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CPT investigation of mining-induced fissures and implications in respect to built development, Staffordshire, UK

Enquête du CPT sur les fissures induites par l'exploitation minière et les implications en ce qui concerne le développement bâti, Staffordshire, UK

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ABSTRACT: Fissures are cracks or openings in rock formations resulting from ground movements associated with underground coal mining. Within the Cannock area of the Staffordshire Coalfield, there are numerous records of fissures within the sandstone formations of the Triassic Sherwood Sandstone Group overlying deep mined Coal Measures strata. The mining-induced fissures, which can extend for hundreds of metres and to considerable depths, present risks to existing property and future development in respect of surface subsidence and structural damage, many instances of which have occurred in the Cannock area. Within the Pye Green area of Cannock, the general location of mining-induced fissures has been identified by geophysical survey in respect to a proposed school development. The precise location of the fissures has not been identified by traditional ground investigation techniques, due primarily to the presence of several metres of granular soils immediately beneath ground surface. Cone Penetration Testing (CPT) has been successfully utilised to investigate the location and extent of the fissures in accordance with the International Standard for Cone and Piezocone Penetration Test. The results of the investigation are presented to define the extent of the fissures, which can be used to inform engineering design of the school buildings with greater certainty.

RÉSUMÉ: Résumé en Les fissures sont des fissures ou des ouvertures dans les formations rocheuses résultant des mouvements du sol associés à l'extraction souterraine du charbon. Dans la région du bassin houiller de Cannock du Staffordshire, on trouve de nombreuses traces de fissures dans les formations de grès du « Groupe Triassic Sherwood Sandstone » recouvrant des couches de mines de charbon profondément exploitées. Les fissures induites par l'exploitation minière, qui peuvent s'étendre sur des centaines de mètres et à des profondeurs considérables, présentent des risques pour les propriétés existantes et les développements futurs en ce qui concerne l'affaissement de la surface et les dommages structurels, dont de nombreux cas se sont produits dans la région de Cannock. Dans la région de « Pye Green » de Cannock, l'emplacement général des fissures causées par l'exploitation minière a été identifié par une étude géophysique dans le cadre du projet de développement d'une école. Les techniques traditionnelles d'investigation au sol ne permettent pas de déterminer avec précision l'emplacement des fissures, principalement à cause de la présence de plusieurs mètres de sols granulaires immédiatement sous la surface du sol.Le test de pénétration au cône (CPT) a été utilisé avec succès pour rechercher l'emplacement et l'étendue des fissures conformément au Standard international pour le test de pénétration au cône et au piézocone. Les résultats des investigations sont présentés pour définir l'ampleur des fissures, qui peuvent être utilisées pour éclairer la conception technique des bâtiments scolaires avec une plus grande certitude.

Keywords: Mining-induced fissure; Cone Penetration Test; CPT; Site Investigation

1 INTRODUCTION

The site is located some 3 km north of Cannock within the South Staffordshire Coalfield of the United Kingdom. The presence of mining related fissures within the coalfield is well documented, which have been responsible for structural damage at a number of locations, including a school, a residential property and a church. Figure 1 (below) shows the location of the site and the distribution of recorded fissures within the region of the site.

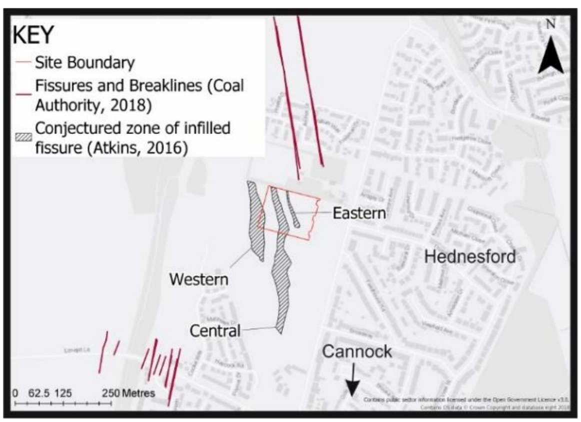

Figure 1. Site location plan showing fissures identified by previous investigations (Atkins, 2016) and The Coal Authority (Coal Authority, 2018)

The site, which is proposed for the construction of a new school, has been subject to a number of previous investigations, including surface geophysics and conventional ground investigation, which identified fissures related to deep mining in broad terms only.

