Application of CPT to investigation of abandoned shallow coal workings, and their remediation by grouting

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ABSTRACT: CPT testing was carried out before and after the grouting of abandoned shallow coal mine workings to understand the conditions of the workings and to infer the extent of underground voids that were filled with grout during their remediation. The site, with 2-3m of coal extracted by bord and pillar workings from between 10 and 13m depth, has a recorded history of widespread surface subsidence and ongoing potholing over the more than 100 year period since mining ceased. Prior to grouting, from 3 CPTs and three drilled boreholes, there was no evidence of open voids, indicating that collapse of the workings was extensive. The CPT was found to be a poor differentiator of subsurface conditions in this instance, failing to clearly differentiate intact roof from subsided roof, or between subsided roof and goaf. Despite the phreatic surface lying only 4-6m below the surface, pore water pressure data was inconsistent, fluctuating unpredictably between positive and negative values. Generally, negative pore pressures were recorded at depths corresponding to the subsided roof and worked interval, probably due to the CPT causing splitting of the more brittle residual clays/extremely weathered siltstone which comprised the roof. The grout, with a target strength of ~1MPa, was difficult to discern in the CPT profiles, and in one interval where prior drilling had encountered a free-standing void, it was barely distinguishable from the roof material. The presence of intruded grout, was not clearly evident in most locations, however, this was consistent with the relatively low grout take recorded during the site remediation.

Keywords: subsidence, void, CPTu, coal mining, grouting

1. Introduction

Subsidence of shallow abandoned mine workings is a common cause of damage to housing in Newcastle, New South Wales due to extensive areas that are underlain by shallow abandoned mines, worked using bord and pillar methods. (Johnston et. al. 2019).

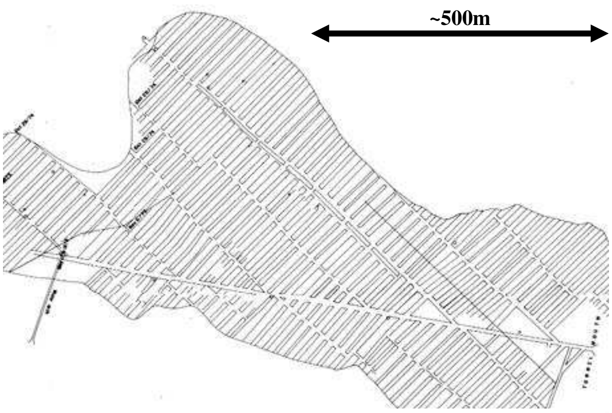


Figure 1. Typical layout of Welsh bord and pillar mine workings from the 19th century in Newcastle, Australia.

Shallow mine subsidence, as opposed to subsidence impacts from deep mining, is generally defined as surface movement due to the collapse or ongoing settlement of mine workings under 30m depth (e.g. Piggott and Eynon (1978)). Subsidence occurring over shallow abandoned mine workings is typically controlled by a roof collapse mechanism in which a progressive roof failure continues through the overburden and progresses to surface level. However, in areas that have been subject to secondary workings or pillar extraction, ongoing consolidation of the shallow mine goaf may present a significantly higher risk to infrastructure and housing than traditional pothole type subsidence events, particularly if affected by adverse surface and groundwater.

Figure 2.Typical surface expression of pothole subsidence of shallow mine workings, and filling with concrete.

A common way of remediating sites affected by shallow mine subsidence is to emplace under pressure a flyash/cement grout mixture directly into the mine workings from the surface to limit any further collapse or consolidation of the rubble. The flyash used is derived from coal-fired power generation, and the target strength of the grout produced is between 1 and 4 MPa, usually closer to 1MPa.

Grouting is typically achieved by drilling a grid of closely spaced boreholes (4-5m) to below the level of the mine workings and pumping grout into the workings at floor level via a tremie line. Verification is usually done by drilling randomly-selected verification boreholes to assess the effectiveness of the remediation program. An idealized section, showing a site remediated via grouting of shallow collapsed mine workings is shown in Figure 3.

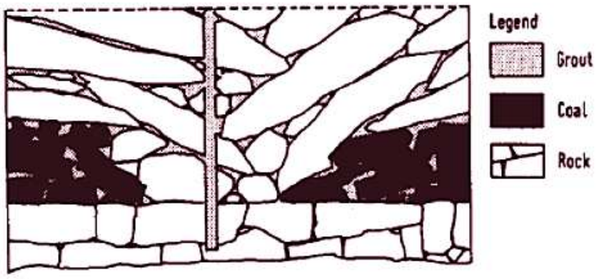


Figure 3. Idealised section of grouted zone in collapsed workings (Healy and Head (1988), after Littlejohn (1979)).

