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A NOVEL TECHNIQUE FOR DEEP SEISMIC CONE TESTS IN CHALLENGING GROUND CONDITIONS

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Abstract: The measurement of in situ s-wave and p-wave velocities using intrusive techniques can be very costly, especially in stiff ground conditions. As part of a ground investigation to provide information for the Bradwell B nuclear power station probabilistic seismic hazard analysis and capable faulting study, a novel approach has been developed which extends the depth of coverage of the seismic cone test to well beyond what would be feasible with conventional operation. The approach, developed through close collaboration between the client, contractor and consultant, follows a similar principle to the modified seismic dilatometer (SDMT) technique developed by Marchetti et al. (2008), and enabled the acquisition of wave velocities from close to ground level to depths in excess of 50 m, with potential for even greater depths. Comparisons between data obtained using the modified technique and data obtained using other intrusive techniques such as the unmodified SCPT and P & S suspension logging were very favourable. The modified approach worked well in stiff overconsolidated clays, even in the presence of claystone (nodular concretion) layers which were impenetrable using the standard SCPT method. In principle, the method could be extended to other challenging ground conditions such as dense sands and gravels.

Introduction

Measurements of in situ shear-wave and p-wave velocities are extremely important for characterising sites for the purposes of seismic hazard studies or seismic design. Obtaining reliable measurements to sufficient depth can be expensive, especially for borehole-based techniques such as surface-to-downhole and crosshole, which have the prerequisite of one or more carefully drilled holes, including grouted-in plastic liners and a borehole deviation survey. Crosshole testing generally requires an array of three in-line holes, precision-drilled to minimise any deviation from the vertical which can otherwise reduce the reliability of the seismic velocity measurements. Penetration techniques such as the seismic cone penetration test (SCPT) or seismic dilatometer (SDMT) offer many of the benefits of the surface-to-downhole borehole technique but can offer cost and time savings as there is no need to install a lined hole or carry out a borehole deviation survey. However, these penetration test methods can suffer from significant limitations in challenging ground conditions such as boulder clays, overconsolidated clays or gravels, where the probe can refuse at shallow depth on hard layers or due to a combination of end resistance and friction.

The current paper presents a recent example of how the SCPT technique has been adapted to allow deeper seismic velocity measurements than would normally be possible at a site characterised by stiff overconsolidated clays with claystones (nodular concretions).

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Project background

China General Nuclear Power Group (CGN) and EdF Energy are developing plans for a new generation nuclear power station at the Bradwell B (BRB) site in Essex, UK, adjacent to the now decommissioned Bradwell A station (https://bradwellb.co.uk/). They have established a joint venture company, Bradwell Power Generation Company Ltd (BRB GenCo) to develop the new station and have embarked on an extensive programme of ground investigation works to support a capable faulting study (CFS) and probabilistic seismic hazard assessment (PSHA) in order to meet UK regulatory requirements (ONR, 2018) and to provide long term support to the safety case. The CFS and PSHA are being undertaken by Jacobs whilst the main contractor for the ground investigations (GI) is Structural Soils Ltd (SSL).

Based on data from historic ground investigations, it was known that the proposed BRB site was characterised by superficial Quaternary deposits of variable type and thickness, areas to the north having up to 10 m thickness of typically soft cohesive intertidal deposits whilst areas to the south having around 5 m thickness of typically sandy or gravelly river terrace deposits. Beneath the Quaternary deposits in the main part of the site are approximately 85 metres of Palaeogene strata, comprising the London Clay Formation, Harwich Formation, Lambeth Group and Thanet Formation, all unconformably overlying the Cretaceous White Chalk. A typical north-south cross-section through the main part of the site, using data from both the historical ground investigations as well as the recent BRB GI, is shown in Figure 1. Excluding the Quaternary strata, the boundaries between the units are typically sub-horizontal.

