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The engineering mitigation of a water bearing fissure in the Chalk at the Tideway Deptford Church Street Shaft

Traitement par injection d'une fissure hydraulique dans la craie sur le chantier Tideway de Deptford Church Street

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ABSTRACT: The Thames Tideway Tunnel is a 25km long stormwater storage tunnel that will capture and transport untreated sewage that currently overflows into the River Thames in London, UK. Higher than expected pumping rates were observed during the pre-diaphragm wall constant rate test at Deptford Church Street site. If realised, the flow rates could not be safely managed during shaft construction. Borehole geophysics identified a steeply inclined north dipping fissure, suggesting cut off on the south side of the shaft but passing 40 metres below the design toe depth in the north. Drilling and pump testing of additional boreholes confirmed that almost all inflow was associated with a single fissure and projection of the plane between all three boreholes suggested it would intercept the base of the shaft. A targeted pressure grouting campaign was implemented, utilising the hydraulic connection between the three wells. Verification pump tests yielded lower groundwater flow rates of 2 l/s, suitable to enable the excavation of the shaft. Geological logging took place throughout the excavation of the Chalk and the rock was visually inspected to assess the effectiveness of the grouting campaign. The absence of significant water flow along the grouted fissure provided the confirmation that the risk of a significant water pathway had been suitably mitigated.

RÉSUMÉ : Le Thames Tideway Tunnel est un projet de tunnel de 25km de long qui permettra le captage et acheminement des eaux usées, actuellement déversées dans la Tamise lors de fortes pluies. Des débits de pompages plus élevés que prévus ont été observés pendant la phase de préparation du puits sur le chantier de Deptford Church Street. Si ces débits s'étaient avérés corrects, ils auraient pu représenter un danger durant la construction du puits. Les forages d'investigation géophysique ont permis d'identifier une faille profonde d'orientation nord, suggérant une intersection sur la partie sud du puits ainsi qu'à 40m sous la base du puits sur sa partie nord. Les forages et essais de pompage supplémentaires ont permis de confirmer que l'eau mesurée était acheminée à travers une faille unique et que sa projection dans le plan entre les trois forages d'investigation suggérait une intersection avec la base du puits. Une campagne d'injection de coulis sous pression a été mise en place, utilisant les connections hydrauliques entre les trois forages d'investigation. Les tests de pression effectués en aval des injections ont mesuré des débits d'eau inférieurs à 2l/s, satisfaisant pour l'excavation du puits. L'inspection géologique de la fouille s'est déroulée pendant l'excavation de la couche de craie ; la roche a été inspectée visuellement pour confirmer l'efficacité de la campagne d'injection. L'absence d'un débit important le long de la fissure injectée a ainsi apporté la preuve que le risque lié à la fissure a été réduit convenablement.

KEYWORDS: chalk, groundwater control, fissure, geophysics, pumping test

1 INTRODUCTION

The Thames Tideway Tunnel is a 25 km long stormwater storage tunnel that will capture and transport an estimated 39 million tonnes of untreated sewage that currently overflows into the River Thames each year (Alder and Appleton, 2017). Largely following the route of the River Thames, it extends from Acton in West London to Abbey Mills in the East, where at this point a connection is made to the existing Lee Tunnel, operational since 2015. The Tideway East section of the route extends from Chambers Wharf, Bermondsey and terminates at Abbey Mills Pumping Station. A smaller diameter connection tunnel also extends northwards towards Chambers Wharf from Greenwich Pumping Station. This paper focuses on elements of construction works at the Deptford Church Street, a shaft site which feeds into the Greenwich Connection Tunnel where investigations and mitigation measures were needed to control potentially high rates of groundwater inflow.