1.1. Mining and Site History

The site considered in this paper lies within the Lambton Subgroup of the Upper Permian Newcastle Coal Measures. Mine workings beneath the site were completed during the mid-19th century in the Borehole Coal Seam, at a depth which was recorded as being 7ft 10.5in (approximately 2.35m) thick beneath the site, with an unrecorded working (mined) section, probably between 1.8 and 2.1m. At this site, the seam occurs approximately between 10 and 13.5m below the surface, although due to a slight surface level fall to the south, the depth to the top of seam/workings varies from 10 to 10.5m across the site.

The immediate roof of the mine is made up of extremely weathered siltstone and claystone rock types of the Tighes Hill Formation (Hawley and Brunton, 1995), although at this site, only 3-4m of very low strength rock is present, and the upper 6-8m of the profile comprises stiff alluvial clays. The immediate floor of the Borehole Seam is the stronger Waratah Sandstone, however mines in the area typically left a small thickness (~300mm) of intact coal (referred to as "*bottoms*") on the floor. The ground profile for the site, as recorded in a logged borehole, is shown in Figure 4.

The mine located beneath the site was recorded as a regularly laid out Welsh bord style mine, typical of the mid to late 1800s mines found in Newcastle, as was shown in Figure 1. The mine was worked on three separate occasions prior to 1900 and although three sets of record tracings of the layout of workings were produced for the area beneath the site, the outline of workings is incomplete and ambiguous. It is likely that mining was so extensive beneath the site that it destabilized the overlying ground to the point of collapse, and this is consistent with physical investigations of the site which revealed that significant undocumented mining had occurred and that almost no coal was left.

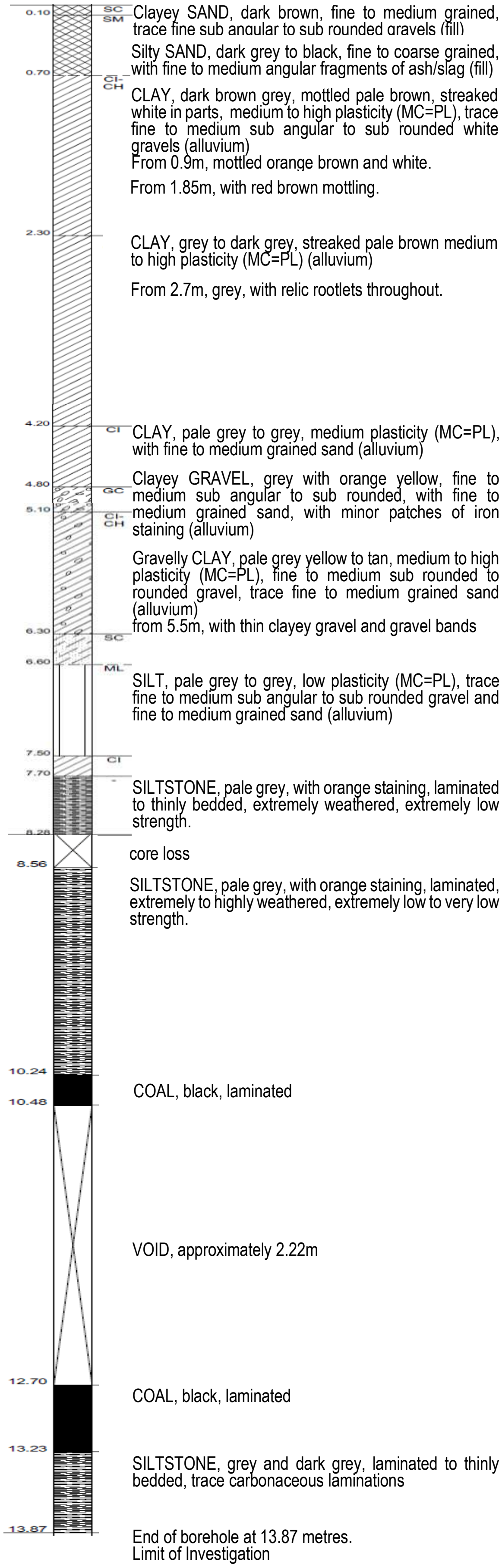


Figure 4. Typical ground profile (BH1) from the site, which recorded standing workings (free-standing void) in the seam. (after GHD, 2017)

Sometime after mining occurred, a single-storey timber-framed weatherboard cottage was constructed on the site, founded on shallow isolated piers, spaced at between 1.5 and 2m. Accessible records of the site are available from 1961 onwards, and these document a number of subsidence events from 1963 to 1980 that severely impacted the property. Subsequent events from 1980, to 2018 resulted in further damage. Figure 5 (top) shows the curvature evident when sighting along the western wall of the house (the centre is higher than the ends by more than 200mm). Figure 5 (bottom) shows the tilt in the garage (which was tilted by 150mm from side to side).

The nature of the ground movements and associated structural distress are more fully documented in Johnston and Fityus (2019).

Figure 5. Damage to structures on the site due to ground movements caused by subsidence.