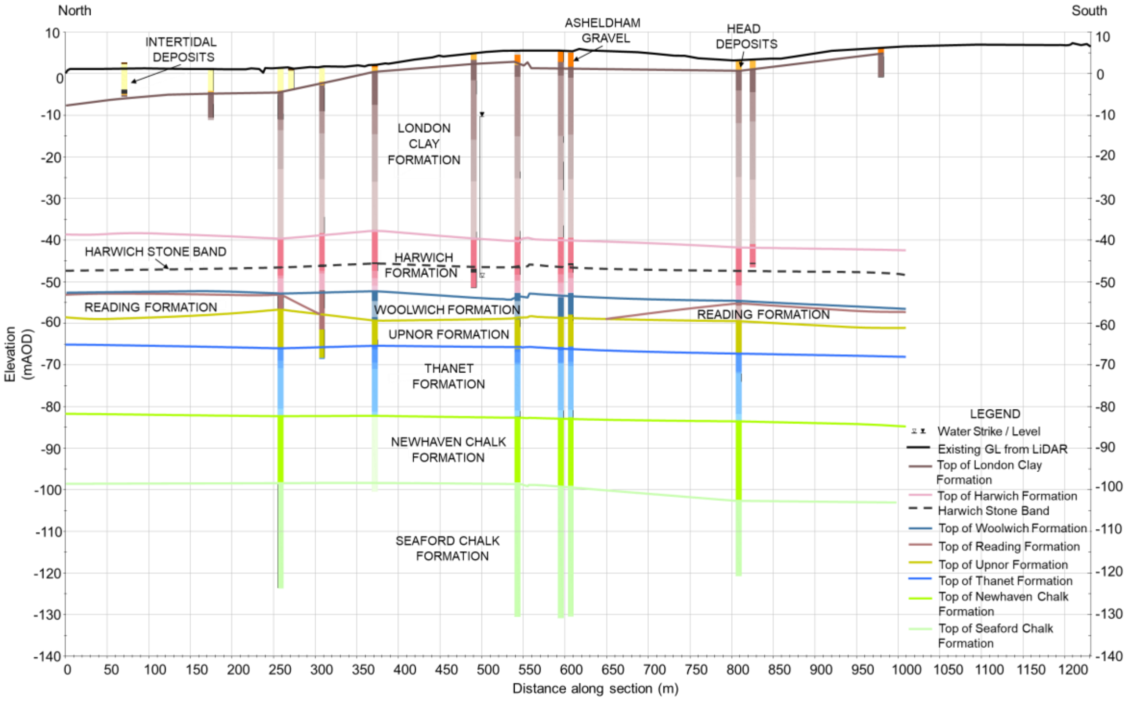


Figure 1. Typical north-south geological section through main BRB project site. Refer to Figure 2 for position of section line.

The historic data helped to inform the scoping of various phases of GI for the BRB project. A range of complementary field and laboratory techniques were selected in order to provide the necessary data for the CFS and PSHA. Good use was made of recent best-practice guidance on selection of techniques emanating from the InterPACIFIC (Intercomparison of methods for site parameter and velocity profile characterization) project, of which EdF France was one of the main sponsors (Garofalo et al. 2016a & 2016b, Foti et al. 2017). In particular, a combination of both intrusive and non-intrusive techniques was employed in order to characterise the shear-wave velocities of the different geological formations from ground surface down to more than 350 m depth across the site. The use of intrusive techniques extended to around 130 m depth to penetrate a minimum of 30 m into the Chalk.

Two clusters of three plastic-lined boreholes were installed down to approximately 130 m for crosshole and surface-to-downhole testing in the central part of the site, thus providing a good reference point for other test types. To achieve good spatial coverage of the shallow layers, including the London Clay Formation, which is likely to be the founding stratum, a combination of P & S suspension logging (OYO) and seismic cone testing (SCPT) was employed. For every hole used for P & S logging, an SCPT was undertaken adjacent. These two techniques are complementary in these ground conditions as the P & S suspension logging provides velocity profiles from around 15 m to 130 m depth within an unlined borehole whilst the SCPT provides data for the shallower part of the profile, with some overlap between the two techniques for calibration purposes. The P & S logging is unable to provide results in the shallowest strata owing to the need for steel borehole casing to stabilise the hole within the Quaternary strata and weathered part of the London Clay. P & S logging generally needs to be conducted in an unlined hole. A total of 10 P&S logging – SCPT pairs (purple and blue circles in Figure 2) were undertaken across the site, plus an additional 18 lone SCPTs (yellow circles in Figure 2). The overall spatial coverage of intrusive testing for seismic velocities is summarised in Figure 2. It is noted that P&S logging and SCPTs were also undertaken at the reference crosshole clusters, to allow comparison amongst different techniques.

