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Treatment of bentonite fluid for excavation into Chalk

1 Carlos Lam DPhil, CEng, MICE, MHKIE

Formerly Lecturer in Geotechnical Engineering, School of Mechanical, Aerospace and Civil Engineering, The University of Manchester, Manchester, UK (corresponding author: carloslam@hotmail.co.uk)
(Orcid:0000-0003-3269-1638)

2 Stephan A. Jefferis PhD, CEng, CEnv, FICE, CGeol, FGS, FRSA

Director, Environmental Geotechnics Ltd, Adderbury, UK;
Visiting Professor, Department of Engineering Science,
University of Oxford, Oxford, UK

3 Tony P. Suckling MSc, CEng, FICE

Director, A-squared Studio Engineers Ltd, London, UK;
formerly Technical Director, Balfour Beatty Ground Engineering,
Basingstoke, UK

This paper is concerned with the treatment of a bentonite support fluid during excavations extending into Chalk. Chalk can disintegrate during the excavation process and can, like any other soil that may disperse into the slurry, significantly alter the properties of the fluid if it is not appropriately managed. A case history in Woolwich, East London is presented to highlight the necessity for treatment of the bentonite slurry used to support grounds that release fines. It was found that, with use of the solids-separation equipment, the slurry could be maintained within specification over the course of the project. Desanders, desilters and a centrifuge were necessary for slurry management during the works. At the end of the works, the centrifuge was used to separate the unwanted residual slurry into a paste and a centrate of near-clear water. Chemical analyses conducted on the centrate confirmed that it was comfortably within specification for disposal to a foul sewer and physical tests on the dewatered bentonite sludge confirmed that it was sufficiently stiff that it could be disposed as a solid waste along with other soil arisings. The centrifuge treatment thus eliminated the high costs of transport and disposal of unwanted bentonite slurry.

1. Introduction

Bentonite support fluids have been used on construction projects across the world for over 60 years. Over this time, contractors, consultants and academics have developed a considerable body of experience with the use of these fluids in bored piles, diaphragm walls and slurry tunnelling. Much of this experience has been summarised in technical guidance and specifications. For example, the Federation of Piling Specialists (FPS) in the UK has published and periodically updated a specification and associated control test procedures for bentonite support fluids for some four decades (FPS, 1975, 1977, 1985, 2000, 2006). These documents have been widely followed by practising engineers along with documents such as the *ICE Specification for Piling and Embedded Retaining Walls* (ICE, 1996, 2007, 2017). Specifications for bentonite support fluids are also available in other countries (e.g. AASHTO, 2017; GEO, 2006).

For many ground conditions, the properties of the bentonite support fluid can be controlled and maintained to within the required limits using desanders and, if necessary, desilters (Cowie and Crawley, 1989; Schlosser *et al.*, 1989). However, special attention has to be paid to the management of slurries

used to support excavations in soils that release significant amounts of fine soil particles. These particles can become suspended in bentonite slurry because of its viscosity and gel, which provide solids-carrying capacity. To avoid the slurry becoming too thick and dense, fines must be managed during the works, typically using soil-slurry separation plant such as desanders and desilters and, occasionally, centrifuges. This paper concerns the performance of a soil-slurry separation plant for a diaphragm wall project where the walls passed through the Thanet Formation and extended into a chalk which broke down to release significant amounts of fines.

Desanders combined with desilters are typically effective in removing soil particles to a useful extent only down to about 30 μm , although the actual solids-removal performance of a hydrocyclone will be strongly influenced by the solids content and viscosity of the fluid to be treated. It follows that finer treatment plant such as centrifuges may be necessary when excavating in grounds that release significant amounts of fine to medium silts and clay-sized material. In the past, it was possible to dispose of over-thick or over-dense slurries as liquid wastes. However, in many countries including the UK, liquid waste disposal to landfill has been banned. This has made the

use of centrifuges cost-effective when compared with disposal of out-of-specification slurry for treatment by others off-site. It may be noted that although centrifuges are regularly used for the removal of fines in slurry tunnelling and pipe jacking (Hindmarch *et al.*, 2008; Liu, 2010), their use is rarer for bored piling and diaphragm walling. Surprisingly, a survey of the literature on bored piles and diaphragm walls revealed little published information on the performance of desanders and desilters, let alone centrifuges. As a first step towards greater awareness of soil-slurry separation plant, this paper presents a case history of the use of bentonite support fluid for diaphragm walling and bored piling in soils including Chalk, which can break down to release a significant amount fines. The excavation was carried out for the construction of the Crossrail station at Woolwich, East London.