1.2. Mine Remediation Program

In 2018, the site was the subject of geotechnical and structural assessments, which included the drilling of 3 cored boreholes (GHD, 2017). On the basis of the extent of the structural damage, and the evidence of extensive coal removal (intact coal was not encountered in any of the boreholes) the decision was taken to demolish the house and remediate the site via grouting of the mine workings. This was undertaken by drilling a series of 29 close-spaced auger boreholes (approximately 4 to 6 m apart arranged in a grid) to the base of the mine workings or to the top of any remnant pillars. The holes were then cased to the roof and a tremie line was run to the floor of the mine workings to pump grout until no more grout could be injected. The grout mixture selected was a standard bulk filling coal fly ash/cement mixture with a nominal grout strength of 1MPa @ 28 days and a variable flow cone of between 25 to 35 seconds.

Initially, all boreholes were filled via gravity to assess "grout take" and then once take was established all boreholes were sealed and pressure grouted. The final step of this process was only partially successful due to the tendency for grout to flow up around the outside of the casing, and push around the borehole plug at the surface , which was installed through the approximately 1m of fill materials on the block. Grouting was also impeded by the limited open voids that were present and could be filled, as indicated by drilling.

Verification of the remediation program was typically done by selecting random locations over the site, and drilling verification holes to identify if any remnant voids were present, with a general 1/5 ratio of verification to grouting boreholes.

1.3. Scope of this research

Given that the site was to be cleared and remediated, it provided an opportunity to deploy a CPT testing unit to investigate the potential of CPTu as a tool for characterizing shallow mine subsidence. Prior to grouting, 4 CPTu tests were performed to provide a baseline for the site in its un-remediated condition. Then, after grouting, the CPTu was once again deployed to whether the CPTu would be a useful tool in both investigation and verification of shallow mine grouting.

2. Details of the CPTu investigations

Two rounds of CPTu testing were completed at the site, with CPTu tests completed at 3 locations in the yard prior demolition of the house and grouting, and 11 completed post-grouting. This was done in order to see if the mechanisms of subsidence could be deduced from CPTu data, and whether differences in subsurface profile could be detected pre and post remediation. CPTu and borehole locations are shown in Figure 7, together with pre-grouting ground surface contours of the southern portion of the sitek.

Both the pre- and post-grouting CPTu tests were positioned in order to get a range of profiles of the site and to study the interpreted profiles pre and post grouting. In addition to the 3 paired CPT tests, two CPT tests were pushed at the locations of cored boreholes drilled prior to demolition of the house in order to borehole data and CPT data to be correlated.

In addition to the 14 CPTu tests and the 3 cored boreholes, a sample was taken with a 0.5m long push sampling tube via the CPT rod string in CPT2a. motivated by the ambiguous results from CPT2. The sampling tube recovered what is interpreted to be a sample of extremely weathered siltstone roof material together with a section of hardwood timber pit prop and weathered coal fragments shown in Figure 6. Due to the highly variable nature and poor spanning characteristics of the immediate overburden of the Borehole Coal Seam, mines in this area were known to heavily "timber" the roof, using hardwood props to provide standing support for the bords being mined. Commonly, this timbering was removed (if safe to do so) post mining, however in areas where secondary extraction (i.e. pillar removal) occurred, much of the timber used to support the roof had to be left in place.

The layout of CPT tests is shown in Figure 7, relative to the position of the (former) house on the site. The positions of drilled site investigation boreholes (including BH1; see Figure 4) are also shown.

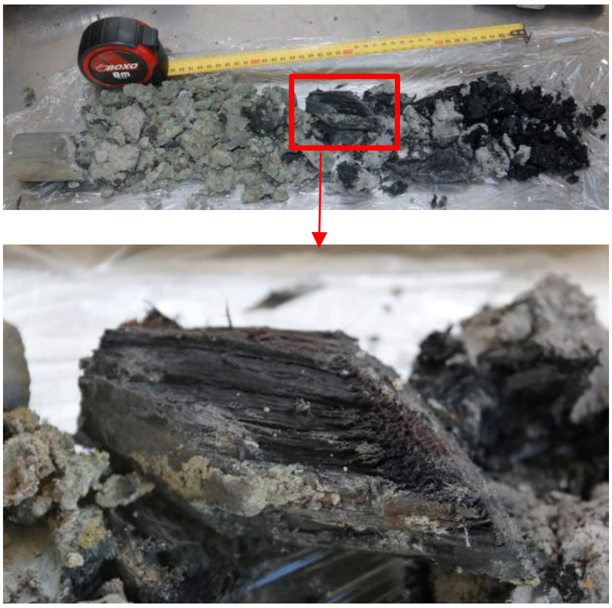


Figure 6. CPT sample pushed at the level of the mine roof at CPT2a: 500mm of recovered material with EW siltstone to the left and coal fragments to the right (top); enlargement of hardwood timber fragment push-cored by the sampling tube (bottom).