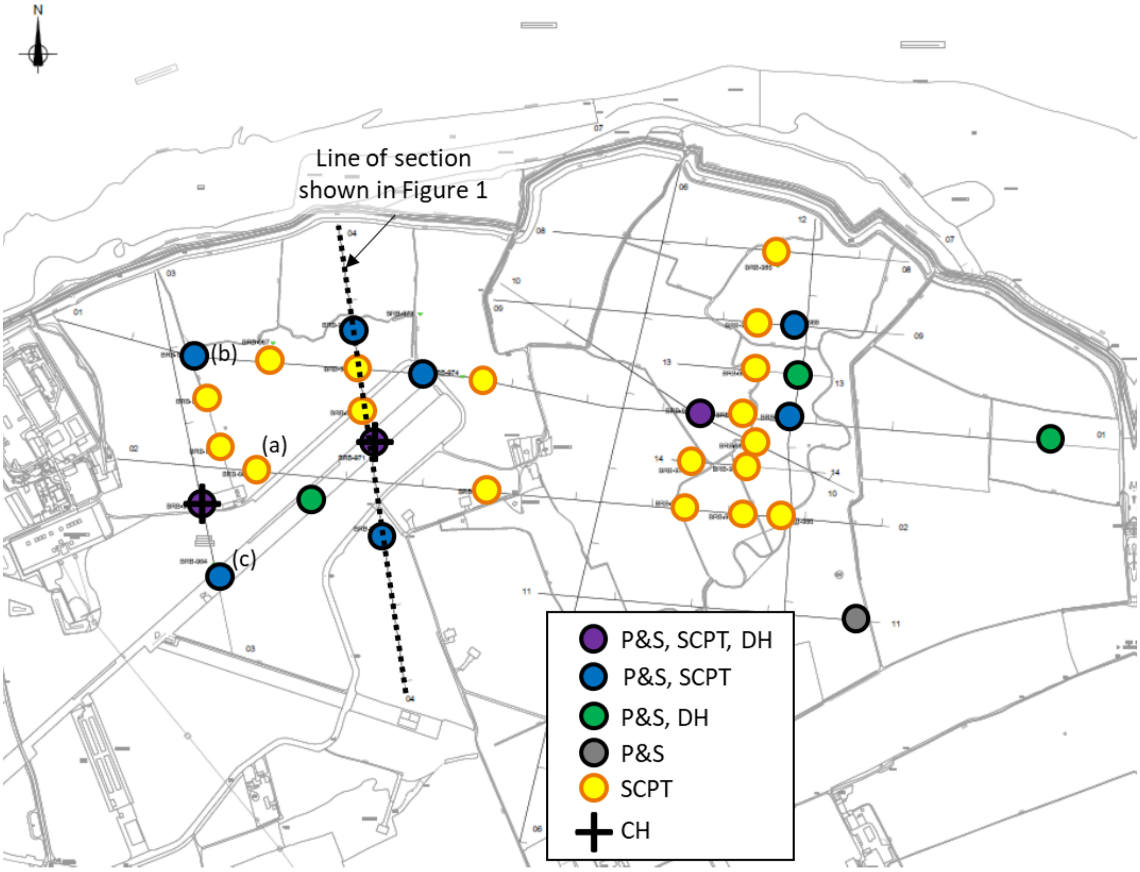


Figure 2. Summary of intrusive test locations for measurement of wave velocities. Main proposed site area is generally indicated by the test locations on the west of the site.. P&S = P&S suspension logging, SCPT = seismic CPT, DH = surface to downhole seismic testing and CH = crosshole seismic testing.

Conventional seismic cone testing

A total of 15 SCPTs were carried out in the main area of the site, with additional tests undertaken to the east to investigate an area of known faulting. The tests were done in accordance with ASTM D7400-08 using a Marchetti seismic dilatometer with a dummy cone, known as the SDMT-CPT. The seismic module incorporated two uniaxial vertical geophones spaced at 0.604 m for measuring the P-wave velocity, and two uniaxial horizontal geophones spaced at 0.5 m for measuring the S-wave velocity. S-waves were generated by striking with a hammer a shear beam placed under the tracks of the CPT truck, whilst P-waves were generated by striking a flat aluminium plate positioned close to the CPT rig (see Figure 3). The twin receiver configuration was selected in order to allow the computation of true interval velocities for both S-waves and P-waves.