The recorded presence of fissures within the site area present a risk of surface subsidence and, potentially, structural damage to future development.

This paper summarises the background of the hazards that fissures present, the Cone Penetration Testing (CPT) method used to investigate the fissures, implications in respect to future built development and an assessment of the results.

The results and assessment of the CPT investigation referred to below, are contained within Wardell Armstrong's report prepared for Entrust Property Services (Wardell Armstrong, 2018).

2 BACKGROUND

2.1 Geology

The site is recorded to be underlain by the Chester Formation (formerly referred to as the Kidderminster Formation) of the Triassic Sherwood Sandstone Group, characterised by conglomeritic beds including "pebbles" of quartzite. The Etruria Formation and Pennine Middle Coal Measures Formation are recorded to underlie the site at depth. Ground investigations undertaken at the site have confirmed the presence of thick deposits of sand and gravel from the weathering of Chester Formation strata.

2.2 Coal mining

Historical deep coal mining has been undertaken beneath the site associated with 9 seams of coal, the last date of working being 1954. Ground movement associated with the deep mining should have ceased. There does exist, however, the potential for ground movement associated with mining-induced fissures, which are considered to occur from tensile stresses produced from deep mining subsidence resulting in the opening of existing discontinuities in overlying Triassic rock strata (e.g. joint sets).

Mining-induced fissures have been observed to reach up to about 1m in width and several hundred metres in length (Donnelly, 2006; Donnelly and Rees, 2001) extending to considerable depths. Where superficial deposits overlying fissures are granular and permeable, surface water and/or groundwater can wash the granular deposits into open fissures causing surface subsidence. Weathering can weaken the sides of fissures producing a "spalled zone" towards surface, with the fissures reducing in width with depth. Figure 2 shows an example of an open fissure which has been exposed by excavation.

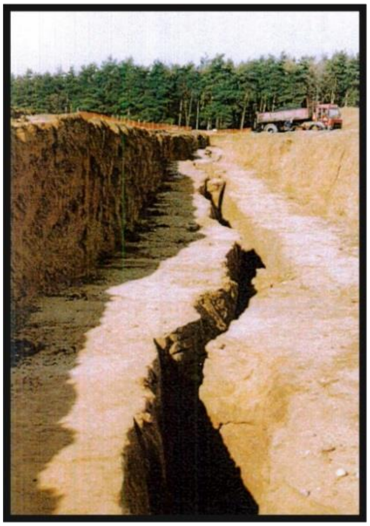

Figure 2. Photograph of an exposed open fissure within Permo-Triassic sandstone, Nottinghamshire Coalfield (Coal Authority, unknown)

2.3 *Site investigation*

A range of investigation techniques have previously been applied in respect to locating mining-induced fissures including surface geophysics, seismic refraction, trial trenching, dyanamic probing and remote sensing (InSAR, aerial imagery and Lidar). Mining-induced fissures are typically present in brittle sedimentary rocks, often masked by a mantle of weathered material which provides a challenge for typical site investigation to locate the precise position of the fissures.

Geophysical surveys have been undertaken at the site in 2011 and 2013 to investigate the location of the fissures employing magnetic gradiometry, resistivity and ground probing radar survey techniques. The results of the surveys recorded 3 main linear features (Figure 1), which have subsequently been defined as the Western, Central and Eastern Fissure respectively (Atkins, 2016). The maximum widths of the broadly defined fissures (conjectured zone of infilled fissures) are recorded to be c.34m, c.18m and c.14m in respect of the Western, Eastern and Southern Fissures (Atkins, 2016).