1.1 Geological setting of the Deptford Church Street Site

Based on site investigations, the Geology at the Deptford Site is typical of South East London, with superficial deposits (Made Ground, Alluvium, River Terrace Gravels and Thanet Sand Formation) overlying the Seaford Chalk Formation. The Bullhead beds, a dense, flint gravel layer at the base of the Thanet Sand separates the two. Ground investigations previously

undertaken by the Client at Deptford Church Street had identified areas of fracturing and some discontinuities, but largely assessed the chalk as CIRIA Grade A1. It is noted that the Greenwich fault zone, described by Mortimore et al (2011), lies approximately 500m southeast of the site (Figure 1).

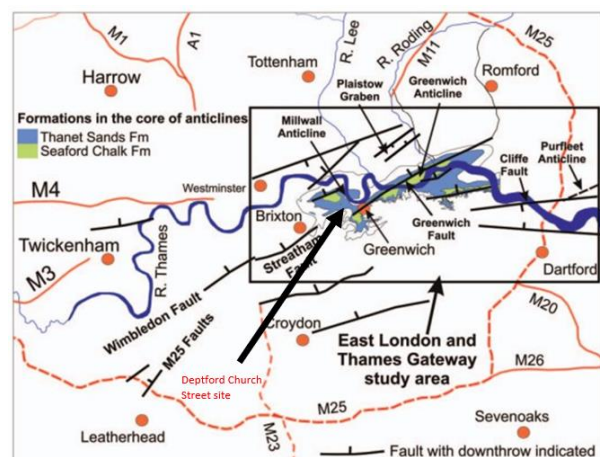


Figure 1. The Greenwich Fault Zone (Mortimore *et al.*, 2011).

Groundwater is encountered at approximately 8m bgl (48m above shaft formation level) and it was anticipated that the upper aquifer (RTD) was in hydraulic continuity with the Lower Aquifer (Chalk and overlying Thanet Sand) due to the general absence of Lambeth Group strata acting as an aquitard.

Although Lambeth Group strata were not generally recognised in investigations, a sporadic presence of the Lambeth Group was identified during excavation of the shallow interception chamber structure at the Deptford site.

1.2 Groundwater cut-off at Deptford Church Street Site

The 17.7m ID drop shaft to be constructed using diaphragm walling techniques at Deptford Church Street would be subsequently excavated to 52m below ground level to collect and direct flows from the nearby Deptford Storm Relief Sewer into the tunnel. The diaphragm wall was to be constructed prior to the excavation works to cut off all groundwater flows within the superficial deposits, reducing groundwater flows to a manageable level within the Chalk. The same construction methodology was successfully implemented during the Lee Tunnel project (Stanley et al., 2012). The diaphragm wall at Deptford Church Street extends 10m below the final excavation depth (Figure 2), designed to provide sufficient cut off for discrete fissures. The depth of the diaphragm wall combined with the installation of pressure relief wells assist with ensuring basal stability during shaft excavation. Client Works Information requirements specified that any dewatering was to be passive in nature and to only impact groundwater levels within the boundary of each worksite. The installation of the diaphragm wall would assist in meeting this requirement.

Baseline geological models of the sites and lessons learned from the Lee Tunnel project enabled a supplementary ground investigation and groundwater control strategy to be developed for the project. Vance et al. (2018) summarise the ground investigation methodology and subsequent testing implemented for the five drop shaft sites:

- 1) A review of the Client ground investigation and baseline reports.
- 2) Supplementary ground investigation undertaken by the Main Works Contractor prior to construction activities. This includes a pumping test to assess the baseline hydrogeological conditions of the site.
- 3) A final pumping test undertaken post diaphragm wall construction, to verify groundwater cut off. This would confirm if inflow rates were sufficiently low to allow shaft excavation to proceed or if additional mitigation measures were required.

2 SITE INVESTIGATION

Higher than expected pumping rates (approximately 14 l/s) were observed during the pre-diaphragm wall constant rate pumping test at Deptford Church Street. The pumping rate was limited by the sewer discharge consents. Subsequent data review workshops indicated that a flow of up to 80 l/s could potentially have been achieved based on drawdown response. This was significantly higher than baseline pumping tests undertaken at other Tideway East worksites, which yielded a maximum of 9 l/s.