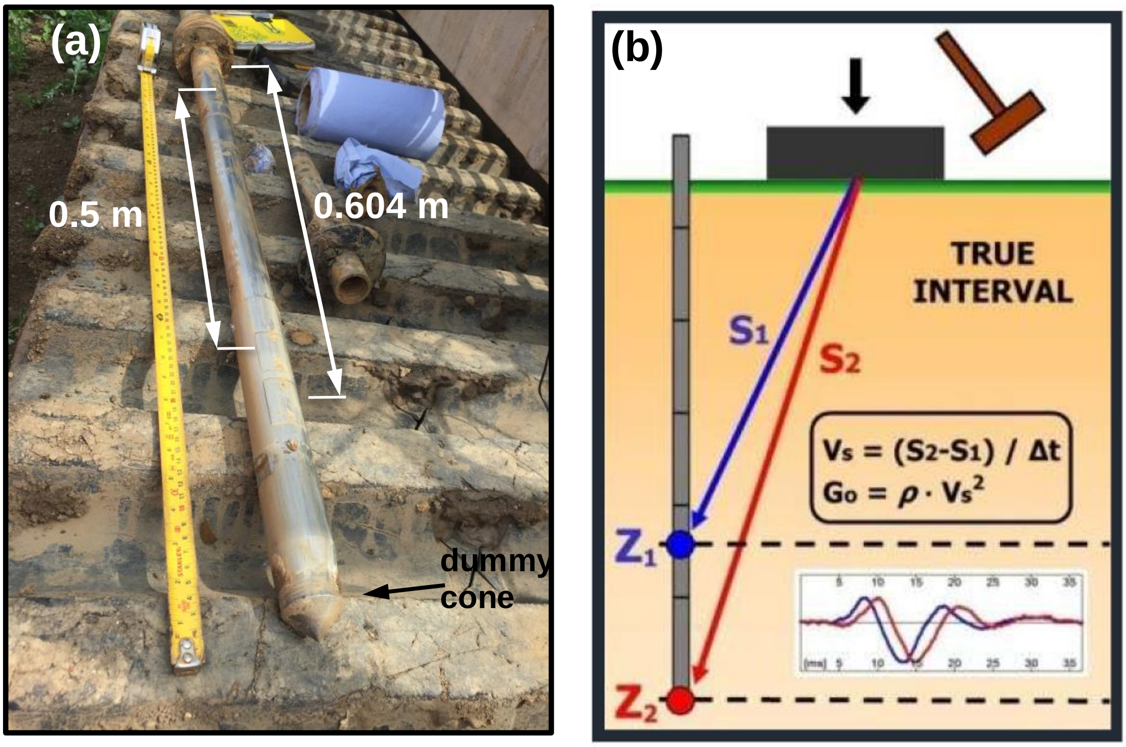


Figure 3. (a) Modified SDMT probe with dummy cone used at BRB. Twin horizontal geophones for Vs measurement spaced at 0.5m; twin vertical geophones for Vp measurement spaced at 0.604 m; (b) Schematic showing S-wave and P-wave sources at the ground surface and the measurement of Vs using the true interval method (after Marchetti et al., 2008).

The SCPT measurements were undertaken by a specialist sub-contractor, In Situ Site Investigation, in collaboration with the specialist geophysical contractor, RSK. The maximum test depth of the standard SCPT technique in the ground conditions present at Bradwell B was limited to around 20 m. SCPT refusal was typically due to exceeding total pressure in the stiff over-consolidated London Clay, sometimes due to a localised harder band. The original scheduled depth for the SCPTs was up to 40 m and in order to extend the survey depth, the following measures were adopted:

- A friction reducer was utilised above the probe and after the insertion of the test equipment into the natural ground. A small quantity of “Purebore” flush mix was poured into the inspection pit to lubricate the rods.
- Following the first refusal, the rods and testing probes were removed from the hole. A small quantity of Purebore flush mix was added into the hole prior to attempting a second push to act as a lubricant and reduce friction close to the refusal depth.

These measures allowed extension of the depth by up to 10 m in certain cases compared to the unassisted case, however, the original scheduled depth was never achieved.

Extended seismic cone testing

In the event of refusal at depths of less than approximately 40 m, in spite of these additional measures, it was initially proposed to extend survey depth by using cable percussion or rotary boreholes backfilled with granular material following the approach developed by Totani et al. (2009) and Failmezger et al. (2016).

This technique has been successfully used where the natural ground is challenging for a push-probe technique, such as dense gravels or stiff clays. For the current BRB project, following discussion of options with the contractor and specialist sub-contractor, it was decided to adopt a modified version of the backfilled borehole approach, but making use of deep cable-percussion boreholes filled with grout, that had already been installed as part of the investigation works for other purposes, rather than drill a new borehole and employ the granular backfill proposed by Totani et al. (2009). Grout is routinely used in UK ground investigation practice to backfill boreholes for environmental purposes such as aquifer protection. During the BRB ground investigation campaign, grouting of rotary drilled boreholes was undertaken in accordance with the UK Specification for Ground Investigation (Soil Mechanics and Association of Geotechnical and Geoenvironmental Specialists. 2012) which involved placement of 1:1:5 cement:bentonite:water grout mix by means of tremie pipe. A trial push was undertaken to verify that the technique was feasible, in particular establishing that the grout was still soft enough to achieve penetration to the depth of interest. The trial was successful and as a result the technique was implemented in two further grout-filled cable percussion holes, focussing on locations where velocity profiles using other techniques were less complete. Grout age in these boreholes ranged from approximately 7 to 12 weeks.

Comparison of conventional and extended SCPTs measurements

To assess the reliability of the extended SCPTs the shear-wave velocity values measured using the new approach were compared with measurements acquired using the conventional approach in the virgin soil. Figure 4 shows pairs of profiles for each of the three locations. In each case, the shear-wave velocities measured using grouted boreholes, as denoted by the filled square markers, are directly comparable to the shear-wave velocities measured using conventional SCPTs in ground immediately adjacent, denoted by hollow circle markers.

