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THE INTERPRETATION OF CPT DATA FROM HYDRAULICALLY PLACED PFA.

By

D.I. Stewart[1], T.W. Cousens[2], and C.A. Charles-Cruz[2]

ABSTRACT

Cone penetration test (CPT) results on an ~20 year old, hydraulically placed pulverised fuel ash (PFA) deposit are reported, along with the results of oedometer compression tests on ‘undisturbed’ specimens recovered during the site investigation and resedimented PFA samples. The latter showed that aged PFA can undergo significant secondary compression. The correlation between volume compressibility and cone resistance, $m_v=1/(\alpha.q_c)$, is fitted to compressibility data from undisturbed samples to determine α. The resulting CPT compressibility profile shows good agreement with compressibility trends for aged PFA estimated from the tests on resedimented ash. It is therefore recommended that a value of $\alpha=11$ should be used for normally consolidated, aged PFA. The danger of biased sampling in very loose non-cohesive materials and the need for depth profiling by in-situ measurement are highlighted.

INTRODUCTION

Pulverised fuel ash (PFA) is a by-product of the coal fired generation of electricity. In the UK this has historically been the main source of the generation of electricity and so very large quantities of PFA have been produced. PFA is a fine particulate solid now usually collected by electrostatic precipitation from the combustion flue gases. Fly ash particles are typically spherical, ranging in diameter from <1μm to 150μm (the type of dust collection system used largely determines the range of particle sizes). The chemical composition of the PFA depends

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[1] Corresponding Author, School of Civil Engineering, University of Leeds, Leeds, LS2 9JT, U.K.
Phone 0113 343-2287, fax 0113 343-2265, email d.i.stewart@leeds.ac.uk
[2] School of Civil Engineering, University of Leeds.

on the types and relative amounts of incombustible matter in the coal used but, for example, a typical ash produced in Yorkshire, UK, from local bituminous coal is about 50% SiO_2, 25% Al_2O_3 and 10% Fe_2O_3. Calcium, magnesium and potassium compounds and carbon make up most of the remainder (Yorkshire ash typically contains 2-3% carbon). Owing to the rapid cooling of burned coal in power stations, PFA consists primarily of non-crystalline particles or glasses (about 80%), and only a small amount of crystalline material (Cabrera et al., 1986; Helmuth, 1987).

Some PFA is used as a secondary material, for example as a replacement for cement or as bulk fill, but much has been disposed of by producing a water based slurry which is pumped to fill voids, for example old open-cast mine workings, resulting in a sedimented fill within the void. Where the void is water filled, pluviation of fine particles can result in a very loose material with a high water content, especially for particles such as PFA where the specific gravity can be relatively low (typically it is in the range 1.9 to 2.6; Cabrera et al., 1986; Joshi and Lohtia, 1997). The behaviour of such unusual very soft sediments is of interest both academically and more generally because the PFA filled lagoons have development potential.

To exploit the development potential of PFA disposal sites, it is necessary to determine the geotechnical properties of the hydraulically placed PFA. However, it is the authors’ experience that it is generally very difficult to take undisturbed samples of hydraulically placed PFA because any disturbance (including stress relief at the bottom of a cased borehole) can lead to strength loss in loose non-cohesive deposits, and instability of the base of any borehole. Where the PFA is very loose it is impossible to recover even notionally undisturbed samples. Thus, unless an in-situ method has been used to measure the material properties, there is a danger that the results of the laboratory test programme will be biased towards the zones within the PFA that could be sampled (i.e. predominantly from firmer layers), which may give an unrealistic picture of its geotechnical properties. As other in-situ testing methods have their draw-backs and difficulties (for example the pressuremeter is expensive to deploy and measures soil properties only in the horizontal plane which can be misleading if the material is anisotropic), the relatively low costs and ease of use make the cone penetration test (CPT) a very attractive method for testing very loose hydraulically placed PFA.

A major site investigation has been carried out on a 50m deep PFA disposal lagoon in West Yorkshire to determine its suitability for redevelopment as a landfill site. During this investigation the CPT was extensively used, partly because it represented an economical way of determining the depth of the PFA (the boundary between the hydraulically placed PFA and the underlying coal measures produced a sharp contrast in the CPT output), and also because in-situ tests were the only way to estimate the geotechnical properties of the PFA where it was very loose.

The CPT is not ideally suited to the reliable estimation of the compressibility of low permeability soils (De Ruiter, 1982; Lunne et al., 1997). However, empirical correlations with cone resistance have been developed that yield approximate values of volume compressibility (Senneset et al., 1982; Robertson and Campanella, 1983a &1983b; Meigh, 1987; Lunne et al., 1997). The difficulty with such correlations is that soil deformations, which around the cone tip are similar to those caused by hemispherical cavity expansion, are primarily the result of shear strains. Indeed, in saturated low permeability soils, the rate of cone advance is such that there is insufficient time for drainage and the soil deforms at constant volume. Thus, empirical correlations that determine volume compressibility from cone resistance rely on there being a correlation between m_v and other soil parameters such as shear strength and shear stiffness. As with any empirical correlation, it is therefore essential that compressibility correlations be calibrated for the particular soil type. Lunne et al. (1997) go further and suggest that site specific correlations be developed to give greater reliability to the compressibility correlation.

This paper is about the interpretation of CPT results from this investigation. A total of thirteen CPT probes were conducted on the PFA deposit, and samples of PFA were recovered from the site. PFA recovered from the site was re-sedimented and then consolidated in the laboratory, replicating the stress history of the very loose zone of PFA found on the site. The compressibility measured for this very loose resedimented PFA and that measured on notionally undisturbed PFA samples recovered from firmer zones on site is compared with compressibility values estimated from correlations with the CPT data. Values are recommended for the constant in that correlation. The work may also be of interest for researchers and engineers working with other very loose particulate systems, both natural deposits and man-made, for example mine tailings.

THE SITE

Details of site have been reported by Cousens and Stewart (2003) but, briefly, the area of interest is a 50m deep PFA disposal lagoon (lagoon 19) adjacent to a river. A large void was created during the 1950s and 1960s by opencast coal mining and the extraction of sand and gravel. This was partially backfilled with colliery spoil and embankments of the same material were constructed to form a series of lagoons for PFA disposal. PFA was pumped into lagoon 19 as a water-based slurry, allowed to sediment, and excess water was allowed to overflow a series of weirs into the nearby river. During filling, lagoon 19 would have rapidly filled with water from the slurry until the water level in the lagoon exceeded the river level, and thus the PFA would have settled-out within a large body of essentially stationary water (the neighbouring lagoon was still being operated in this manner into the 1980s, with a water level about 3m above river level). Once the PFA level reached the initial overflow level, the overflow height would have been raised incrementally using weir-boards on the outflow structure. During this stage of filling the water and PFA levels will have been similar to avoid impounding water. PFA disposal into lagoon 19 took place from 1970 to 1994, with most occurring during the early to mid 1970s, none in the early 1980s, and a final 2-3m added before 1994.

GROUND INVESTIGATION

In July 1999 a ground investigation was carried out on the site described above to determine the depth, variability, strength and compression characteristics of the PFA. The main investigation was performed by Norwest Holst Soil Engineering Limited, and consisted of five boreholes advanced by cable percussive techniques, with the collection of both disturbed and undisturbed samples for laboratory testing. As part of the investigation thirteen CPT probes were undertaken by Fugro Limited. In addition, further bulk disturbed samples were taken in 2003 by the University of Leeds so that laboratory testing of resedimented samples could be undertaken.