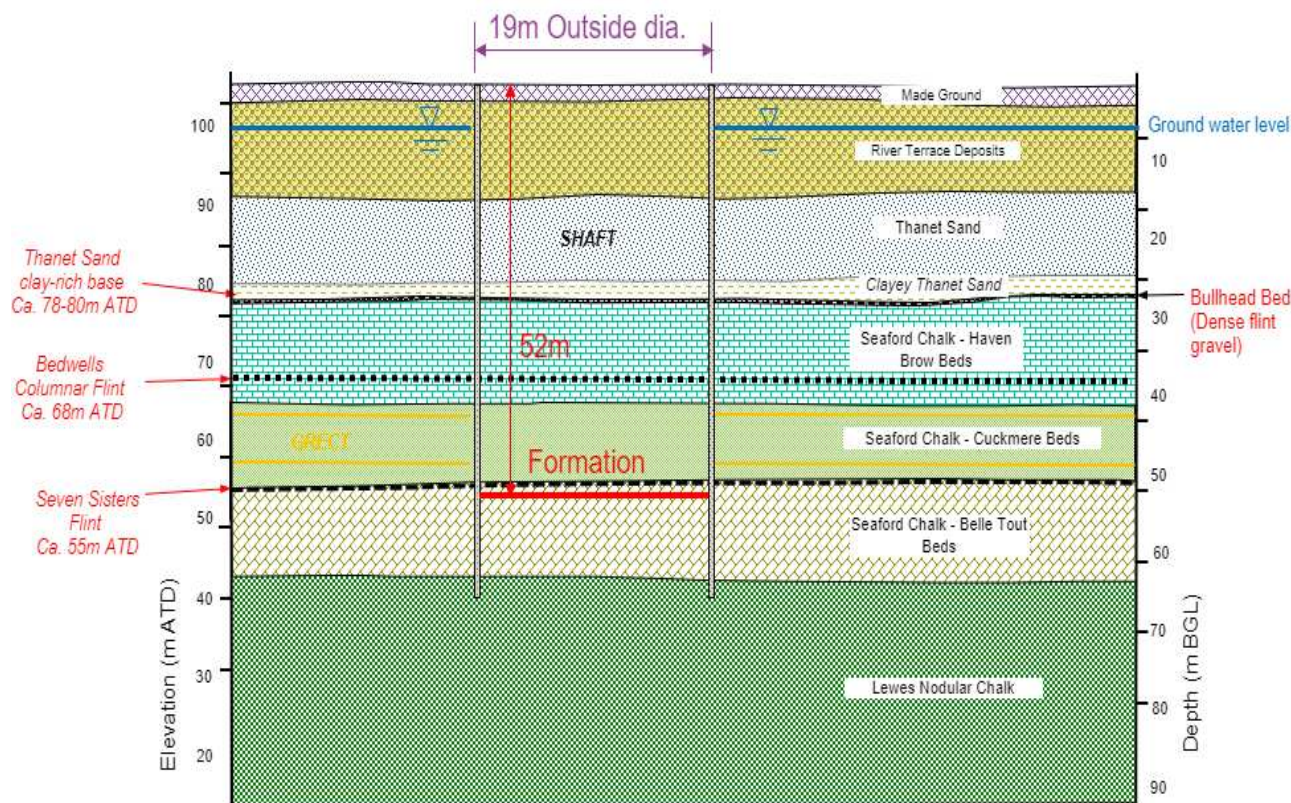


Figure 2. Geological cross section of Deptford and the construction detail of the drop shaft

Borehole wireline geophysics was also carried out in the pumping test well. This involves using probes lowered inside the test well to record a suite of parameters including Caliper for assessment of the borehole wall integrity, Conductivity & Temperature, Acoustic Images and Up-hole velocity. The use of borehole geophysics is described by Parker et al (2019) and when implemented to a high standard, produces good quality data. This was fundamental to understanding the large flows encountered within the pumping well. Reductions in up-hole velocity indicate where groundwater is entering a well. Where permeability is fairly uniform, case studies typically indicate a gradual stepped reduction to zero as inflows are provided by the fracture network.