The full dataset of 15 No. shear-wave velocity profiles from SCPT, including both conventional and modified techniques (see Figure 5) illustrates the homogeneity of the site below the Quaternary deposits, as anticipated from the sub-horizontal layering observed in Figure 1. The shear-wave velocities in the London Clay appear to be consistent across the site. Variability is associated with the shallower Quaternary units. For example, the Asheldham Gravel river terrace deposits (orange markers) are stiffer than the underlying Head Deposits (light orange marker) or Intertidal Deposits (light yellow markers). The Asheldham Gravels are encountered in the south, south-east and east part of the site and are typically described as firm light brown slightly sandy slightly gravelly clay over reddish brown slightly sandy/gravelly sand or gravel . On the other hand, the Intertidal deposits are very soft brown mottled light bluish grey clays with rootlets overlying very soft dark grey spotted black clays with pockets of peat. The differences in the stiffness of these superficial deposits are consistently noted in measurements of other non-intrusive techniques and agree with observations during the detailed borehole logging exercise.

A distinct feature in Figure 5 is the greater scatter in the shear wave velocities below about -40 m OD, within the Harwich Wrabness Member, denoted by pink solid squares. All of the measurements which deviate from the general trend observed at shallower depths were made on the second of the two days taken to complete this particular profile. Whilst data from day 1 typically showed a clearly defined S-wave arrival with a high level of repeatability, the majority of data recorded on the second day were much harder to interpret and failed to meet the repeatability criteria for a reliable measurement. An example of the good data is presented in Figure 6 whilst an example of the poor data is shown in Figure 7. Whilst it is not unusual for measurements from the surface-to-downhole technique to get harder to interpret with depth, owing to the inevitable reduction in signal-to-noise ratio, in this case, the problems were thought to be associated with the retraction of the rods at the end of day 1 and the subsequent reinsertion of the rods on day 2 down the existing open hole formed from the first push through the grout. It is worth highlighting that such problems with data interpretation were not experienced at any other location where the modified SCPT technique was used, even to equivalent depths. However, in all other cases, the whole profile was measured in a single push on a single day. It is therefore recommended that where the modified SCPT approach is adopted, it is undertaken in a single push where possible.

