe (2004) and Heymann (2007).

Soil stiffness depends on complex interactions of state (i.e. bonding, fabric, etc), strain level, stress history, and type of loading. A key concept in understanding soil and structure interaction is that the stiffness/strain relationship is very strongly non-linear, and that different structures are designed to accommodate different strains. The results of the CSW tests are given as G_0 (shear stiffness at small strain) with depth, which is much higher than the stiffness used for, say, the design of foundations for a large bridge (see Figure 1). The shear stiffness can also be related back to an equivalent Young's Modulus through Poisson's Ratio.

Once the problem has essentially been framed (probably by use of other investigative techniques or previous experience), the CSW can be used to target specific questions related to the ground conditions, or to supplement other methods to provide greater confidence in the interpretation of the ground conditions. Three practical examples are provided below, each highlighting a particularly useful trait of the test.

JUKSKEI BRIDGE AT STEYN CITY, GAUTENG

This is a five-span bridge with equal spans of 30 m and central pier heights of up to 15 m. Early in the development of the project the reliability of the previous geotechnical investigation was questioned. SMEC SA's geotechnical team were therefore appointed to re-do the investigation.

The bridge is situated on the Halfway House Granites, which are notoriously variable. Given this variability and the questionable quality of the previous investigations (a quality which the client appears to have become accustomed to), the client was hesitant to invest in additional geotechnical investigations and design. The previous investigations, based on very crude percussion-drilled boreholes, essentially indicated that all piers and abutments would need to be founded on piles of 10–15 m. Percussion drilling involves air-drilling boreholes, which achieves limited sample recovery, and is probably the least suitable investigative technique to be used on a granite profile.

The subsequent investigations, which included core-drilling and CSW, indicated that only one of the abutments and the two central piers immediately adjacent to the river would require piles; with the recommendation of piles for the central piers based on concerns about scour and constructability rather than the consistency of the soils.

In this instance the CSW was used to derive a stiffness profile of the granite at some of the piers where the granite gradually graded with depth to competent rock. The original assumption of founding only once solid bedrock was encountered had ignored the favourable weathered granitic dense sands and even soft rock overlying the solid bedrock at depth. The profile developed for one of the piers from the CSW is indicated in the graph in Figure 2, together with the soil profile from a corresponding borehole. The figure clearly shows the improvement with depth.

Pier foundations were designed for bearing pressures of 400 kPa and 10 mm of settlement. Settlements measured during construction were within the expected range for the loads applied at that stage. Retrospectively, the decision to found only some of the piers on piles was justified in that a R2 million saving was achieved at the nominal cost of around R450 000 for the drilling and CSW tests.

ENGINEERING BUILDING EXTENSIONS, UNIVERSITY OF STELLENBOSCH

The second example deals with extensions to the existing engineering building at the University of Stellenbosch. A number of additions, including a library, a laboratory and workshops, were constructed adjacent to the existing engineering building.

The significant feature of the geology of the area is the presence of the wide paleofluvial plain of the Eerste River on which Stellenbosch is situated. Locally the university sits on a plain of coarse boulder clay alluvium over 3 m thick, which was essentially formed after large sandstone blocks had slid gradually from the adjacent mountains into the valley floor, due to deep weathering of the underlying phyllite, and were transported through fluvial processes (Söhnge & Greeff 1985). What must be highlighted from an engineering point of view, is that the combination of deep weathering of the phyllite and the formation and weathering of the boulder alluvium results in highly variable ground conditions with weathered and poor soils.

The effect of the 2–3 m thick boulder layer is that most buildings in Stellenbosch (generally four storeys, but up to seven storeys) have been founded at shallow depth (2 m or less) on this interlocking boulder layer, albeit using low-bearing pressures (in the order of 300 kPa), and are according to Brink (1985) "remarkably free of cracking". This includes the existing engineering building, which is reported to be founded at 1.8 m depth, on the boulder clay layer with a bearing pressure of 225 kPa.