Subsequent trial trenching in 2013 to investigate the nature of the ground conditions across the width of the infilled fissures, confirmed the presence of made ground overlying the fissures ranging in thickness up to 4.0m, 2.5m and 1.05m within the Western, Central and Eastern Fissures respectively (Atkins, 2016). The made ground includes ash, brick, sand, gravel, metal, ceramics and tyres and has clearly been imported to infill the fissures associated with past ground subsidence. No evidence of the location of the fissures, such as voided or broken ground, was identified by the trial trenching (Atkins, 2016).

Remedial works were undertaken in 2016 to produce development platforms for the new school, including ground treatment of the infilled mining fissures by excavation, re-compaction and placement of a geogrid across the conjectured extent of the fissures to mitigate future ground settlement. During the remedial works direct evidence for the presence of fissures was not recorded, with the exception of a localised ground collapse, which highlighted the hazardous nature of the fissures (Atkins, 2017).

3 CONE PENETRATION TESTING

3.1 Methodology

None of the previous investigations had identified the location of the fissures with any degree of accuracy. A specialist ground investigation method was therefore required to define the actual location and geometry of the fissures to inform construction design of the new school buildings.

CPT was chosen as the preferred method of investigation, which defines the geotechnical engineering properties of soils by pushing an instrumented probe at the end of a series of steel rods into the ground at a controlled rate (2cm/second +/- 10%), and by of measuring the "cone resistance" of the conical tip and friction produced from a friction sleeve, measured as "sleeve friction". All measurements are electronic. A pressure transducer is located immediately behind the cone to measure pore pressure at the U_2 position shown in Figure 3.

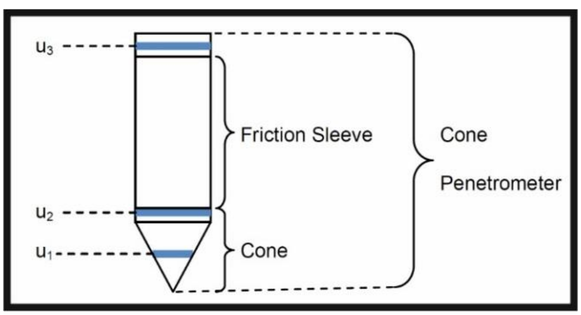

Figure 3. A simplified schematic of the cone tip and the pore pressure filter locations (In Situ Site Investigation, 2018)

The following parameters are obtained from the testing to determine the geotechnical nature of the soils, and to identify very soft or voided ground which may indicate the presence of a fissure.

- Cone resistance (measured as the total force acting on the cone, divided by the area of the cone) with results presented as MPa;
- Sleeve friction resistance measured as the total frictional force acting on the friction sleeve divided by its surface area with results presented in kPa;
- Pore pressure/pore water pressure; if the material is free draining, it will measure hydrostatic pressure, if not free draining, it will measure total pore pressure; and
- Inclination – determines the inclination of the tested depths from vertical.

The measured parameters are subsequently processed to produce soil behaviour type indices and material descriptions, in addition to derived N_{60} values, relative density, friction angle etc.

The rig utilised for the cone penetration testing is shown in Figure 4 below.

Figure 4. Photograph of the 15 tonne Morooka based tracked CPT rig undertaking the probehole fissure investigation

3.2 CPT test results

Eighty-five CPT probeholes, generally at a spacing of 0.3m to 0.5m (up to 1.0m), were probed along five sections (GL-A to GL-E) across the broadly defined Eastern Fissure, four within the vicinity of the proposed school building and the fifth within the proposed car park area.

The testing commenced outside of the fissure zone to determine the depth to rockhead, which was used as a "base-line" for the test results. Probing then progressed across the section lines and probeholes were taken to a depth of refusal or terminated at depth within a fissure. The probehole refusals were reported as "tip end resistance" and "inclination failures", the latter where probeholes had been deflected at an angle.