3. Assessment of the CPTu results

In general, the CPTu results confirmed that the site subsurface profile was generally made up of approximately 0.5 to 1.0m of fill; overlying a soft to firm alluvial clay to approximately 4.5m with an intermittent gravel band at the base between 4.5 and 6m; overlying very stiff clay (the extremely weathered siltstone) down to 10m. Where the CPTs did not refuse at this level, the next 3m produced erratic and irregular responses (considered likely to represent goafed mine workings) that will be discussed in further detail below. Refusal occurred at depths between 10 and 14m across the site. Of the 10 different CPTu test locations, 8 reached a level of 12-14m, consistent with the depth of the floor of the mine workings, whilst 2 refused at approximately 10m depth; consistent with the top of the coal seam. These two are interpreted to have refused on intact coal pillars.

The soil types listed above and interpreted from the CPT tests are consistent with the materials expected from the borehole profile of Figure 4.

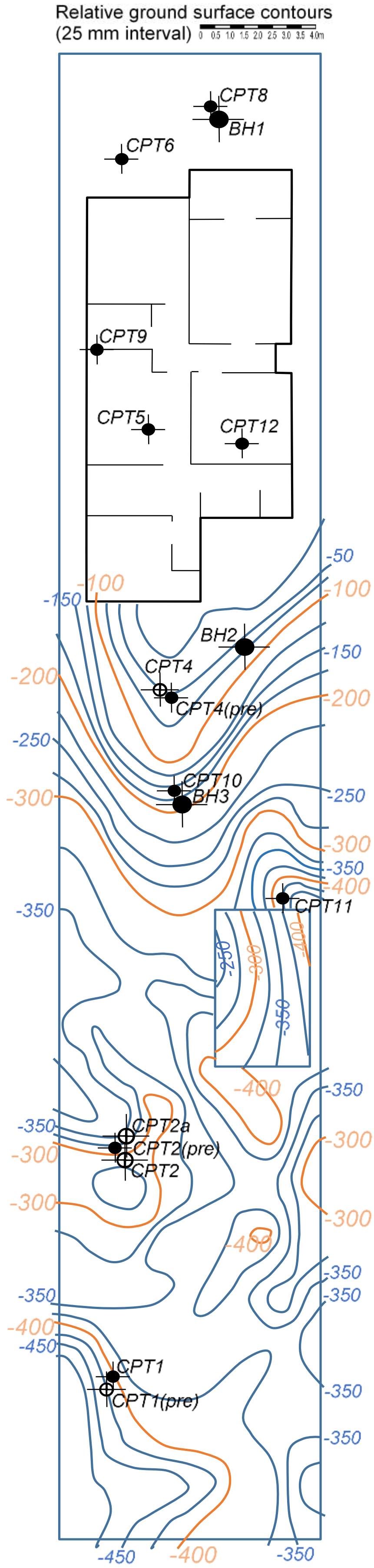


Figure 7. Site map showing the location of the house (prior to demolition) and the test locations. The contours show relative ground surface levels (in mm) prior to the site being regraded.

3.1. Information from tip resistance

A selection of tip resistance plots is presented in Figure 8. Tip resistance was only moderately useful to differentiated units in the subsurface profile. The fill layer at the surface was generally evident as a stiffer material with values between 4 and 7 MPa, reflecting some degree of surface compaction by site activity.

Below this, the alluvial clays generally displayed a consistent increase in stiffness with depth with few stiffer peaks. The gravel layer was only strongly evident in about half of the CPTs, and its tip resistance signature varied greatly both in terms of magnitude and position.

The interval between the gravel layer (~6.6m) and the top of seam (~10m) resembled the stiff clay above, except it was slightly stiffer, more erratic and did not exhibit the same consistent increase in strength with depth. For example, in CPT11, where the gravel layer was not present, the demarcation between the alluvial clay and underlying EW siltstone (~6m) is not at all distinct. Also as an example, in CPT8, despite a weakly developed gravel layer, the alluvial clay and underlying EW siltstone have essentially the same tip resistance signature.

The interval corresponding to the seam/workings is perhaps the most erratic, becoming more so approaching the base of seam/floor. This will be discussed further below.