DESCRIPTION OF THE PFA

Figure 1 shows the particle size distribution of a sample taken from a depth of 14.5m in borehole 1B, which was located near the centre of the lagoon. The particle size distributions of most of the samples taken from the site were very similar to that shown in Figure 1, which suggests that the PFA is relatively uniform over the site with 5-10% clay sized particles and 60-80% silt sized. Occasional thin coarse layers were detected in the PFA, but their extent is unknown although they appear to be limited. Scanning electron microscopy on the silt and clay sized fraction of a near surface sample of PFA shows that it consists primarily of very rounded, almost spherical particles with sizes predominantly in the range 1-20μm (see Figure 2). Some micrographs also showed a weak open matrix (Figure 2b) which probably represents unburned carbon in the ash.

The local bituminous coals in Yorkshire usually produce Class F PFA (low calcium ash that doesn’t self-harden) upon combustion (Cabrera et al., 1986). Helmuth (1987) categorises PFA produced at the site in the early 1960’s as Class F. None of the PFA had exhibited any self-hardening while in the lagoon confirming this categorisation. In low-calcium ashes, complete removal of carbon is rare. The measured specific gravity of the PFA is 2.3, which is in the middle of the range of 2.23 to 2.40 reported by Cabrera et al. (1986) from ashes produced by burning local bituminous coals in Yorkshire power stations.

The average liquid limit of the PFA was 46% (range 38-56%) with an average plastic limit of 42% (range 32-54%). The average plasticity index was 4% with some samples showing no plasticity. The PFA classifies as an inorganic silt with slight plasticity. The in-situ moisture content of the PFA showed a general pattern of a central band with a very high moisture content (55% to 78%) with lower values above and below (38% to 44%). These values suggest loose material, especially in the central band. The in-situ bulk density is estimated as varying between 1.54 and 1.66 Mg/m^3, which correspond to void ratios of approximately 1.28 to 0.88 assuming full saturation, the former values corresponding with the soft zone. A void ratio of 1.28 corresponds to a moisture content of 55% at saturation, thus either the very high moisture content samples contained additional water from the borehole, or it was not possible to obtain a sample sufficiently intact to obtain a bulk density from the very loose material. These voids ratios are quite high; for example, in the extended Casagrande soil classification system void ratio values for silt at maximum dry density are given as less than 0.7 (Road Research Laboratory, 1952).

METHODOLOGY

Cone Penetration Testing

The CPTs were made using twenty tonne capacity hydraulic penetrometer equipment mounted in a crawler ballasted to provide a reaction weight of about 14 tonnes. A 7.5 tonne capacity electric cone was used throughout, with a rate of penetration of approximately 2cm per second. Load cells measured the cone end resistance and local side friction and the data were recorded at 2cm depth intervals.

Oedometer Testing of Re-sedimented PFA

A series of one-dimensional compression tests were conducted on PFA recovered from lagoon 19 and re-sedimented in the laboratory. A 70mm diameter fixed ring oedometer was used with top and bottom drainage. To avoid the need to move the specimen, with the inherent risk of sample disturbance, sample preparation was undertaken with the oedometer within the lever-arm loading apparatus.

To replicate the very high void ratios determined for the PFA deposit on site, and to reproduce the primary feature of the deposition process on site, the specimens were prepared by water pluviation. During sample preparation an extension tube made from acetate film and adhesive tape was fitted to the water-bath. Only a small head of water was used, and a perfectly adequate water seal was achieved by ensuring a close fit between the water bath and the extension tube and by coating the contact surfaces with silicon grease. A second, slightly shorter, extension tube made from acetate film was close-fitted inside the top of the oedometer collar. An equal water level was established in both the inner and outer tubes about 120 mm above the oedometer cell, and approximately 80g of PFA was sprinkled slowly into the inner tube. The PFA had been air-dried, passed through a 2mm sieve, and then disaggregated with light pressure from the flat surface of a palette knife. Once the required amount of PFA had been added, it was left to settle for at least 1hr, after which only a slight discolouration was visible in the water in the inner tube. At this stage the inner tube was carefully removed, the water level was lowered to the top of the water bath, and the outer extension tube was removed. This technique resulted in a specimen of very loose PFA initially just over 20 mm in height.

The top-cap, with a porous stone and filter paper, was placed very carefully on top of the specimen and a seating load applied (the combined stress due to the top-cap and seating load was equivalent to 13 kPa). The sample was loaded in increments typically of 13, 25, 52, 104, 208, 415, 832 and 1788 kPa to a maximum vertical stress of about 3.5 MPa. Each loading step was monitored for a period 30 minutes, which was found experimentally to exceed the time for 90% consolidation for all loading increments (t_{90} was found in the conventional way by plotting the settlement against √time). After some loading increments the specimen was monitored for up to 3 days to observe any secondary (or creep) compression. Small stress increments were used initially on reloading after a creep period. Unloading was undertaken in two or three large increments because the rebound was very small and the response was essentially instantaneous. After unloading the specimen was extruded and its height measured. After weighing, the whole sample was oven dried so that its dry weight and moisture content could be determined. Disturbance during extrusion meant that the sample height could not be determined accurately, and the final void ratio of the specimen was determined from the final moisture content (assuming that the specimen was fully saturated).

RESULTS

Cone Penetration Testing

Typical CPT data from the deeper part of the lagoon are shown in figures 3, 4 and 5 (of the three CPT shown, 4C was the northernmost and closest to, and 7C was the southernmost and furthest from the PFA slurry input point). All the tests clearly indicated the bottom of the PFA deposit, and characterize the PFA as either "granular" or "cohesive" depending on the cone resistance (q_c) and friction ratio (R_f). Much of the PFA can be described as a very loose to loose granular material or soft to firm cohesive material, although there are dense/firm zones and inter-layering is common. As the particle size distribution data show little variation in the silt sized PFA over the site, the variations in classification using q_c and R_f must reflect variation in density rather than composition. Thus there are considerable depths of loose/soft material but it is very difficult to discern a pattern in the variation of the PFA, either vertically or laterally, from the q_c and R_f data except for an increasing depth of loose material towards the south of the site.

Figure 6 shows plots of the relative density of the PFA against depth which have been produced using the relationship for high compressibility quartz sands described by Meigh (1987). In this relationship between relative density and $q_c/(\sigma_v')^{½}$, the in-situ vertical stress, σ_v', has been calculated assuming a total unit weight of 15.5 kNm^{-3} and that the water table is at a height of 19m AOD (6m below average ground level). It is inappropriate to place too much faith in the absolute values of relative density from such a relationship (the relationship between cone resistance, in situ stress and relative density is significantly influenced by soil compressibility; Campanella et al., 1984), but the variation of relative density reveals an interesting pattern. The data suggest an upper relatively dense layer above a height of 15m AOD over a far looser zone. In the middle of the lagoon the PFA is loosest at a height of about 10m AOD and the relative density increases gradually with depth.

Given the levels of the lagoon (present ground level about 25m AOD) and river (about 15m AOD) and the filling procedure used to deposit the PFA the density pattern might have been created in the following way. Initially the void, whose deepest point is about -30m AOD, would either have been water-filled, or would have rapidly have become so as the PFA slurry was pumped in, resulting in the PFA sedimenting through water. This would have continued with the excess water overflowing through settling ponds into the river once the water level reached about 17m AOD. As the inlet point was at the northern edge of the lagoon, the PFA would tend to sediment from the north, possibly resulting in slumping failure of the PFA underwater, which would give a very loose packing. As the depth of sedimented solids reached 17m (i.e. the water level in the lagoon) the pattern of deposition would have changed to one where the slurry would have dewatered while flowing over the ground surface (i.e. the water would have drained downwards out of the PFA), rather than particle sedimentation through water, which would have given a denser structure, an effect possibly increased by surface drying.