2. Background

2.1 Ground conditions

The new Woolwich station is located at the former Woolwich Arsenal site in East London. The geology at the site consists of 3 m of Made Ground and Terrace Gravels overlying 11 m of Thanet Sand with a 1 m thick Bullhead Bed at the base and then Chalk (Pennington, 2015; Symes, 2012). The groundwater level lies at 5–10 m below ground level. The particle size characteristics of the Thanet Sand, Bullhead Bed and the Chalk were of particular relevance to the slurry-supported excavation works at this site, so a brief description is now given. Thanet Sand is a fine sand and is known to have a higher fines content near the bottom of the stratum. Lam *et al.* (2014) carried out a sieve analysis of samples taken from the top of the Thanet Sand layer at Stratford, East London, and determined D_{10} , D_{30} and D_{60} values of 0.07, 0.10 and 0.14 mm respectively. A fuller discussion of the particle size distributions of Thanet Sand is given by Menkiti *et al.* (2015). The Bullhead Bed is a distinct unit that is commonly present at the base of the Thanet Formation and usually comprises angular to rounded coarse flint gravels in a sandy clay matrix. The flint nodules can be up to 500 mm in size and are difficult to recover in boreholes (Menkiti *et al.*, 2015). As regards the Chalk, Bundy (2013) studied the particle size distributions of Chalk samples collected from several sites in the UK. The D_{50} of these samples was found to range narrowly between 2 and 4 μm , which matched the longest dimension of individual coccolith plates as observed under an electron microscope. Bundy (2013) also studied the effect of milling on D_{10} , D_{50} and D_{90} . There were only small changes in the D_{10} and D_{50} values as a result of milling, but D_{90} reduced from around 100 μm to 20 μm when the milling duration was increased from 30 s to 14 min, indicating a breakdown of the aggregated chalk particles. Breakdown of aggregated chalk particles also can occur in slurry-supported excavations due to the grinding action of the digging tools. Phillips (2016) reported the disaggregation rates of several British soils in relation to pipe jacking coupled with a slurry cutter head. Chalk was not included in that study

programme and the disaggregation behaviour of chalk in bentonite slurry has been little reported to date, although contractors who have worked in Chalk will be aware of the risk of fines generation and will operate processes to minimise the risk so far as it is predictable. In addition to fines from Chalk, Thanet Sand also will contribute fines to excavation slurry.

2.2 The fluid-supported excavation work

The station box of the Woolwich station was approximately 260 m long and 23–29 m wide, with an internal depth of 12–18 m (Pennington, 2015). For construction of the station box, over 500 linear metres of diaphragm wall were required, all founded in the Chalk. The wall was constructed from 88 separate panels that were 24.5 m deep, 1 m wide and up to 7.1 m long. A total of 51 bored piles with diameters of 1500 mm and 1800 mm and lengths ranging from 32–46 m were constructed to provide the necessary uplift resistance for the station box. In addition, the contractor installed lean-mix walls at the ends of the station box for the entrance and exit of the tunnel boring machine that was to pass through the box. A cement–bentonite cut-off wall was also installed midway along the box to enable dewatering of the site prior to the staged bulk excavation works. Altogether, about 20 000 m³ of excavation was carried out under bentonite slurry. As the excavation had to pass through the Bullhead Bed, which posed a high risk for slurry loss, it was grouted prior to the works. A detailed discussion of the pre-excavation grouting can be found in Pennington (2015).

3. Solids-separation equipment and procedures

3.1 Treatment process

Figure 1 shows a diaphragm wall trench under excavation at the site. The excavation was carried out using clam shell grabs. It can be seen that the bentonite slurry in the trench was

Figure 1. Diaphragm wall trench supported by bentonite fluid

creamy white in colour, which was due to the suspended chalk particles in the slurry. Special attention was paid to the setup of the solids-separation plant so that the properties of the bentonite slurry could be maintained within the specified limits over the course of the project. Figure 2 shows a photograph of the plant, comprising a desander (SM250DP), a desilter (SU300DP), a second desander (Casagrande D14) and a centrifuge (S3-01-H). The silos in the background were used to store fresh and treated bentonite slurry. Figure 3 shows a schematic diagram of the bentonite slurry mixing and treatment process. The bentonite used was a sodium-activated bentonite with the trade name Berkent 163. This bentonite is commonly used in the UK for bored piling and diaphragm walling projects (Lam *et al.*, 2015; Suckling *et al.*, 2011). The bentonite slurry was mixed at a concentration of 40 kg/m³ using local tap water pre-treated with sodium carbonate (soda ash) to precipitate calcium hardness. The density of the fresh slurry was 1.02 g/cm³.

Figure 2. Solids-separation plant and storage tanks

After use in an excavation, the bentonite slurry was first sent to one or, if necessary, both of the desanders for removal of the coarse soil particles. Some of the slurry was then passed to a desilter for the removal of silt-sized soil particles. Due to its limited capacity, the desilter could not take the full flow from the two desanders when operating together. In addition, the centrifuge continuously processed some of the slurry to reduce the solids content. In this paper, this operating mode is referred to as the slurry thinning mode. In this mode, some but not all of the solids were removed from the slurry so that the underflow was a paste largely consisting of chalk with more minor amounts of bentonite and the overflow was a bentonite slurry with some residual chalk particles. After treatment, the bentonite slurry was sent to storage tanks.