The "most probable" location of the fissure was determined primarily on the following parameters:

- Probehole refusal significantly deeper (e.g. between 12m and 16m depth) than the baseline rockhead depths; and
- Cone end resistance and sleeve friction resistance values are typically 0 to 4 MPa and 0 to 50 kPa respectively and derived material properties are characterised by the presence of extremely low to low strength clay and fine-grained soils, compared with typically higher strength mateials (e.g. cone resistance values of 10 to 20 MPa), outside the fissure zone.

Spalled zones are also conjectured to be present based on the following parameters:

- Probehole refusal significantly deeper than the baseline rockhead depth but shallower than within the adjacent fissure;
- Cone end resistance and sleeve friction resistance values are generally higher (e.g. 4 to 15 MPa and c.30 to > 100 kPa respectively) than within the conjectured fissures and lower compared to the baseline values; and
- Derived material properties include high strength fine grained materials and medium dense to dense granular materials, similar to outside of the fissure but do include very low strength to low strength fine grained materials.

The results of the assessment confirmed the presence of the Eastern Fissure along four section lines within the vicinity of the proposed school building, with a spalled zone indicated to be present on either side of the fissure. The width of the fissure is indicated to vary from c.0.6m to c.2.0m, with the spalled zone varying from c.0.2m to c.1.5m in width. The maximum width of the fissure and spalled zone is indicated to be c.4.0m. Probeholes within the fissure ranged in depth from c.8m to c.16m, with depths within the spalled zone varying from c.4m to c.7m. Outside the defined zone of the fissure, rockhead or dense/very dense soil was generally recorded at depths of c.2.5m to c.4.0m. Shell and auger boreholes drilled within the vicinity of the fissure reported rockhead depths of 3.8m to 4.1m, which accord with the rockhead depths generally indicated by the CPT. The material above rockhead within the shell and auger boreholes predominately comprised sand and gravel.

3.2.1 Section line GL-B

An example of the definition of the Eastern Fissure along line GL-B1 to 10 (01-10) is shown as Figures 5 and 6 below.

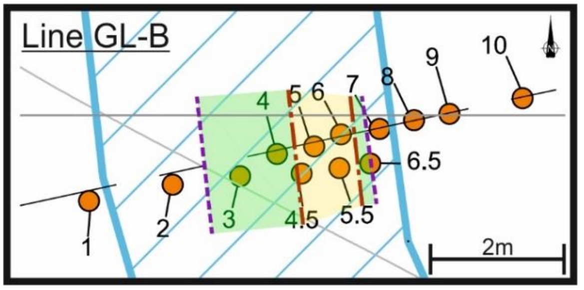

Figure 5. Section line GL-B showing broadly defined extent of infilled fissure prior to investigation (cross-hatch), conjectured extent of fissure (yellow), spalled zones (green) and probehole locations (Wardell Armstrong, 2018)

The depth of probeholes within the fissure vary from 12m to 16m, within the spalled zone from 3m to 5m depth and immediately outside the fissure probehole refusal depths were of the order of 3m. The fissure width is reasonably well defined at c.0.8m, indicated by a significant change in probehole depths. The materials within the fissure are characterised by the presence of extremely low strength fine grained soils and loose to very loose sands. Cone and sleeve friction resistance values reach almost zero within the fissure.