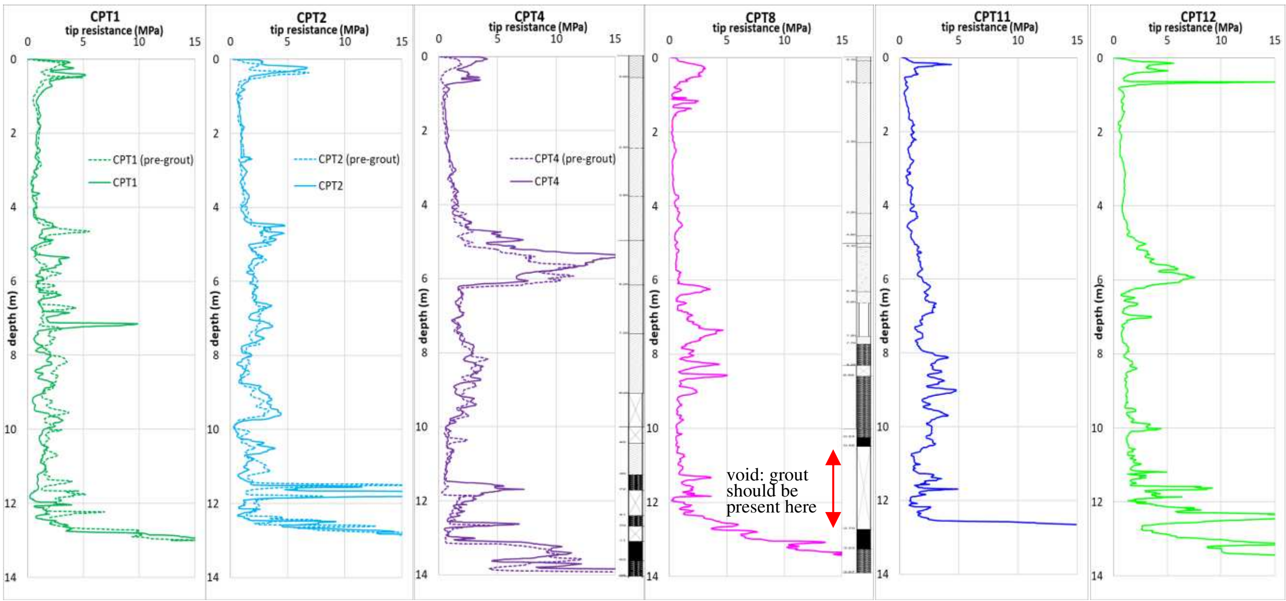


Figure 8. Individual tip resistance plots for selected CPT test locations.

Figure 9 shows the specific intervals corresponding to the units identified in the borehole log of Figure 4. Figure 9a) compares the tip resistance profiles of the alluvial clays, which actually vary in average strength from around 300kPa (CPT8) to about 1MPa (CPTs 2 and 11), or, from soft to stiff. CPTs 2 and 5 seem to contain thin, stiffer lenses between 2.5 and 3.5m.

Figure 9b) compares the tip resistance profiles between 4m and 6.5m, which captures the gravel unit, where present. It is most well developed in CPT4 where it reaches a tip resistance of 15MPa, and less evident in CPTs 10 and 12.

Figure 9c) compares the interval from the base of the gravel to the top of the seam, and which contains the extremely weathered siltstone roof. The trends are variable, indicating that the roof material varies from a stiff to a hard clay. The only anomaly is the significant spike in CPT1 which possibly corresponds to an ironstone nodule, which are often found in the local siltstones of the area.

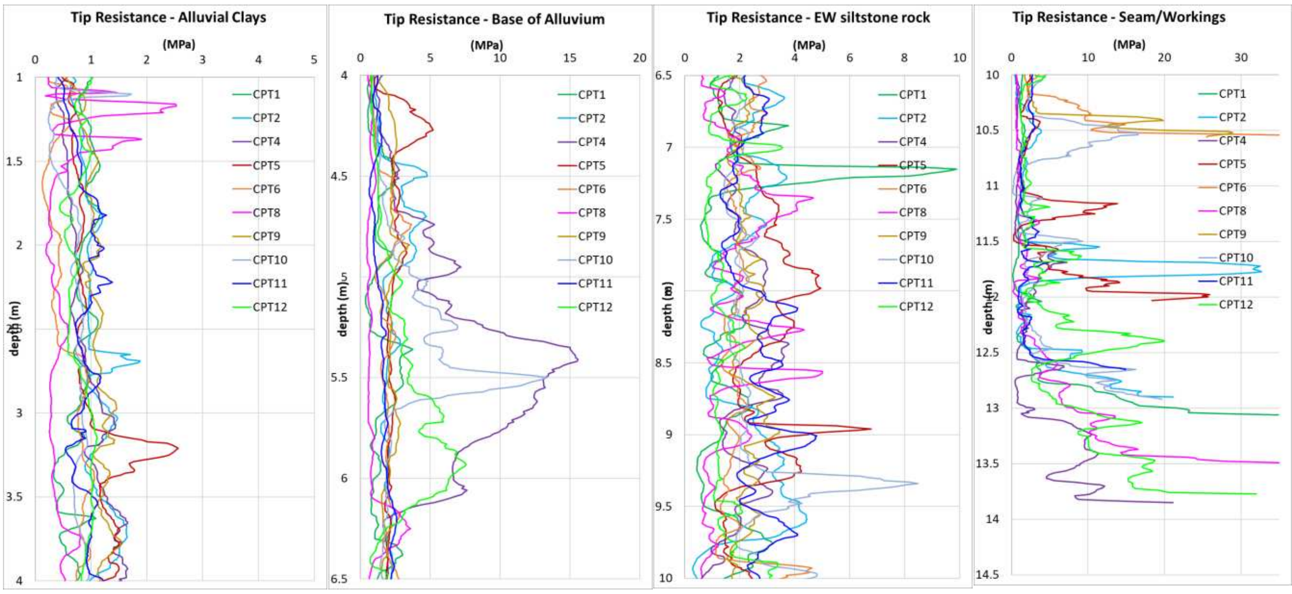
Figure 9d) is perhaps the most interesting interval as it corresponds to the interval that would contain the seam, or voids, or goaf (collapsed material). Overall, the interval is characterized by significant peaks at various levels throughout the extracted height of the mine, dropping back to values of greatly lower, and highly variable strength. Significantly, despite several profiles showing very low strength soils in this unit, no intervals with zero tip resistance were encountered at any of the locations tested. Whilst this may be expected in profiles post grouting, if all voids were filled with grout, it also applies to the three pre-grouting CPT profiles in Figure 8 (CPTs 1, 2 and 4). The effectiveness of the CPT tests to identify the presence of grout is considered further later in the paper.