The problem with the above profile is that there is no means of testing the layer to derive a modulus of compressibility for the boulder clay layer; the existing buildings possibly being constructed on a trial-error or experiential basis. A requirement

Soil Legend	Depth (m)	Description
🟦	3.2	**Gravel and cobbles** Sub-rounded to rounded granite, gravel and cobbles (max 80 mm, ave 15 mm), no matrix recovered Transported
🟥	9.3	**Very soft to soft rock granite** Moderately to highly weathered, pale orange, highly jointed (oblique, slightly rough, partly stained black) fine to medium-grained Highly fractured at 5.85–6.03 m, 6.15–6.4 m and 7.75–8.14 m
🟩	15.4	**Hard to very hard rock biotite granite** Fresh to slightly weathered bluish grey, mottled pink, speckled black and white, medium to highly jointed (vertical and oblique, slightly rough to rough, stained black, white and orange, occasionally filled < 1 mm clay) medium to coarse-grained

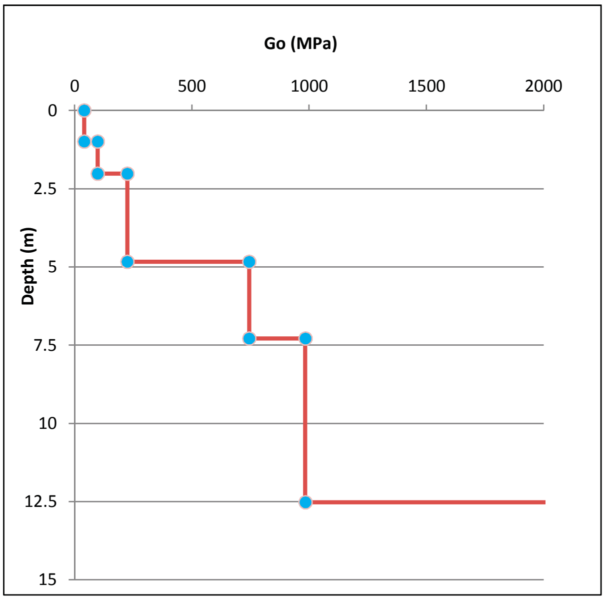
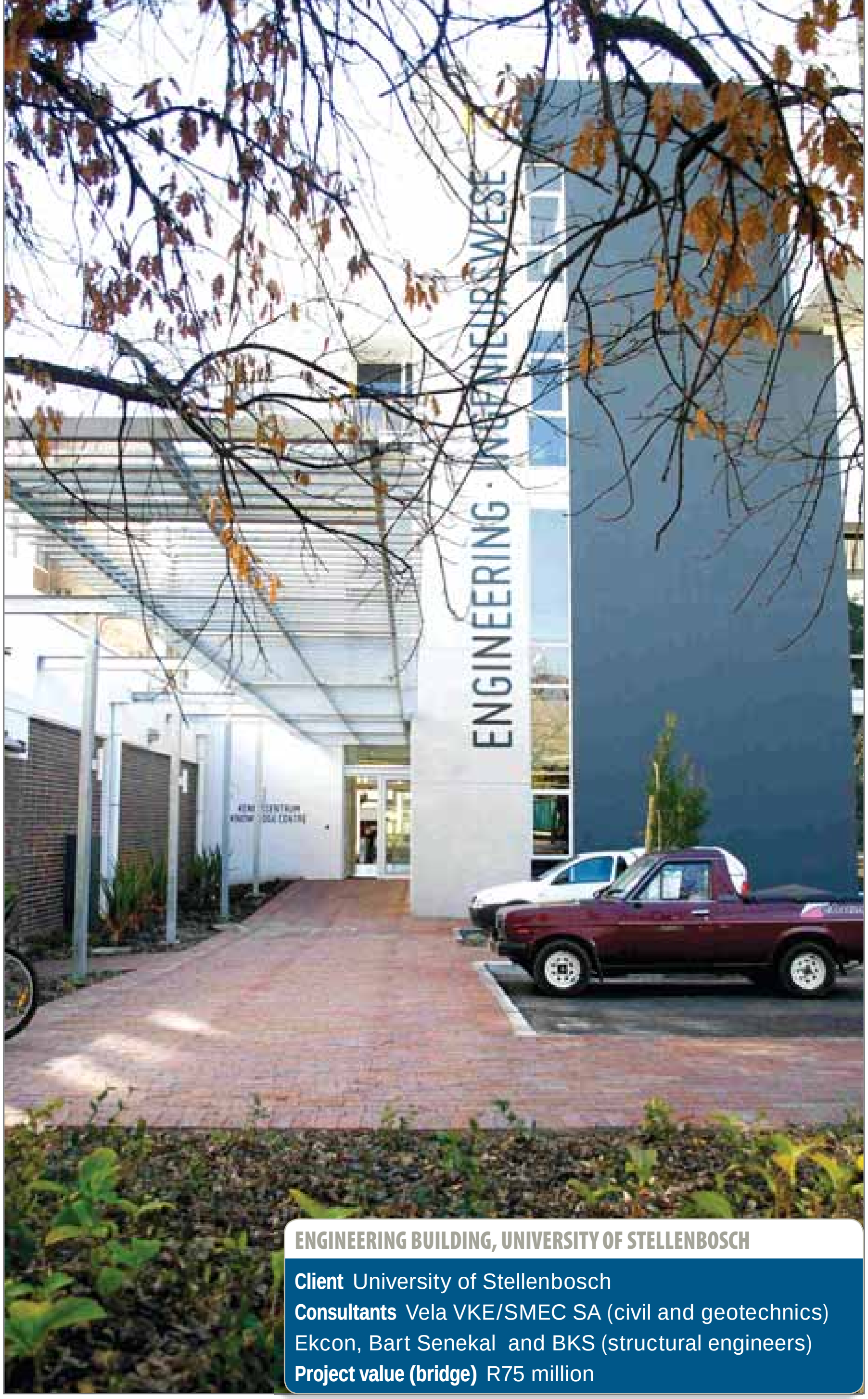