Therefore it would appear that the PFA below 15m AOD is close to a normally consolidated state, as it has been deposited through water to achieve a very loose state, and then subsequently compressed by the material deposited above. It is also likely to have undergone secondary compression over the time since deposition (approximately 20 years). The stress history of the material above 15m AOD appears to have been more complicated, with surface deposition and subsequent pore suction variations resulting in a denser state than that resulting from sedimentation through water, and thus it can be generally described as “over-consolidated”

Oedometer Testing of Re-sedimented PFA

The variation in void ratio with vertical effective stress of water pluviated PFA is shown in Figure 7. Three tests are shown in this figure. The tests presented were all very loose on first loading and exhibit normally consolidated behaviour almost from the start of testing (the specimens exhibited large plastic strains from first loading, and the relationship between void ratio and the logarithm of vertical effective stress is highly linear from a surcharge stress of 100 kPa to one exceeding 3 MPa). Upon unloading the relationship between e and $\log\sigma_v'$ was also linear but the response is far stiffer than that exhibited on loading. All the tests conducted gave very similar values of both C_c and C_r (the average values are 0.27 and 0.036, respectively), and the only significant difference between the tests was the value of the initial void ratio. The method of sample preparation meant that the initial specimen height is unknown and the final specimen height can only be measured after sample extrusion. Thus there is some uncertainty in the measured specimen dimensions. Thus the void ratios of the specimens were determined from their final water contents by assuming complete saturation, and the measured change in specimen height. This introduces a small uncertainty into the absolute values of void ratio presented in Figure 7. Thus it is believed that all the test specimens were exhibiting essentially the same behaviour with most of the differences in void ratio being due to slight inaccuracies in measurement and saturation at the end of the test.

At selected loading increments during tests 4 and 6 the loading was held constant after the consolidation response had been observed (i.e. after t_{90} had been reached) so that the secondary compression (or creep) response could be observed. The data have been fitted with straight-lines of the form:

$$\Delta e_{creep} = C_{\alpha} \log_{10}(t_{creep}/t_{90}) \qquad (1)$$

where Δe_{creep} is the change in void ratio during secondary compression, t_{90} is the time taken for 90% consolidation and t_{creep} is the time elapsed since a change in the loading. The average value of C_{α} measured over 5 creep stages was 0.0036 (which is only slightly less than would be anticipated for normally consolidated clay; Lambe and Whitman, 1979).

DISCUSSION

The oedometer data can be used to estimate the volumetric compressibility, m_v, of the PFA for comparison with that estimated from correlations with the CPT data (see Bjerrum, 1967). For PFA that is normally consolidated upon first loading, the starting void ratio after a period of creep can be estimated by combining equation 1 with the equation of the normal consolidation line to give;

$$e_o = e_{1kPa} - C_c \log_{10}(\sigma_v'{}_o) - C_{\alpha} \log_{10}(t_{creep}/t_{90}) \qquad (2)$$

where e_{1kPa} is the void ratio on the normal consolidation line when σ_v'=1kPa (see Figure 8). If the PFA is then subjected to a stress increment that is sufficient to bring it back onto the normal consolidation line, the compressibility on reloading can be estimated from;

$$m_v = \frac{1}{1+e_o}\frac{\Delta e}{\Delta\sigma_v'} = \frac{1}{1+e_o}\frac{C_c \log_{10}(\sigma_v'{}_1/\sigma_v'{}_{ncl})}{\sigma_v'{}_1 - \sigma_v'{}_o} \qquad (3)$$

where e_o is the void ratio after creep, and $\sigma_v'{}_{nlc}$ is the effective stress at the point on the normal consolidation line where $e=e_o$: the value of $\sigma_v'{}_{nlc}$ can be estimated from e_o and the equation of the normal consolidation line. If the stress increment is insufficient to bring the PFA back onto the normal consolidation line, the compressibility can be estimated from the void ratio after creep, e_o, and the slope of the rebound line from;

$$m_v = \frac{1}{1+e_o}\frac{C_r \log_{10}(\sigma_v{'}_1/\sigma_v{'}_o)}{\sigma_v{'}_1 - \sigma_v{'}_o} \qquad (4)$$

The m_v profiles shown Figure 9 have been calculated using equations 3 and 4 by assuming a unit weight of 15.5 kN/m^3 for the PFA, ground surface at 25m AOD and a water table at 19m AOD. The NCC (normal consolidation, creep) trend is given by equation 3 using average e_{1kPa}, C_c and C_α values from the oedometer data and a stress increase of 100kPa. All the oedometer tests gave essentially the same C_c value, and m_v is not particularly sensitive to small errors in e_{1kPa}, so void ratio errors in the consolidation data have a small effect on m_v, but the amount of creep consolidation controls how far the initial condition of the specimen is from the normal consolidation line and potentially can have a big effect on m_v. The PFA level was close to its current level by the late 1970’s and filling ceased after adding a further 2-3m in the mid to late 1980’s. Thus the upper m_v profile for sedimented PFA shown in Figure 9 has been estimated by assuming a creep duration of 20 years. However the C_α value has been evaluated over a time period more than 3 orders of magnitude less than this and thus must be treated with caution.

The OC (over-consolidation) trend on Figure 9 is based on equation 4 and approximates to the situation where there has been sufficient creep for the reloading stress-path to remain on a rebound line. It has been calculated for a stress increment of 100 kPa using the average C_r value from the oedometer tests. It can be seen from equation 4 that variations in the initial void ratio have only a fairly small effect on m_v for stress-paths following a rebound line (for the entire range of e_o exhibited by the PFA of $0.7 \le e_o \le 1.4$ the $1/(1+e_o)$ term only varies between 0.59 and 0.42), and so the e_o value used to calculate m_v for specimens that undergo sufficient creep to remain on a rebound line on renewed loading was that calculated for 20 years of creep.

The m_v values measured on specimens from U100 samples recovered during the site investigation are also shown in Figure 9. These m_v values were for a stress increase of 100 kPa from the estimated in-situ vertical effective stress. When reviewing this data it should be remembered that during the site investigation attempts at sample recovery from the very soft region between 15 and -10 m AOD were frequently unsuccessful. Therefore the reason that sample recovery was possible at two locations in this zone may be due to there being a locally stiffer region of PFA, and thus the m_v values for the two specimens recovered from this depth range may be unrepresentative. The m_v values measured on the U100 samples from the zone that was sedimented through water (i.e. the zone that has probably undergone normal consolidation followed by secondary compression) fall between the two estimated m_v profiles.

Two further m_v profiles are shown in Figure 9 as dashed lines. These profiles are for comparison with the data for the PFA that was surface deposited above the water level during the first filling stage (i.e. in the zone that was deposited in a denser state and has probably become over-consolidated due to seasonal variations in the water table and the resulting pore suctions). The initial void ratio and subsequent response of the PFA in this region cannot easily be estimated by using consolidation data, so the profile has been estimated using an initial void ratio of 0.9 (a representative value for this region) and the rebound index C_r for a 100kPa stress increment. The rebound index, C_r, has been used in the estimation of m_v in this region on the assumption that the PFA has become over-consolidated as described above. The u=0 trend assumes that there is no pore water pressure above the water table, whereas the SAWT trend assumes the PFA is fully saturated above the water table with the pore water in suction.

The oedometer specimens from the U100 samples from shallow depths were inundated with water once a seating load had been applied, thus m_v values will not be representative of the PFA on site, which will have been stiffer due to the effect of pore suction. These m_v values are comparable with the u=0 trend shown in Figure 9. Here, despite the uncertainty about the initial void ratio, the data fit is reasonably good. This gives some credibility to using equation 4 and an estimated initial void ratio to estimate m_v in this region of the PFA.

The coefficient of volume compressibility can also be estimated from CPT data using the equation:

$$m_v = 1/(\alpha . q_c) \qquad (5)$$

where α is a constant of proportionality that depends on the soil type (Robertson and Campanella, 1983a &1983b; Meigh, 1987; Lunne et al., 1997). Suggested values of α for cone resistance measured with a reference tip are 3 to 11 for normally consolidated sands, 5 to 15 (or even 30) for over-consolidated sands, 3.5 to 7.5 for low to medium plasticity silts, and 2.5 to 10 for organic silt.