Generally the floor is characterized by increasingly stronger peaks within the last metre of the profile.

3.2. Information from sleeve resistance

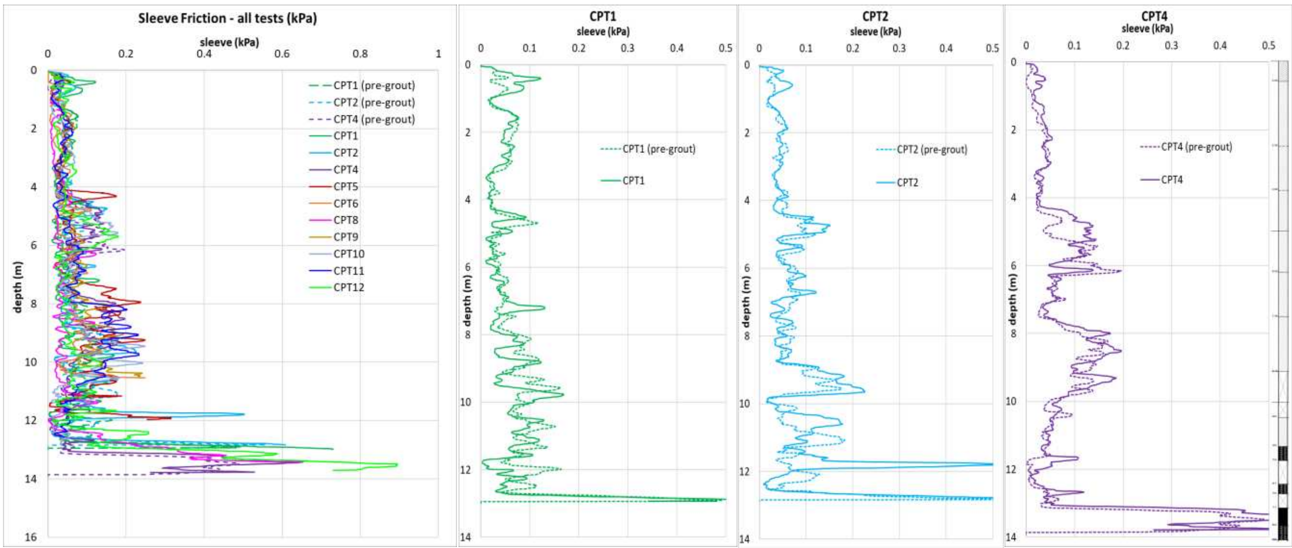
Sleeve resisistance profiles are shown in Figure 10. Figure 10a) compares the sleeve resistance for all CPT tests. The sleeve signatures of each unit have similarly limited value as the tip resistance signatures previously discussed. Perhaps the only significant difference lies in the signature of the EW siltstome interval, which for the tip resistances more resembled that of the alluvial clay interval, but for the sleeve resistances more resembles that of the gravel.

Figures 10b)-10d) compare the CPTs for the site in its pre grouted and grouted condition. As for the tip resistance data, there were no discerbable differences in the sleeve resistance due to grouting.



a) b) c) d)

Figure 9. Tip resistance plots for identified subsurface units.



a) b) c) d)

Figure 10. Sleeve friction plots for : a) all tests and, b) – d) paired pre and post grouting tests.

3.3. Information from the Friction ratio

Friction ratio profiles are shown in Figure 11. Figure 11a) compares the friction ratios for all CPT tests completed acoss the site. As can be seen from Figure 11a), the 4 identified units can be generally consistentlu inferred, however as with tip resistance and sleeve friciton, there was significant variation in individual profiles.

Figures 10b)-10d) compare the CPTs for the site in its pre grouted and grouted conditions. As for the tip resistance and sleeve friciton data, there were no discerbable differences in the friction ratio due to grouting, with relativly even amounts of positive and negative variations throughout each profile.