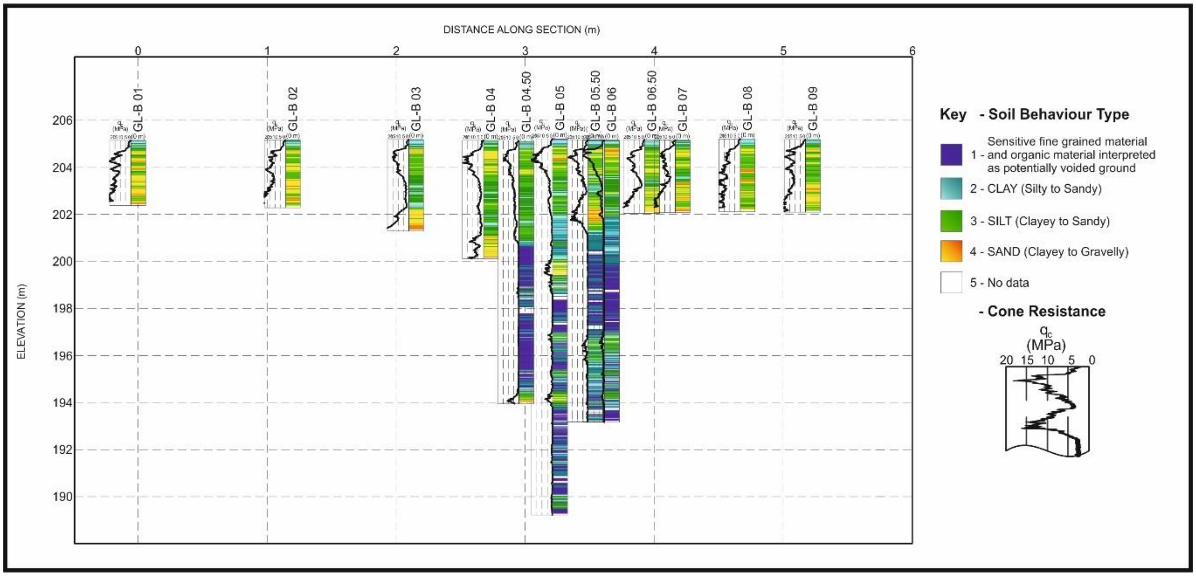

Figure 6. Cross section of line GL-B showing depth of probeholes, cone resistance values within and outside of the fissure and soil behaviour types. Produced by In Situ Site Investigation (In Situ Site Investigation, 2018) and edited by the authors

Illustrations of and cone resistance and sleeve friction responses to define the fissure along the section are shown as Figures 6 and 7 respectively. This comprises responses at test locations 02 (outside of fissure), 04 (within the spalled zone) and 06 (within the fissure).

Location 2 (outside the fissure) - High cone and sleeve friction resistance responses are recorded, with cone and sleeve friction resistance reaching 20 MPa and 500 kPa respectively. The material is reported as high strength silt and clay overlying dense to very dense sand and gravel, with probehole refusal at 2.9m.

Location 4 (within the spalled zone) - High cone and sleeve friction resistance responses are recorded at levels of up to c.20 MPa and 400 kPa respectively to c.1.6m depth, which is considered to represent engineered made ground. Below to a depth of c.4m the cone and sleeve resistance levels falls to c.2.5 MPa and c.27 kPa respectively, this material being defined as high strength to very high strength silt. Below the cone and sleeve resistance increases to c.14 MPa, and 300 kPa respectively, the material being defined as medium dense gravelly sand, with probehole refusal at 5.03m.

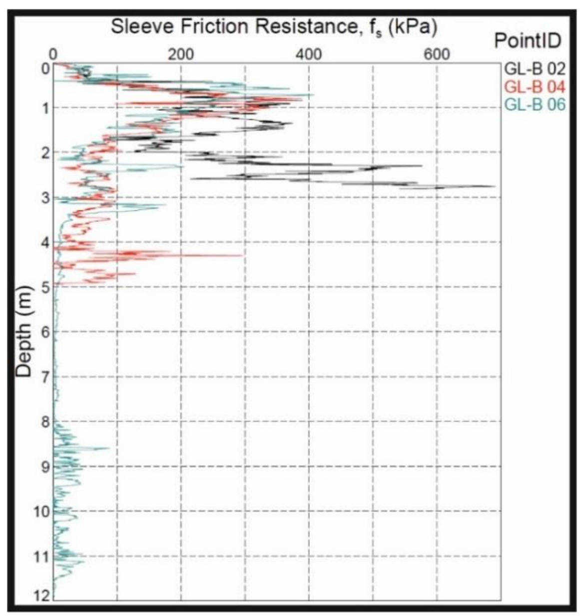

Figure 7. Examples of sleeve friction resistance responses within probeholes along section line GL-B, outside the fissure (02, black), within the spalled zone (04, red) and within the fissure (06, grey).