The CPT data from CPT4C, CPT6C and CPT7C has been visually fitted to the m_v values measured in oedometer tests on specimens from U100 samples recovered from the site (for a 100kPa stress increase from $\sigma_v'_o$) by varying the α-value until there is good agreement. As cone resistance is primarily a measure of strength, which in an undrained material will be a function of the void ratio, it should be anticipated that α may vary with OCR as normally and over-consolidated soils at the same void ratio have very different compressibility (indeed, different α-values are recommended for normally and over-consolidated sands; Robertson and Campanella, 1983a; Meigh, 1987). Therefore only the compressibility of specimens recovered from below 15 AOD, where the PFA is thought to be normally consolidated, were intentionally fitted by the

CPT correlation. Also, as borehole BH1 is fairly near to CPT4C, BH2 is close to CPT6C and BH3 is close to CPT7C, particular emphasis was placed on the relationship between the CPT estimate and the compressibility of specimens from the nearest borehole when selecting a suitable α-value for the m_v correlation. The best visual fit of the CPT estimates to the compressibility of the undisturbed specimens was obtained with an α-value of 11.

The compressibility profiles estimated from the CPT data using an α-value of 11 are shown in Figure 10, together with the compressibility of the undisturbed samples and the compressibility profiles estimated from the oedometer tests on the resedimented PFA. Below 15m AOD, where the PFA is thought to be largely normal consolidated, the volume compressibilities estimated from CPT data fall largely between the NCC and OC trends calculated from the consolidation behaviour of the resedimented PFA.

In detail, the compressibility estimated from CPT4C data straddles the NCC trend at depth, but between -15 and -8m AOD it falls closer to the lower, OC trend (the U100 specimen from BH1 recovered from within this depth range had a compressibility only slightly above the over-consolidated trend). Between -8 and 10m AOD the CPT estimate typically falls just below NCC trend. Generally the trend in the compressibility estimated from CPT6C are similar to that from CPT4C, except that it falls close to the OC prediction from about -20 and -4m AOD (although a single peak falls on the NCC trend at -9m AOD). The compressibility estimated from CPT6C straddles the NCC trend from the bottom of the PFA to 12m AOD. At depths just below the water level during the first stage of filling, the CPT estimates of compressibility fall away from the NCC trend towards the OC trend (the CPT7C estimate even falls slightly below the OC trend). Given the uncertain history of the PFA sedimented through water (arising from the tendency to form underwater mounds near the inlet, which then slump to fill the lagoon) it is quite remarkable that the compressibility of aged, water-sedimented PFA falls so overwhelmingly between the NCC and OC trends, which represent a best estimate and a lower limit on the compressibility of an originally normally consolidated deposit that has become lightly over-consolidated through creep.

As already stated, it is inappropriate to assume a-priori that the α-value for PFA that has undergone surface deposition and subsequent pore suction variation, and may therefore be in an over-consolidated state, is the same as that for PFA that has sedimented through water (i.e. initially normally consolidated but now lightly over-consolidated through creep). Also, m_v has not been correctly measured on the U100 samples from the surface deposition zone, because the oedometer specimens were inundated with water once a seating load had been applied relieving any pore water suction, and so the PFA is in a different state from that tested during the CPT. Thus it is difficult to make definitive statements about a suitable α-value for PFA that has undergone surface deposition. However, it can be observed from the CPT estimate of m_v that surface deposition and subsequent pore suction variation appears to result in a material with a far more variable compressibility than sedimentation through water. It is also interesting to note that in the surface deposition zone the CPT estimates of compressibility based on an α-value of 11 generally fall around the SAWT trend line for over-consolidated PFA that is saturated above the water table except very near the ground surface where it falls near the u=0 trend line for over-consolidated PFA. As the methodology used to estimate the PFA compressibility in this zone is given some validity by the fit of the u=0 trend to the m_v values from the inundated oedometer tests, it is reasonable to treat the SAWT trend as a guide to the compressibility in this region (and particularly just above the water table). Thus it is tentatively suggested that an α-value of 11 is of the correct magnitude for over-consolidated PFA.

CONCLUSIONS

In very loose hydraulically placed PFA it is not possible to establish the variation of engineering properties within a deposit simply by the laboratory testing of undisturbed specimens recovered during a site investigation. This is because it can be impossible to recover even notionally undisturbed samples of the loosest, and therefore weakest and most compressible material. Thus it is essential that an in-situ method is used to depth profile the material, otherwise there is a danger that the results of the laboratory test programme will be biased towards the zones within the PFA that can be sampled.

In the current work the CPT has been successfully used to establish the variation in the volume compressibility of aged hydraulically placed PFA deposits by employing the widely used correlation with cone resistance, $m_v=1/(\alpha.q_c)$. As the CPT is not ideally suited to determining the compressibility of low permeability soils, it was necessary to determine the constant in this correlation for the material being investigated. Two approaches have been used to determine a suitable value of α. Firstly the m_v profile from the CPT correlation was compared with m_v measured in oedometer tests on undisturbed PFA samples taken from depth. However, as the volume compressibility estimated from the CPT was at some locations more than twice that measured, further corroboration was considered necessary. Therefore PFA was resedimented in an oedometer cell and its consolidation response was measured. It was found to undergo significant secondary compression, which must be accounted for when estimating m_v for aged PFA deposits. Thus, m_v profiles for aged PFA deposits that were in good agreement with the measured compressibility values, and bounded the CPT correlations, were derived. In this way it was established that a value of $\alpha=11$ should be used for the constant of correlation for normally consolidated PFA that has aged for 20 years.

Calibration chamber testing has been widely used to determine the correlation between CPT data and various soil properties. An implication of this work is that it is inappropriate to rely on a correlation derived from chamber tests, where ageing cannot be replicated, to determine the compressibility of a material that undergoes significant secondary compression.

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List of Figures

Figure 1: Typical particle size distribution of the PFA.

Figure 2: SEM images of the PFA.

Figure 3: Data obtained from CPT4C

Figure 4: Data obtained from CPT6C

Figure 5: Data obtained from CPT7C

Figure 6: Relative density profiles determined from (a) CPT4C, (b) CPT6C, and (c) CPT7C.

Figure 7: Oedometer tests on loose PFA prepared by water pluviation.

Figure 8: Schematic diagram showing the stress path of PFA that has undergone primary consolidation and secondary compression upon subsequent stress increase.

Figure 9: Idealised m_v profiles and m_v values from the U100 samples recovered from the boreholes.

Figure 10: Volume compressibility, m_v, determined from (a) CPT4C, (b) CPT6C, and (c) CPT7C using α=11 (trend lines are defined in Figure 9).