3.4. Information from the pore water pressure

The pore water pressure (PWP) results for each CPTu are displayed in Figure 12, together with paired tests or the profiles from closely located boreholes (if applicable). From Figure 12, it can be seen that the profiles of each CPTu test location vary significantly across the site, with inconsistent results, both pre and post grouting. Similar reoccurring features such as sudden drops in PWP and consistently negative pore water pressures are evident in all profiles, but at inconsistent locations. These anomalous drops in PWP and zones of negative PWP occur throughout the entire profile and are not limited to a single unit. CPT 11 recorded negative PWP values over almost its entire depth, whereas CPT 9 is predominantly

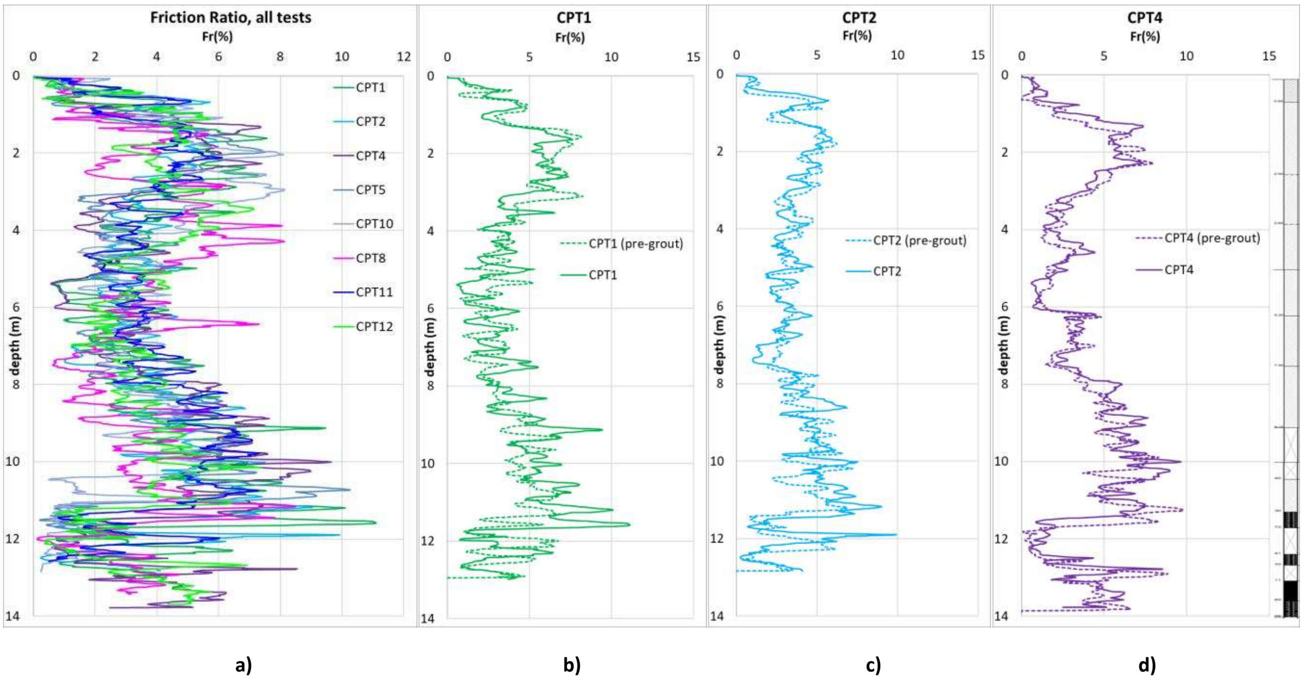


Figure 11. Friction ratio plots for : a) all tests and, b) – d) paired pre and post grouting tests.