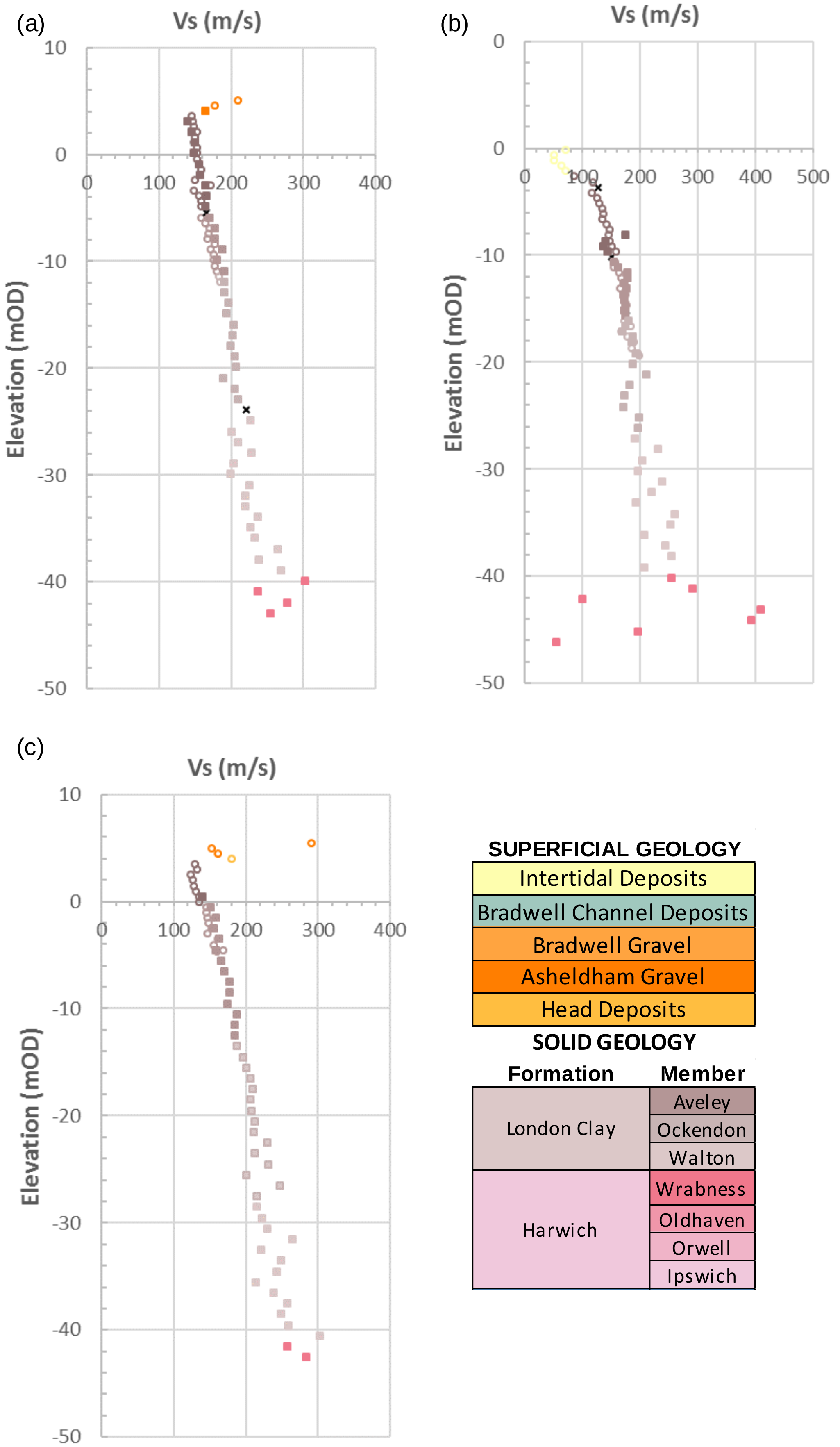


Figure 4. SCPT data in "virgin" soil (open squares) and in grouted adjacent holes (filled squares). Locations of a, b and c indicated on Figure 2.

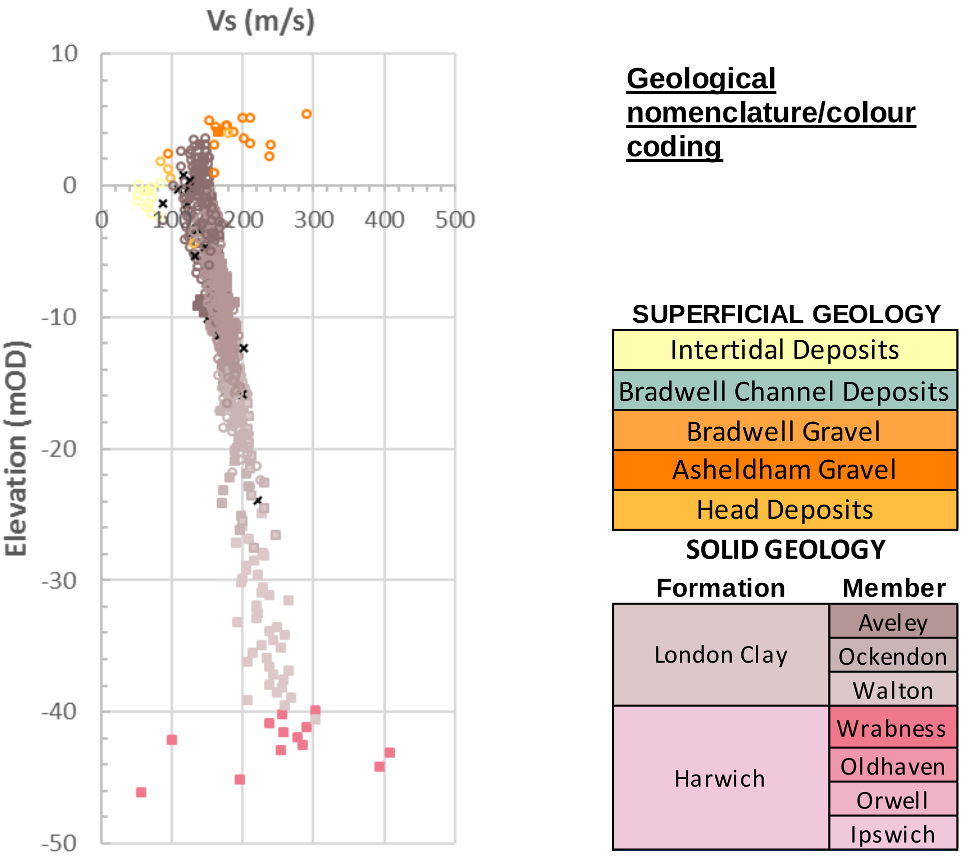
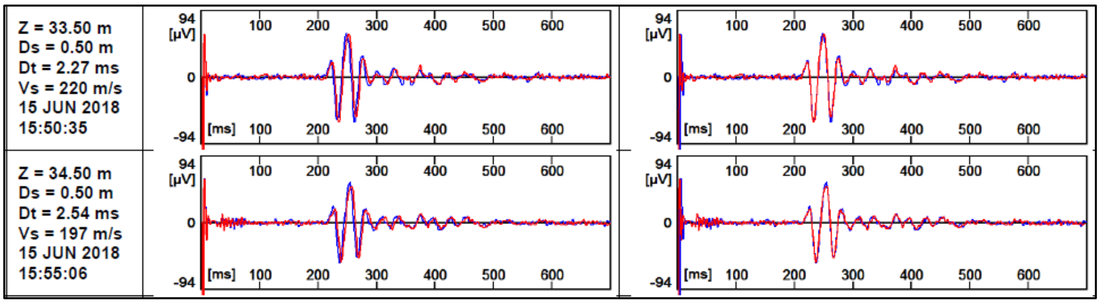