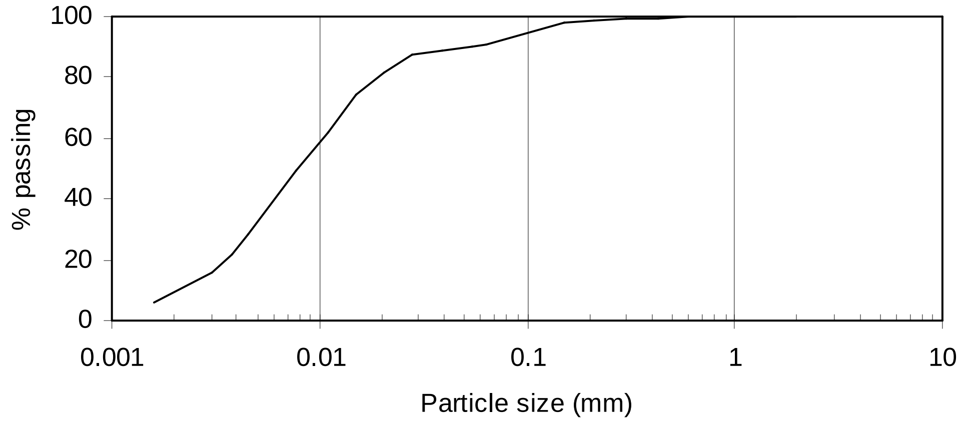
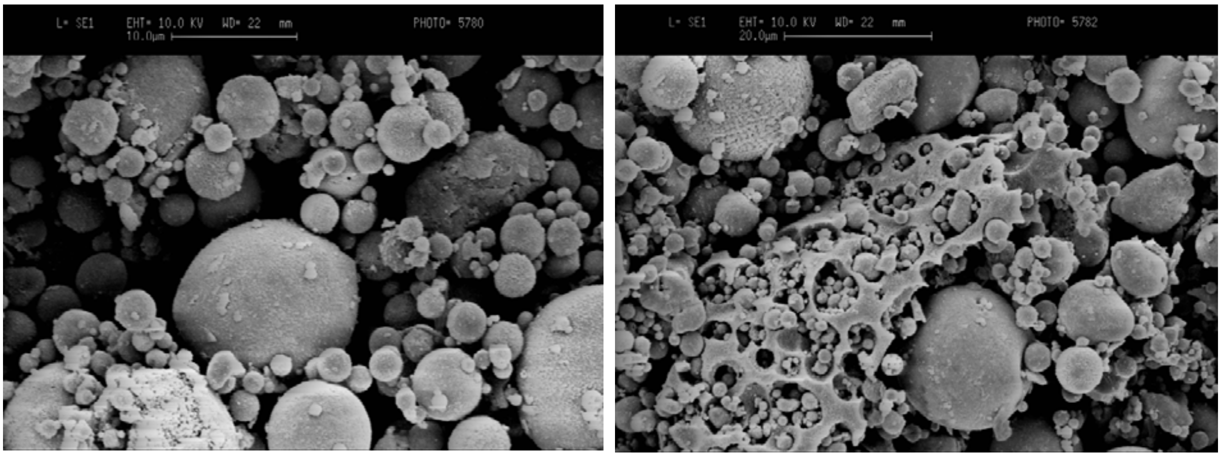
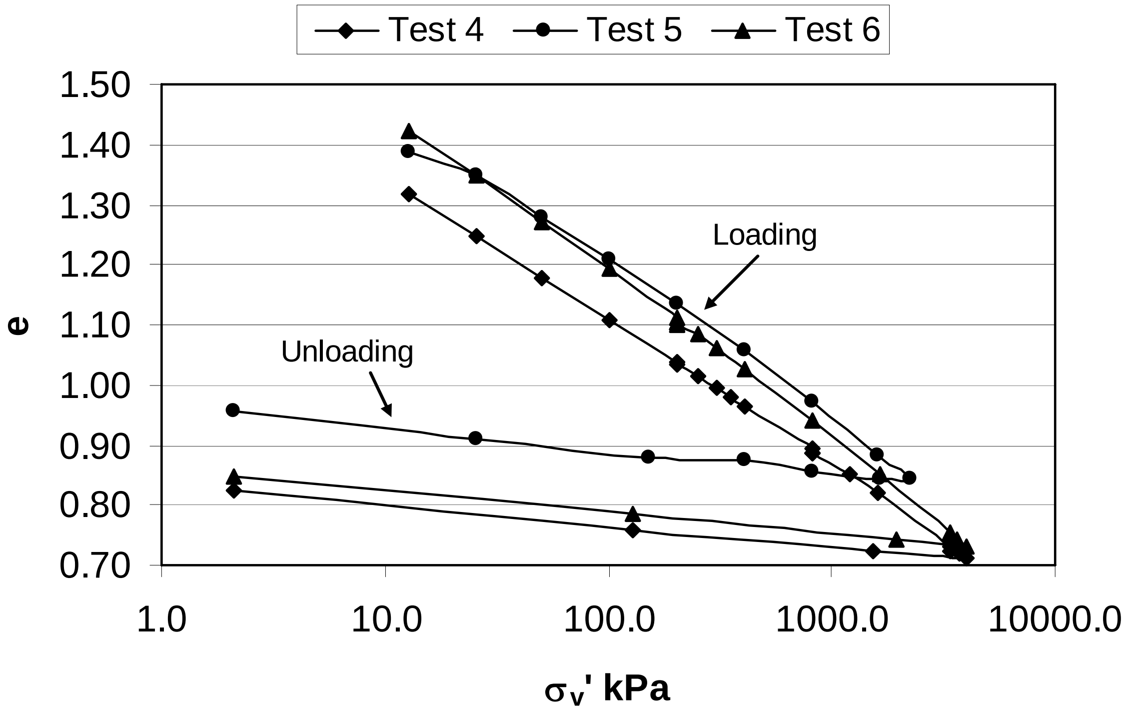


Figure 1: Typical particle size distribution of the PFA.



(a) (b)

Figure 2: SEM images of the PFA.



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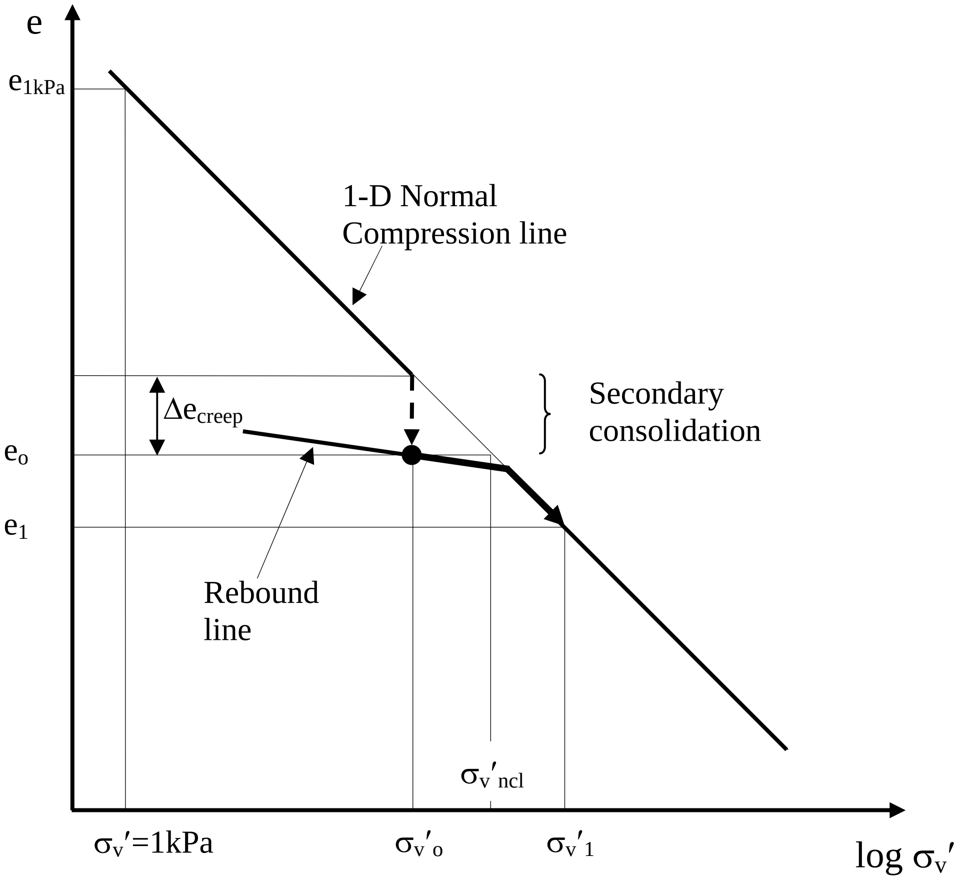