However, during the geophysical testing of the initial pump well at Deptford Church Street indicated that almost all the groundwater inflow entered the well at 66 metres below ground level (Figure 3), approximately 4 metres below the proposed toe of the diaphragm wall, evidenced by a large step to near zero up-hole velocity. The optical borehole log identified a steeply inclined north dipping fissure at the same depth in the chalk. The apparent dip of the fissure was 67 degrees to the horizontal towards the north (000) suggesting that it would be cut-off by the diaphragm wall on the south side of the shaft but potentially pass up to 40 metres below the design toe depth of the diaphragm wall to the north.

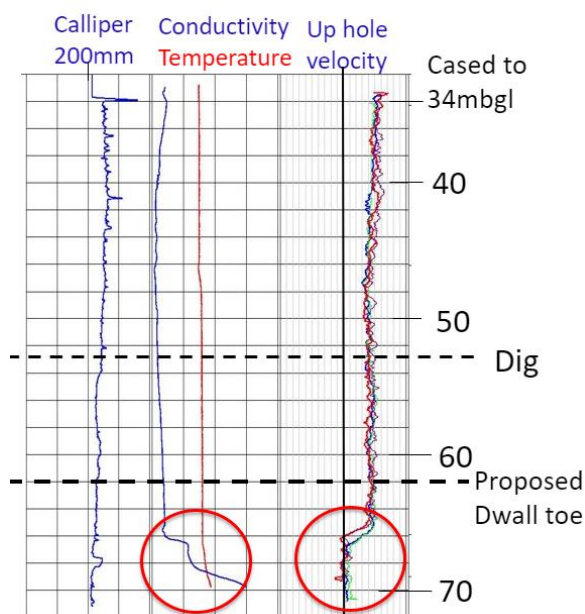


Figure 3. Geophysical logging of BH7401, identifying a feature at 66 mbgl. (original image courtesy of WJ Groundwater and European Geophysical Services)

It was concluded from the high groundwater flows and steeply inclined nature of the fissure that an extension to the diaphragm wall design depth would not sufficiently reduce the potential water inflow into the shaft during the excavation stage. In addition, the same diaphragm walling equipment (Hydrofraise) used at other Tideway East sites was to be utilised at Deptford. The particular model of the equipment mobilised to Deptford Church Street, due to the site's size, had a maximum performance depth which would not be able to enable an extension of the diaphragm wall to occur. Given the short timescale between completing pumping tests and the commencement of diaphragm walling, it was not feasible to procure alternative equipment.

In view of the uncertainties in flow rates and constraints on extending the diaphragm wall toe depth, additional investigations were required to understand the full extent of the feature so that mitigation measures could be implemented. Despite known

fracturing of Chalk in the area (Mortimore et al, 2011; Newman et al., 2016) and the assessment of Chalk as CIRIA Grade A1, the presence of a water bearing fissure of this magnitude was not anticipated. The subsequent investigations for targeting the fissure were considered a new activity and had to be undertaken in such a way to minimise programme delays.

2.1 Understanding the water-bearing feature

Additional boreholes positioned to the north and south of the originally identified feature were drilled simultaneously. Two specialist subcontractors drilled different sections of the borehole to enable efficient recovery through the superficial deposits, high quality chalk core recovery and to achieve a final borehole diameter suitable for subsequent pump testing. Acidisation and development of the wells was undertaken to allow for an increased yield of the wells. The drilling operations were a programme sensitive activity, therefore simultaneous working enabled the activity to be completed in a timely manner. The concurrent drilling activities were constrained to the shaft footprint, with the mobilisation of diaphragm walling equipment continuing to the East of the shaft as this activity could not be interrupted. Management of space and lifting operations was crucial for ensuring the additional ground investigation and mobilisation works were both completed successfully.