Location 6 (within the fissure) - High cone and sleeve friction resistance values are again recorded to c.1.6m depth (engineered made ground). Below to a depth of c.3.4m, the cone resistance falls to between c.2 and 6 MPa and the sleeve friction resistance to between c.9 and 216 kPa, the material being defined as high to very high strength silt. The materials to 8.2m comprise extremely low to very low strength fine grained soils, which are characterised by cone and sleeve friction resistance values close to zero, indicative of the presence of a fissure. Below the cone and sleeve friction resistance increases to c.5 MPa and c.109 kPa respectively (e.g. loose gravelly sand and extremely low strength soils) to refusal at 12.0m. It is considered that where the cone and sleeve resistance values are close to zero voided ground may be present rather than very low strength soils.

4 DISCUSSION

A number of techniques have been used within the industry to investigate the location of mining-induced fissures, including non-intrusive (e.g. geophysical) and intrusive (e.g. trial trenching) investigation. Non-intrusive techniques generally broadly define the location of fissures and intrusive techniques have been used to define the location of fissures with greater certanty. Intrusive techniques can, however, be constrained where fissures are present below several metres of weathered strata, as is the case at this site.

For detailed design of structures within the immediate vicinity of fissures, a high level of accuracy is required in respect to fissure location and a suitable method of investigation is necessary to determine the configuration of fissures within the vicinity of ground surface.

Geophysical survey and trial trenching at the site had not located the fissures with any degree of accuracy. CPT probing was utillised as a technically suitable and cost effective method of locating the fissures, with a large number probeholes being able to be drilled within a single day.

The definition of the Eastern Fissure by the CPT investigation has been affected by the relatively complex nature of the near surface ground conditions associated with the fissure, including the presence of made ground (engineered in part) infilling the fissures, weathered bedrock (sand and gravel) with apparent adjacent zones of spalling, and by a number of limiting factors associated with the test results. The limiting factors include the following, which were addressed when assessing the location and extent of the fissures:

- Tip end resistance termination on large cobbles or very dense sand and gravel, not necessarily indicating that competent rockhead had been reached;
- Inclination failure can occur by deflecting around cobbles to take the path of least resistance, therefore probeholes may have been able to progress further if deflection had not occured;
- CPT probeholes may not remain vertical for the entire drilled depth;
- A probe may deflect into a previously drilled probehole; and
- Insuffcent probeholes at some section locations to define the spalled zone precisely due to time constraints.

The CPT investigation and assessment has defined the location and extent of the Eastern Fissure to a level that can inform engineering design of the proposed school building. However, whilst the continuity of the Eastern Fissure between the investigated section lines has been confirmed, the precise details of the fissure location between the section lines has yet to be determined, as faulting is indicated to be present.

The engineering options for the school building include defining an appropriate safe stand-off to built development and foundation construction to bridge the defined fissure. Further investigation of the fissure may be required, however, for the detailed design of the school building.

There are health and safety issues in respect to fissures and the risks presented to current site users, personnel undertaking investgations and future site users. Robust risk assessments should be undertaken to address the risks with appropriate control and mitigation measures put in place.

5 CONCLUSION

Mining-induced fissures are recorded to be present within the site area, which are considered to present a risk to proposed built development. Previous investigations have defined 3 fissures within the site area in broad terms only.

The CPT investigation has defined the location and configuration of the Eastern Fissure more precisely than previous investigations. The main parameter used to confirm the location of the fissure was the depth of probehole refusal, along with the presence of very low strength materials.

The level of definition of the Eastern Fissure is considered suitable to inform engineering design of the proposed school building, with further investigation probably required to supplement the initial investigations.

It is considered that the CPT investigation has proved a successful technique in locating fissures in brittle strata overlying former mine workings, where a significant thickness of soil cover is present and, therefore, could have industry wide application.

6 ACKNOWLEDGMENTS

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