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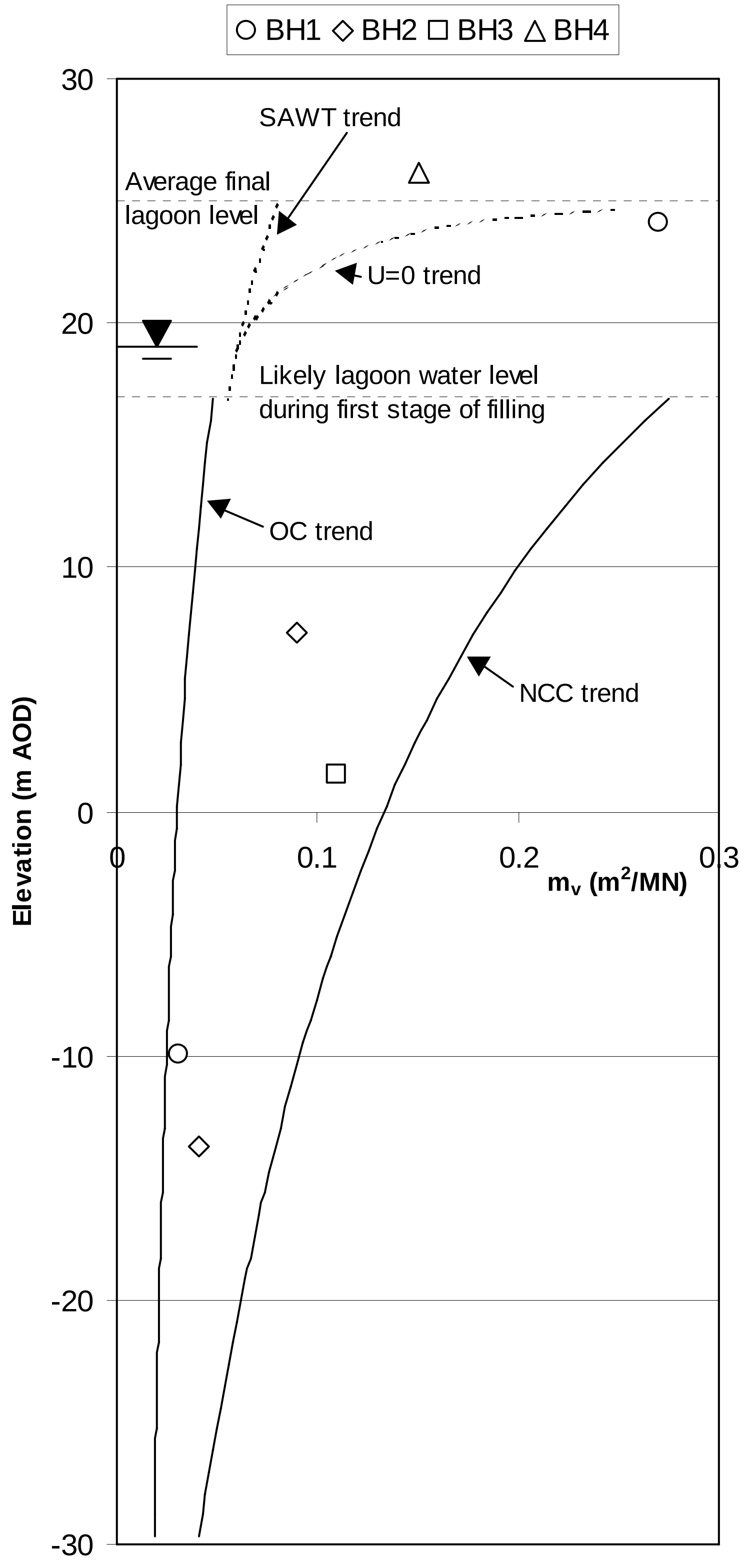


Figure 9: Idealised m_v profiles and m_v values from the U100 samples recovered from the boreholes.