BH7403 was drilled deeper than BH7404 to the South, with calculated drill depths a response to the large angle of dip. Pump testing of both wells confirmed that almost all inflow was associated with single fissures intercepted at 54 metres below ground level (up dip) and 80 metres below ground level (down dip) of the original feature. The downhole image logs showed an almost identical feature, very close to the predicted horizon and dip angle, confirming that all three wells showed hydraulic connection with the fissure. An extract from a 4D model of the boreholes drilled, depth of fracture encountered in relation to the design depth of the diaphragm wall is shown in Figure 4.

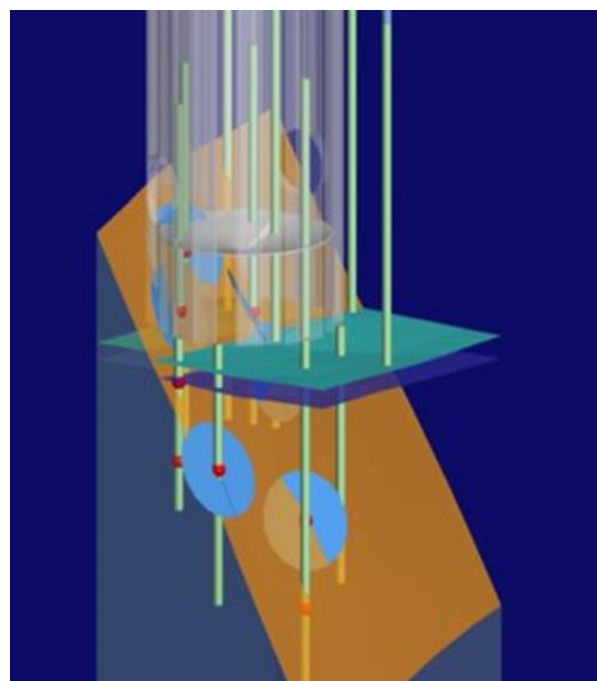


Figure 4. 4D model extract of the fissure (postulated in orange) with known strikes in each borehole indicated as red dots and disks indicating orientation where measured in downhole geophysics. Produced by Mott MacDonald.

The projection of the fissure plane between all three boreholes suggested that it would intercept the base of the drop shaft, which

was still to be constructed. As such the fissure presented a risk of large inflows and inundation of the drop shaft during excavation. As hydraulic connection with the fissure was present in all three wells as confirmed by pump test, the opportunity was taken to implement a targeted pressure grouting campaign. The boreholes provided a direct pathway into the feature and an opportunity for eliminating the requirement of any additional groundwater control works, such as the completion of a stepped grout curtain or base grouting exercise.

Night shifts were utilised to undertake the fissure grouting exercise, further decreasing the programme delay, and reducing impact on the ongoing hydrofraise mobilisation works. A conventional cement-based grout was used and theoretical grout volumes for each borehole were calculated, based on an assumed 50mm aperture of the fissure. The volume of grout injected was greater than the theoretical hole volumes (Table 1) and based on the estimated volume of the fissure aperture across the entire shaft footprint, approximately 38% was infilled with grout. The diaphragm walling activity commenced immediately after the grouting campaign, with only minor delays to the construction programme.

Table 1. Pressure Grouting Campaign Theoretical vs Net Volumes.

	<i>Theoretical hole volume</i>	<i>Net volume</i>
BH7403 (N)	3.12m ³	6.18m ³
BH7401	2.25m ³	10.292m ³
BH7404 (S)	2.36m ³	2.749m ³

3 VERIFICATION

On completion of diaphragm walling, two final wells were drilled within the shaft footprint in order to undertake a verification pumping test as per the final stage of the Tideway East Ground Investigation Methodology. The wells would also be used to provide pressure relief throughout the excavation of the shaft. The post diaphragm wall, post fissure grouting pumping tests on both wells yielded much lower groundwater pumping rates of approximately 2 l/s, in line with pump test values from other Tideway East drop shaft sites and suggesting that the grouting campaign had been successful in its objective. The reduced groundwater flow rates would be easier to manage during shaft construction through the construction of sump pumps and discharge lines to surface for disposal as per the discharge consent conditions. Throughout the shaft excavation, groundwater flow rates from the passive dewatering did not exceed 2.5 l/s.