Figure 5. SCPT measurements across the main site area

Where data did not meet the repeatability criteria, they were removed from the dataset. This resulted in the removal of all of the extreme outliers from Figure 5; the shear-wave velocity scatter within the Harwich Formation was not noticeably higher than the scatter observed within the shallower geological units.


Z = 33.50 m
Ds = 0.50 m
Dt = 2.27 ms
Vs = 220 m/s
15 JUN 2018
15:50:35

Z = 34.50 m
Ds = 0.50 m
Dt = 2.54 ms
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Figure 6. SCPT at BRB-963S-A: example good quality S-wave arrivals from the first push for depths of 33.5 m and 34.5 m

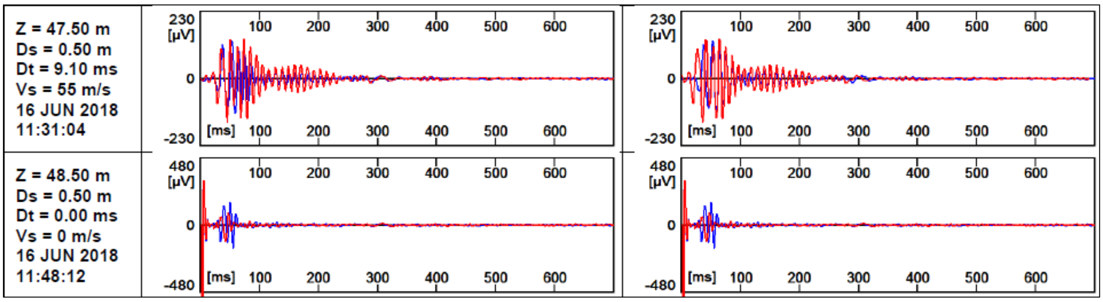

Figure 7. SCPT at BRB-963S-A: example poor quality S-wave signals from the second push at deeper depths

Comparison with other intrusive techniques

The shear-wave velocity measurements for the conventional and extended SCPT are directly comparable to shear-wave velocities measured using other intrusive techniques such as the P&S suspension logging (OYO). This is illustrated in Figure 8 with two representative examples from the BRB GI at locations where SCPTs have been carried out immediately adjacent to boreholes used for P&S suspension logging. In both cases, where the depth ranges overlap, the SCPT velocities, represented by the solid horizontal line markers, are almost indistinguishable from the P&S velocities, represented by hollow circles. These favourable comparisons suggest that the conventional and extended SCPTs can be successfully used to complement the P&S measurements and generate continuous profiles from the ground level.