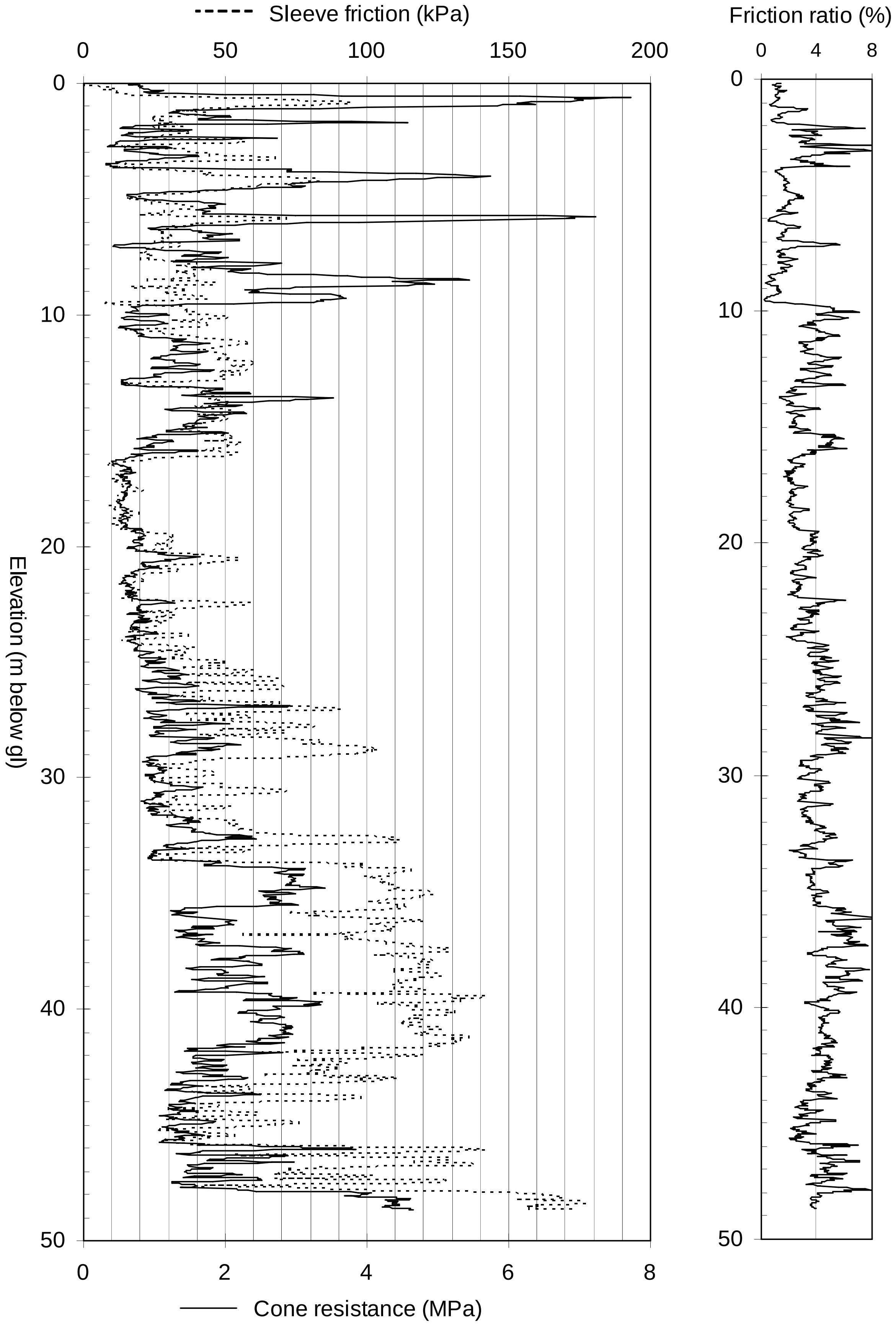


Figure 3: Data obtained from CPT4C

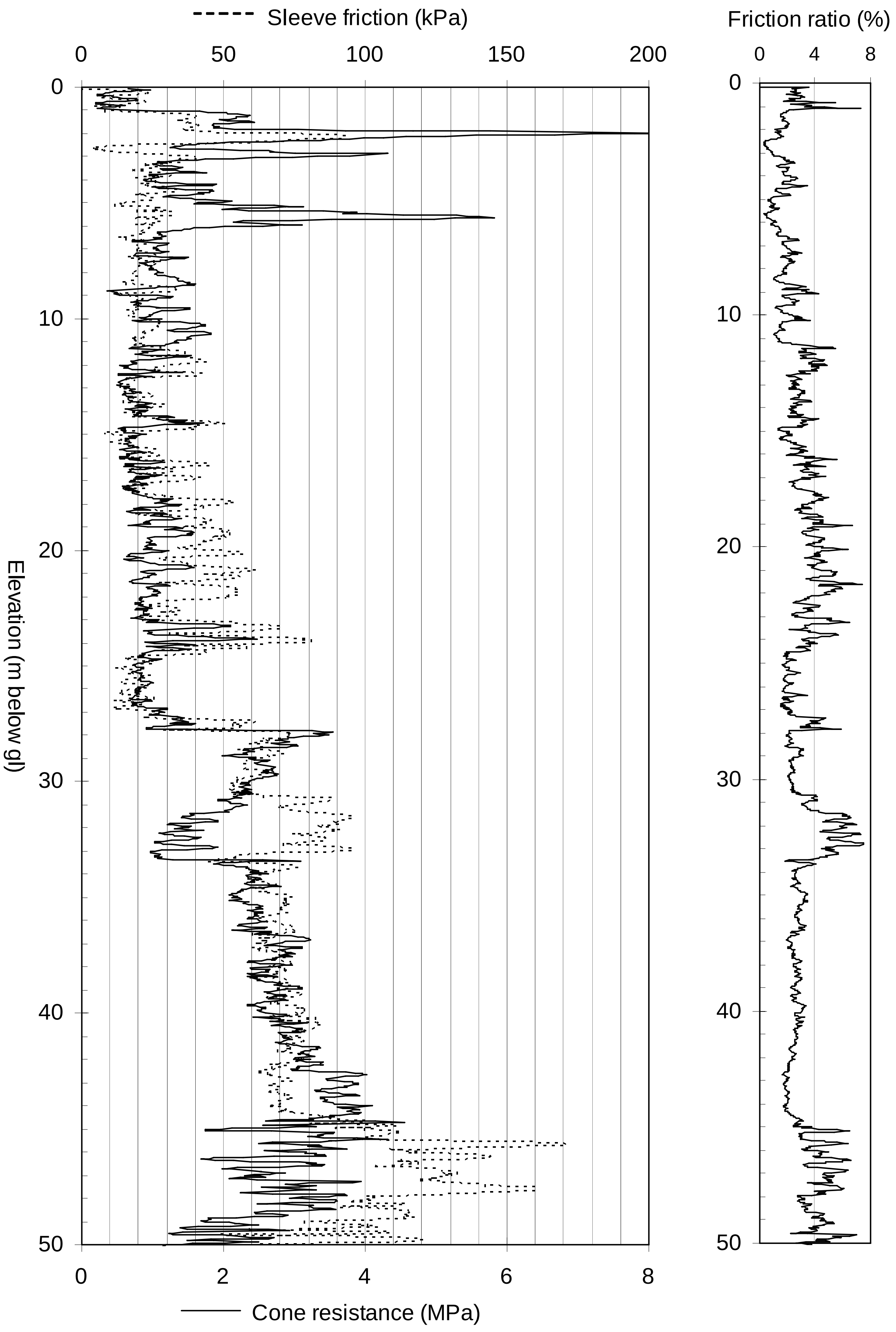


Figure 4: Data obtained from CPT6C

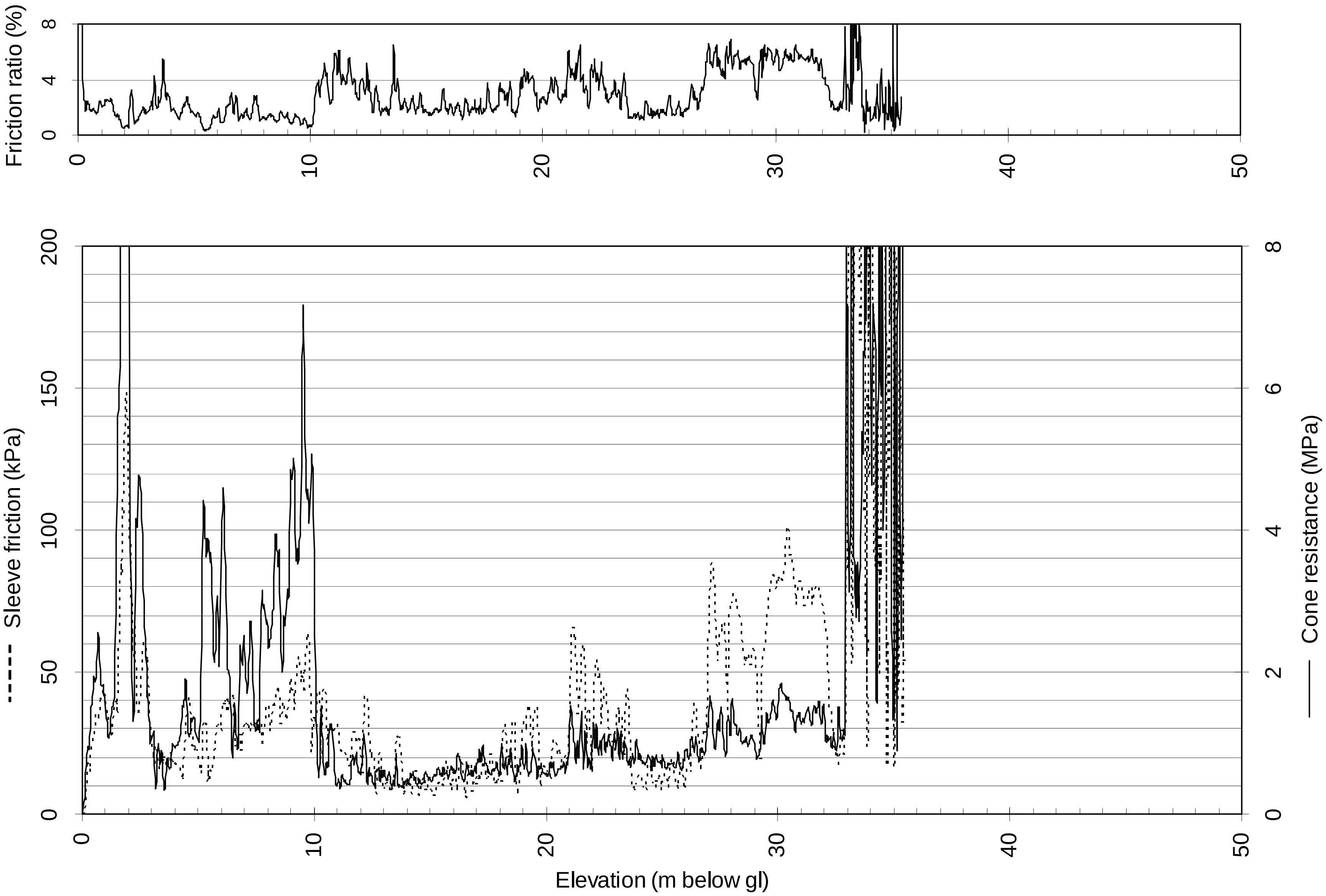
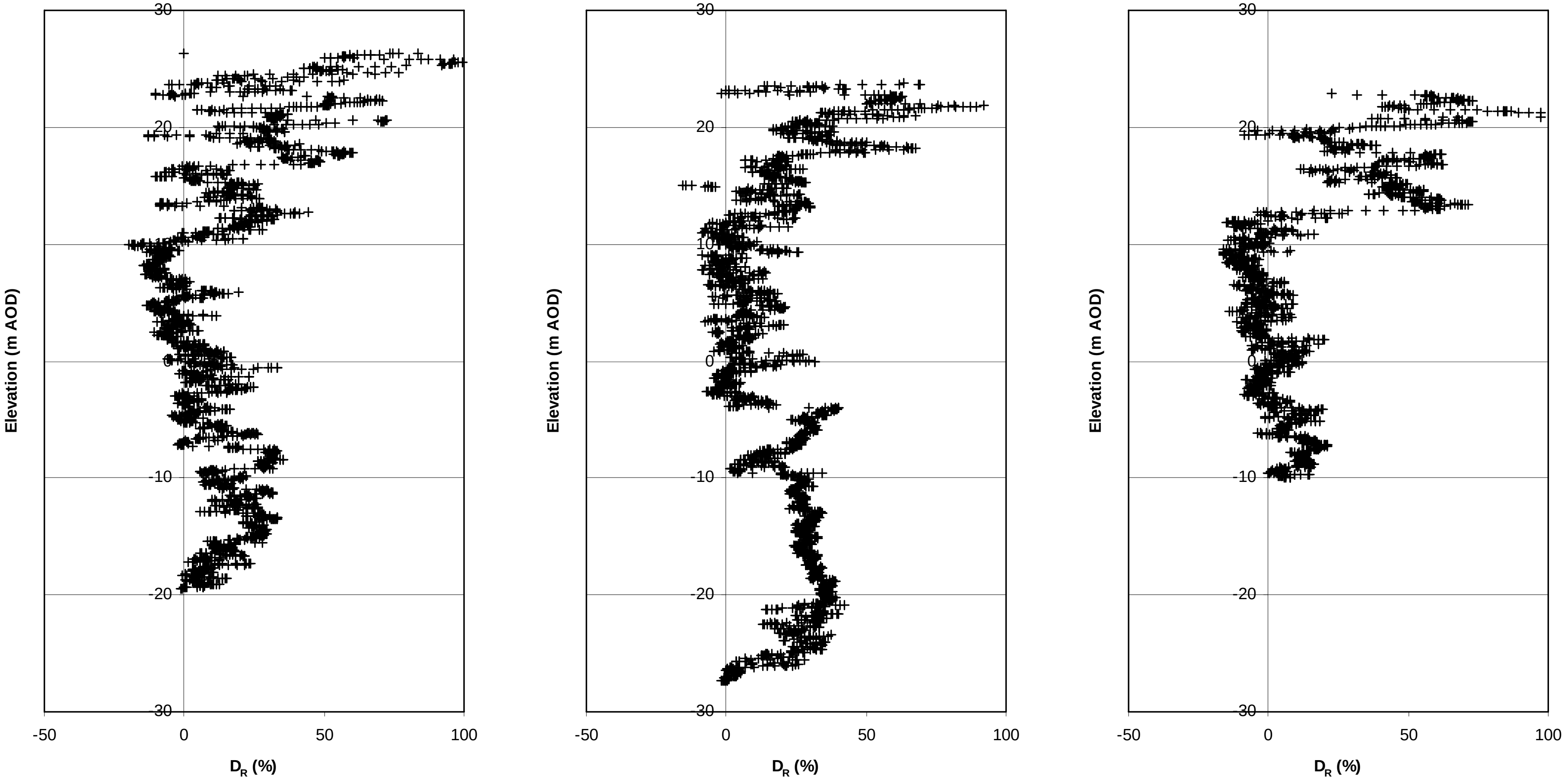