To further confirm the success of the grouting campaign, additional verification investigations were made before the commencement of shaft excavation. Reservation tubes are often included within diaphragm wall panels to allow verticality checks and for any Instrumentation and Monitoring installations that may be required for long term assessments of the structure (Schwamb et al., 2016). The reservation tubes provided an opportunity to drill below the toe of the diaphragm wall to provide confirmation of grout infill within the fissure. High quality Geobore S methods enabled high quality recovery of chalk from a range of depths below the toe of the diaphragm wall. Four boreholes positioned around the circumference of the shaft were geologically logged to identify fissures and key marker bands. All of these boreholes encountered a fissure around the projected depth, two containing grout fill and the other two locations showing the fissure to be closed with undulating, striated, grey and black stained surfaces (Figure 5). These observations confirmed that grout had travelled to the shaft perimeter in the open parts of the fissure, but also indicated that

the fissure was closed in some places due to small scale undulation on the fissure surface.



Figure 5. Areas of grout identified within boreholes drilled below the toe of the diaphragm wall

During the shaft excavation, regular visits by the Project Geologist, Designer and Imperial College PhD Students were completed. These provided an opportunity to visually inspect the treated chalk to further assess the effectiveness of the grouting campaign; verification rarely possible following an in-situ grouting campaign. The grouted fissure was encountered towards the base of the chalk excavation (Figure 6), with travel of grout observed at the very edge of the shaft corroborating with the observations of grout inside the reservation tube boreholes. This confirmed that the potential risk of shaft inundation would likely have been realised without the mitigation measures. The absence of significant water flow along the grouted fissure provided the further confirmation that the risk of a significant water pathway had been suitably mitigated at the time.



Figure 6. Grouted fissure exposed during the shaft excavation (photo by Tim Newman).

Fracture logging and review of marker horizon depths (Shoreham Marls) estimated that north-south across the fissure, a maximum of one-metre offset was apparent. This in combination with the striation observations confirmed that the fissure was a small offset, normal fault.

In this instance, the presence of a high angle, open fracture meant that the Tideway East groundwater control strategy of solely utilising a diaphragm wall to cut off water flow in the superficial deposits and discrete chalk fissures was not a suitable method to implement for the chalk and required additional support in the form of the fissure grouting works.

4 CONCLUSIONS

A pre-diaphragm wall pumping test identified the potential for high inflows, with geophysical borehole logs indicating an inclined fissure at approximately 67 degrees to the horizontal, dipping towards the north. Additional ground investigation

boreholes were drilled to intercept and confirm the presence and inclination of the fissure. An extension to the diaphragm wall cut off depth would not prove sufficient to limit dewatering to an acceptable level to be in line with Works Information and Regulator consent requirements, or be considered practical as the fissure projection would have resulted in an extension in excess of 40 metres. Ground treatment utilising pressure grouting was used to successfully seal the fissure prior to the commencement of diaphragm walling. Post diaphragm wall well installation and pump testing concluded that groundwater flow was reduced to a manageable level.

Boreholes drilled below the diaphragm wall panels and logging of grout infill within the chalk rock during the shaft excavation provided further verification required to confirm that the risks from the fissure had been suitably mitigated. The Deptford Church Street drop shaft was excavated safely and to programme in June 2019. The positioning of the site on the edge of the Greenwich Fault Zone may have led to fracturing of the chalk rock, allowing the opportunity for a fissure to develop, subsequently providing a pathway for groundwater.

5 ACKNOWLEDGEMENTS

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