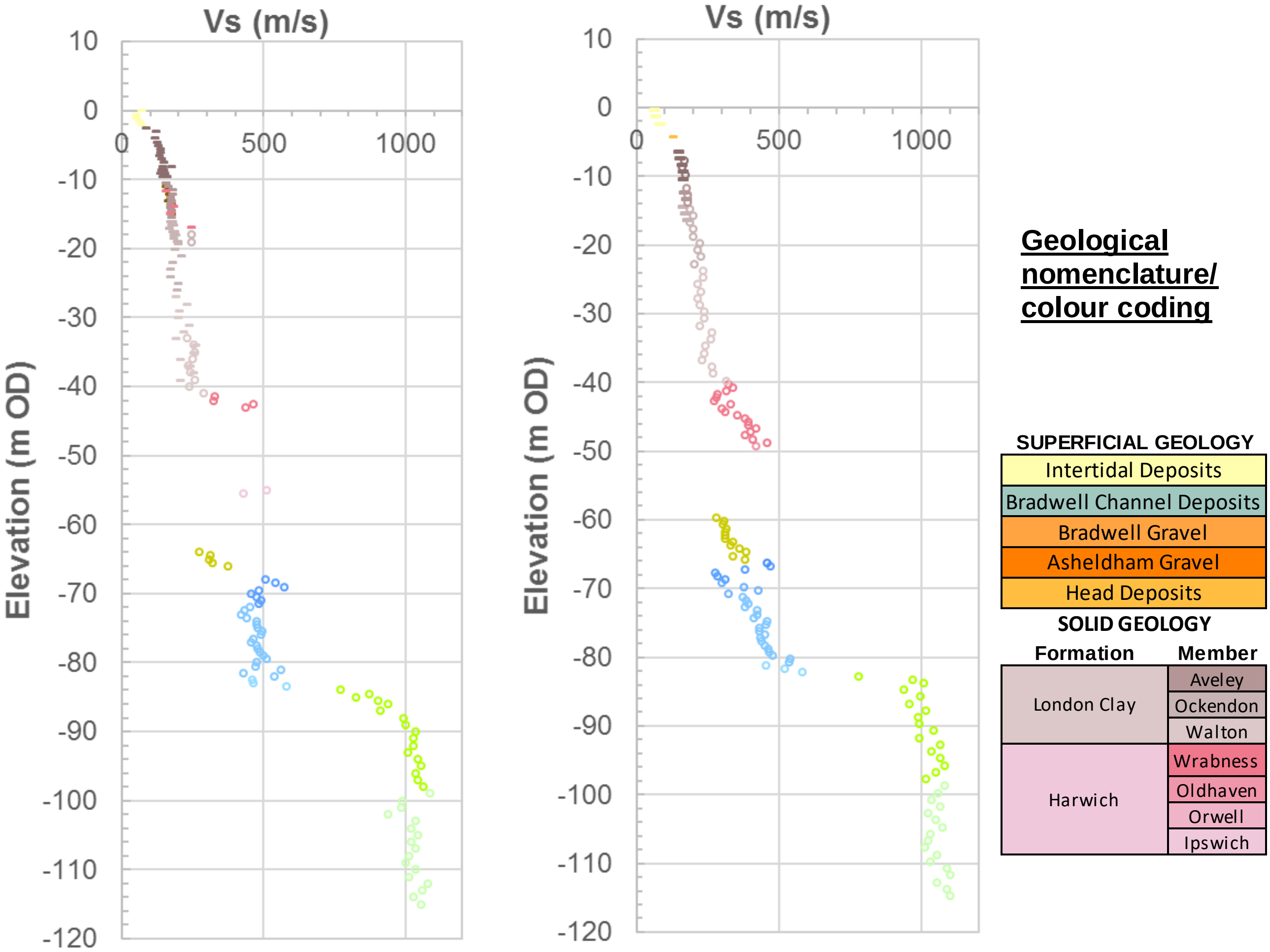

Figure 8. Vs profiles from SCPT and P&S suspension logging from adjacent measurements at two different locations at the BRB site

Cost and program benefits

The potential benefits of undertaking SCPTs within the grout backfill of completed boreholes depends on the context and scope of the wider ground investigation campaign but could include the following:

- More certainty of achieving deeper SCPT depths where some or all of the geological strata might be too stiff or dense for normal SCPT penetration. Such strata could include stiff clays or weak mudstones, or stiff clays containing discrete rock layers or nodular concretions (for example claystones in the London Clay Formation), or dense sand and gravels.
- More certainty of achieving deeper test depths and being able to complete testing in more unstable strata where open boreholes might be too unstable for downhole P&S logger testing or for installing a grouted liner for surface to downhole seismic testing. At the Bradwell B site both P&S logger testing and borehole reaming with liner installations had to be undertaken in several separate runs over several days due to the need to remove borehole casing, and ream and grout in intervals to provide support to the borehole and to clean out the borehole through unstable zones. This increased the cost, program and risk of there being zones where no data acquisition would be possible, particularly for P&S logger testing.
- Allowing direct correlation between SCPT data and the borehole log from the same location, as well as correlation with downhole testing in the borehole and with laboratory testing on recovered samples.
- Potentially less onerous reinstatement requirements of the borehole upon SCPT completion compared to surface to downhole seismic testing where the installation may need to be decommissioned (i.e. liner removed and/or backfilled) with associated second mobilisation.

The greatest benefits of undertaking SCPTs in grouted boreholes are realised where there is already a requirement for both boreholes and SCPT's as part of the ground investigation scope. The method can reduce risk of cost increase, program delays and lack of data acquisition where ground conditions might be unfavourable for deep SCPT penetration, P&S logger testing in open boreholes or liner installation for surface to downhole seismic testing.

Conclusions

The method has been shown to provide a flexible and relatively low risk technique for increasing the overall confidence in seismic parameters derived for a site. Additional work is recommended to compare results obtained from SCPTs in grouted boreholes with other seismic testing methods, from a variety of geological settings and from a range of depths, in order to confirm the robustness of this technique.

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