Figure 5: Data obtained from CPT7C

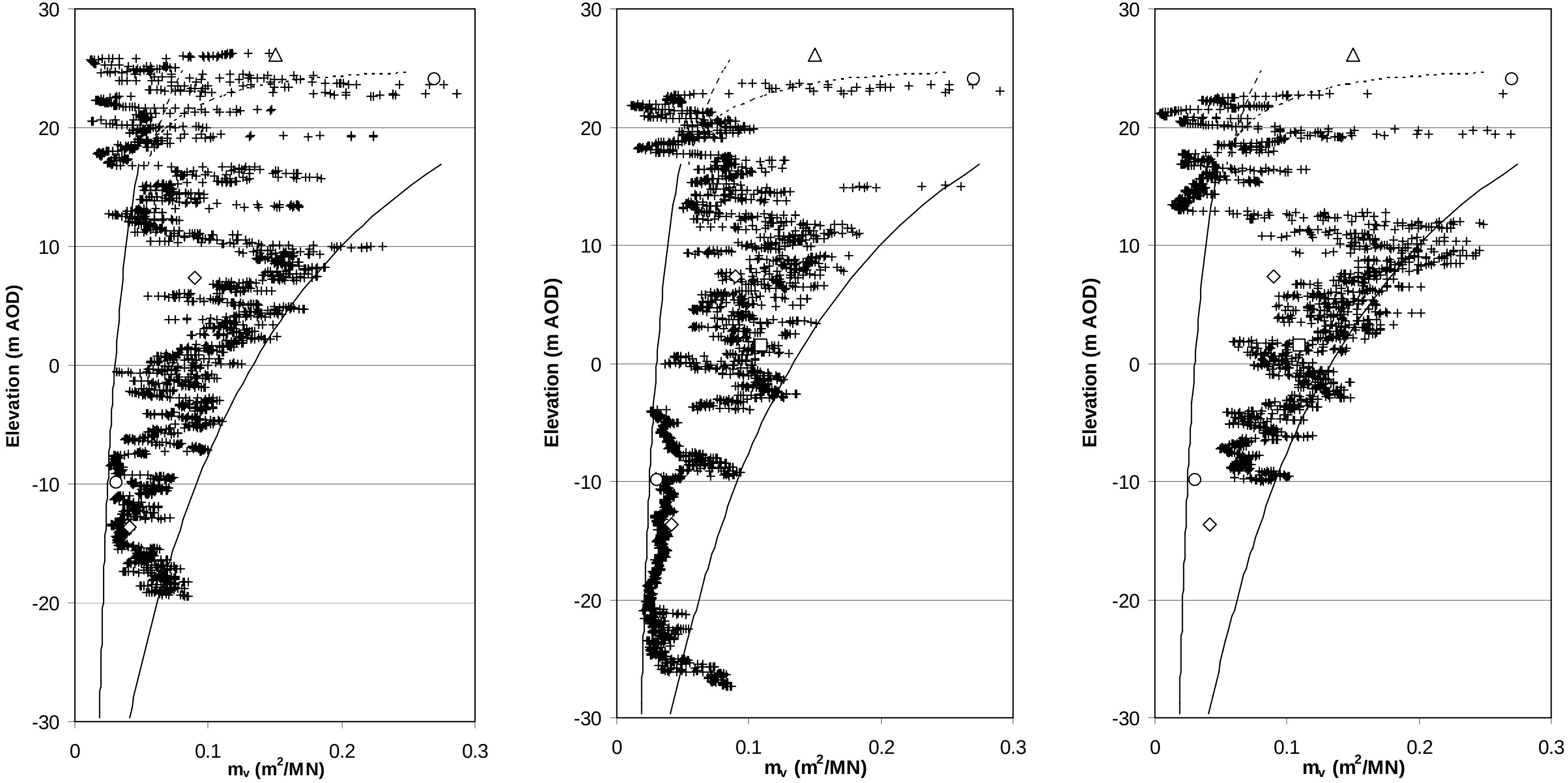


(a) CPT4C

(b) CPT6C

(c) CPT7C

Figure 6: Relative density profiles determined from (a) CPT4C, (b) CPT6C, and (c) CPT7C.



(a) CPT4C

(b) CPT6C

(c) CPT7C

Figure 10: Volume compressibility, m_v, determined from (a) CPT4C, (b) CPT6C, and (c) CPT7C using α=11 (trend lines are defined in Figure 9).