Figure 2: CSW test results at one of the pier positions for the Jukskei Bridge at Steyn City, Gauteng



ENGINEERING BUILDING, UNIVERSITY OF STELLENBOSCH

Client University of Stellenbosch
Consultants Vela VKE/SMEC SA (civil and geotechnics) Ekcon, Bart Senekal and BKS (structural engineers)
Project value (bridge) R75 million

for laboratory testing would be to obtain good quality samples with minimal disturbance, but unfortunately this is not practically possible and any type of penetration test would simply "refuse" on the boulders.

Brink highlights this difficulty by providing a broad range of bearing pressures which have been used previously on the boulder clay, from as little as 175 kPa to upwards of 400 kPa. CSW tests were subsequently undertaken to evaluate the overall stiffness of the boulder layer in a more sophisticated manner. The profile developed for one of the building extensions, based on the CSW test, is indicated in the graph in Figure 3, together with the soil profile from the corresponding test pit. The CSW showed the stiffness for the boulder clay and residual phyllite to be surprisingly consistent, with no significant change in stiffness and a gradual improvement with depth.

Foundations were eventually placed at a nominal depth of 1 m on the boulder clay layer and designed for a bearing pressure of 200 kPa. Although not very different from that used previously for the engineering building, the bearing pressure was at the lowest end of the range provided by Brink. No untoward settlement was recorded during construction or in the year subsequent to construction.

SUBSIDENCE ON R21 FREEWAY, OLIFANTSFONTEIN

In the last example Vela VKE were appointed design engineers for the R2.5 billion 45 km upgrade of the R21 freeway as part of phase 1 of SANRAL's visionary network improvement project – the GFIP