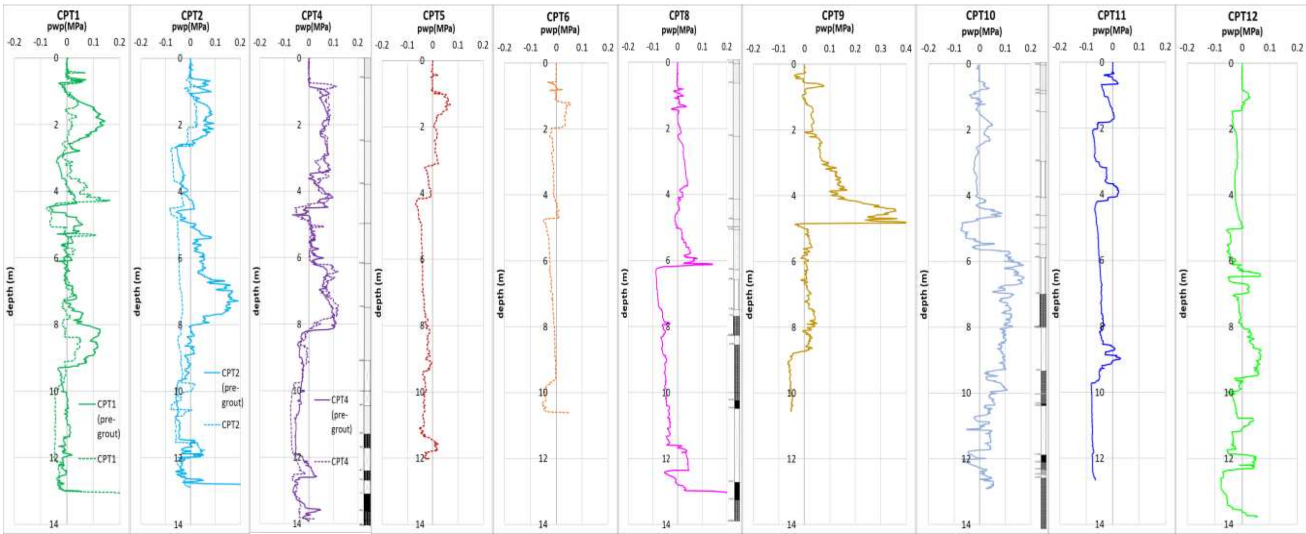


Figure 12. Pore water pressure results for paired CPTu tests, individual tests and CPTu/cored borehole paired tests.

positive; CPT4 is predominantly positive in its upper part, and negative below, whereas CPT 9 is inclined to be negative in its upper parts and positive below.

There are no obvious reasons for the sudden changes and localized anomalies, but it is suspected that it may be indicative of a highly disturbed groundwater profile at the site. The boreholes on this site recorded standing water at relatively consistent depths of 7-7.5m, however on an adjacent site, water levels beteem 5.5 and 9m have been noted. Further evidence of a highly disturbed groundwater profile at the site exists from notes on the drilling logs of the grouting contractor noting that in around boreholes across the site anomalously wet clay was identified.

The CPT holes were dipped within hours of testing and water levels between 6.5 and 8m were noted, however attempts to dip the CPT holes up to 2 weeks after they were pushed generally found standing water at around 1.6m at the southern end of the site (CPT1); >1.85m in the centre of the site (CPT3); but at only 0.85m m at the northern end (CPTs 5 and 6).

It should also be noted that despite the site's location lying within 200m of a large creek line that has since been concrete lined to serve as a stormwater canal, other sites in the same coal seam within a 0.5km radius have identified dry mine workings at 15m below surface level.

Overall, the PWP results, despite showing a highly anomalous groundwater table at the site, were not useful in understanding the physical characteristics or mechanisms of the subsidence that had occurred.

4. Discussion

This case study provides an example of the use of CPTs to investigate mechanisms of mine subsidence on a residential block. Whilst the CPTu profiles were generally able to provide information to define much of the subsurface profile at the site, its utility with respect to assessing subsidence was disappointing and results obtained were highly inconsistent.

The CPTu was found to be a good tool in defining the subsurface units present at the site, however it was unable to define or determine many of the characteristics of the former mine workings once seam level was reached. The CPTu interval corresponding to the goafed mine workings not easily defined, most likely due to mixed rubble/debris at mine level being formed from relatively soft, extremely weathered (EW siltstone) rock, together with possible partial/full convergence of the mine roof to the mine floor.

Additionally, the CPT was found to be a poor instrument in determining grouting effectiveness at this site. The only profile highly likely to contain grout was CPT8 (shown in Figure 8), and the expected grouted interval was found to have a similar profile to the alluvial clay unit encountered nearer to the surface, over most of its thickness. The difficulty in confidently distinguishing grout on the post-grouting CPTu profiles was not helped by the low grout volumes that were recorded as being pumped underground at the site: in most locations, less than a cubic metre of grout could be injected, so widespread lenses/bodies of grout cannot be expected. This is a further indicator of likely significant convergence of the mine roof and mine floor over the majority of the site.

It 1s noted that the applicability of the CPT for investigating other sites subject to shallow mine subsidence may be limited, due to the relatively unique combination of deep alluvial profile and extremely weathered, low strength siltstone that makes up the immediate roof of the abandoned mine at this site. These conditions are not typical for many abandoned mines in Newcastle or in Australia in general, with shallow mines more often located in more hilly terrain (above any alluvial soils), where typically stronger roof units entirely comprising less weathered rock, afforded safer extraction of coal.

5. Conclusions

The assessment of abandoned mine workings is a considerable challenge in Newcastle, given the long time since mining and the relatively dubious nature of record tracings that are relied upon for assessment (Johnston et al. 2018b). In this case, a CPTu testing regime was completed in conjunction with a more traditional borehole investigation to assess whether the CPT could prove to be a useful tool in assessing various characteristics of the old mine workings and the nature of mine subsidence.

Whilst some information was able to be used to better define the general subsurface profile of the site, the CPT was shown to not be a particularly useful tool in distinguishing any real characteristics of the mine workings themselves, with tip and sleeve resistance, friction ratio and pore water pressure all showing highly inconsistent profiles once mine level was reached. The CPTs did not identify voids (defying expectation) and the CPT signature for the injected grout was not reliably distinguishable from that of other units in the profile.

Given the particular site conditions needed to make this work possible, the applicability of the CPTu as a tool in the assessment of mine subsidence is limited.

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