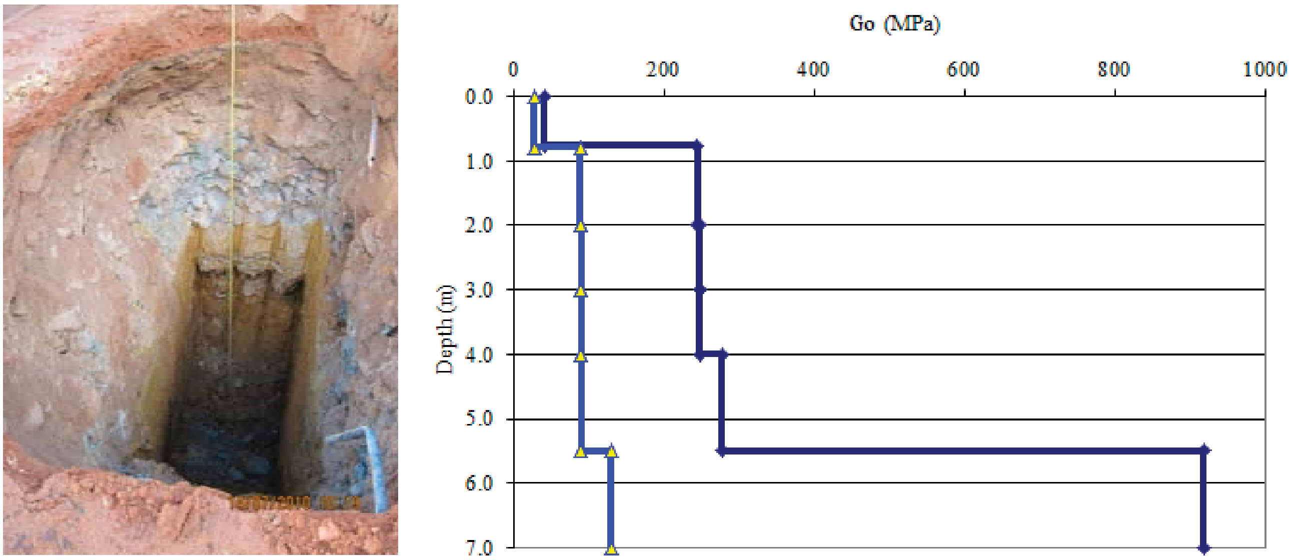


Figure 3: CSW test results and trial pit photograph for extensions to engineering building, University of Stellenbosch

(Gauteng Freeway Improvement Project). Over half of the R21 route is located on dolomitic land, and for a large portion actually follows the contact between the Timeball Hill Shales and Malmani Dolomite along which some of the poorest dolomite can be found. Towards the end of construction a subsidence formed just south of the slip-lane to the off-ramp of the Olifantsfontein Interchange.

Geotechnical investigations of the depression followed, leading to a remedial contract shortly after. The depression was ascribed to a deeply weathered dolomitic profile. With no significant cavities identified, the remedial work was thus aimed at stiffening the ground profile where the subsidence had occurred. This was done by pounding in stone columns by means of dynamic compaction (as shown in the accompanying photograph), placing a geotextile over the compacted area, as well as a 1 m thick granular engineered soil mattress (in this instance a Colto G6 material) on top of the geotextile. There after the pavement layer works were reinstated.

SUBSIDENCE ON R21 FREEWAY, OLIFANTSFONTEIN (dynamic compaction of stone columns)

Client SANRAL
Consultants Vela VKE/SMEC SA
Contractor Raubex (and Franki as specialist sub-contractor)
Project value (remedial works contract) R15 million

In this case the CSW was used to evaluate the effectiveness of the dynamic compaction and of the G6 raft. For the dynamic compaction, and particularly the stone columns, the CSW is probably on the limit of its practicality. But for the

G6 layer clear correlations could be drawn between the CSW and the CBR and plate load tests which were conducted.

One would typically expect a G6 material with a CBR of 25–45% to have a small strain stiffness in the range of G_0 = 110–210 MPa. The differences in small strain stiffness, as identified through CSW testing, were in the range of G_0 = 180–260 MPa. The plate load test, although a crude test, can provide a good estimate of the soil stiffness; the plate-load-test-derived Young's modulus was in the range of E = 97–25 MPa, corresponding to a G_0 = 125–290 MPa. The various degrees of soil stiffness thus derived from the plate load tests correspond closely to those determined from the CSW test and what is expected for a G6 material.

CONCLUSIONS

The geotechnical engineer's role on a project (to characterise the near surface soils and derive engineering parameters in order to design the structures which are to be founded on them) is greatly enhanced by having a varied toolbox of investigative techniques and test methods. Ultimately no single method is globally applicable to all ground profiles and projects. Nor can reliance be placed on the outcome of one single method of investigation, even on a small project.

The CSW, however, considerably enhances the geotechnical engineer's armoury. It provides the stiffness profile for near surface soils; in one of our examples it in fact provided the overall stiffness of a difficult alluvial profile. It is non-intrusive, which makes it cost-effective and, in the case of a construction project, would not disrupt the works.

There are a number of limitations to the use of such geophysical methods, and certainly on its own its applicability is limited. For example, the presence of near surface buried structures or extremely stiff layers can affect the interpretation of the results, and even reduce the depth of penetration of the test. It can also not be extended to interpreting soil behaviour such as heave or collapse.

However, the above examples show how CSW tests have been successfully utilised in geotechnical investigation, design, and construction assurance. Beyond that, this method has proved useful in saving clients' money when used appropriately by experienced geotechnical engineers. Given the multitude of factors controlling the interpretation of ground conditions, and the fact that many of the soils encountered across the country are difficult to sample and/or test in a laboratory, the CSW test will increasingly play an important role in geotechnical engineering as it becomes better known.

ACKNOWLEDGEMENTS AND REFERENCES

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NOTE

The list of references, as well as a list of the works cited, is available from the authors. ☐

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