3.2 Details of the solids-separation equipment

Descriptions of common solids-separation equipment can be found in textbooks on drilling and diaphragm walling (e.g. ASME SSC, 2005; Boyes, 1975; Verfel, 1989, Xanthakos, 1994). The equipment used in this project was as follows.

The SM250DP desander was provided by Pigott Shaft Drilling Ltd. Its rated capacity for recycled slurries is up to 250 m³/h. It is designed to separate coarse and medium sands from recycled clay-based fluid, having a Marsh funnel time of up to 100 s. In operation, the solids-laden slurry first passes through a coarse vibrating screen with an aperture size of 6 mm. The screen underflow then passes to the recycle tank, from where it is pumped to three 250 mm (10 inch) dia. hydrocyclones (Figure 4(a)). The hydrocyclones concentrate the coarse particles into the underflow, which falls onto a vibrating dewatering screen with an aperture size of 500 µm. The dewatered solids are discharged at the front of the screen deck (Figure 4(b)). The fluid passing through the screen drops back

Figure 3. Schematic diagram of bentonite mixing and treatment process

(a)

(b)

Figure 4. Desander SM250DP: (a) hydrocyclones; (b) dewatered solids

(a)

(b)

Figure 5. Desander D14: (a) hydrocyclone; (b) hydrocyclone underflow

into the recycle tank. The overflow from the hydrocyclones, which will still contain silt- and clay-sized particles and a minor amount of coarser material, passes to a treated slurry tank. From this tank the slurry is either pumped to the desilter or flows back to the recycle tank for recycling through the hydrocyclones.

The Casagrande D14 desander has a flow capacity of 140 m³/h. It has a different layout to the SM250DP desander but operates in a similar way. In operation, the solids-laden fluid first passes through a vibrating coarse screen with an aperture size of 8 mm. From the screen, the fluid falls into a tank, from where it is pumped to an obliquely mounted 420 mm dia. hydrocyclone (Figure 5(a)); note that the centrifugal forces in a hydrocyclone are sufficiently high that its orientation to the vertical has no impact on its performance. The coarser solids are concentrated and discharged as the

underflow onto a vibrating dewatering screen (Figure 5(b)). After dewatering, the solids are discharged at the front of the unit. The overflow from the hydrocyclone is then sent to storage tanks or the desilter.

The SU300DP desilter was supplied by Pigott Shaft Drilling Ltd. It has a flow capacity of up to 300 m³/h. As its name suggests, it is designed to remove silt-sized soil particles from the slurry after treatment in one of the primary desanders. The flow circuit of the desilter is very similar to that of the SM250DP desander. The principal difference is that the hydrocyclones are of smaller diameter and finer dewatering screens are used. Hydrocyclones with a smaller diameter are used as the cut point of a hydrocyclone reduces with its diameter. However, a reduced diameter also reduces the throughput per hydrocyclone and increases the risk of blockages. Typically, the minimum hydrocyclone diameter for excavation slurries is

about 100 mm and long-bodied hydrocyclones are used as these have a lower cut point than shorter hydrocyclones of the same diameter. In operation, the desanded slurry is first pumped from the unit's recycled fluid tank to 12 hydrocyclones of 125 mm (5 inch) diameter (Figure 6(a)). The soil particles in the fluid are concentrated in the underflow and discharged onto two decks of vibrating dewatering screens. For this project, screens with openings of 300 μm and 106 μm were used, with corresponding American Petroleum Institute (API) screen numbers of API 50 and API 140, respectively (API, 2014). The solids that are separated by the screens are discharged at the front of the unit (Figure 6(b)) while the slurry

passing through screens returns to the recycled fluid tank. The overflow from the hydrocyclones is either pumped to the storage tanks or flows back to the recycle tank for recycling through the hydrocyclones.

The centrifuge (model S3-01-H) was also supplied by Pigott Shaft Drilling Ltd. It comprises a horizontal chamber, known as a bowl, of diameter 530 mm and length 2270 mm. The bowl can rotate at speeds of up to 2200 rpm and can develop centrifugal acceleration up to 1425g. Slurry for treatment is pumped into the rotating bowl and the soil particles migrate to the wall due to the high centrifugal acceleration. Inside the bowl, there is a scroll conveyor rotating at a slightly higher speed than the bowl so that it continuously pushes the settled solids to the discharge outlet, while the treated fluid is discharged to a storage tank below the centrifuge (Figure 7). In this project, the centrifuge was used to treat desilted bentonite slurry (slurry after passage through the desilter) both for reuse and for final disposal. For the first purpose, where the centrifuge was required only to reduce the solids content of the slurry, the bowl speed was 1250 rpm and the scroll speed was 16 rpm higher. This setup allowed the recycled fluid to be treated at a rate of around 6 m³/h. For the second purpose (i.e. separation prior to disposal), the centrifuge was used to separate the unwanted bentonite slurry into an underflow paste and a near-clear water overflow. For this, a higher bowl speed and a lower flow rate were necessary; the bowl speed was increased to 1650 rpm and the scroll was operated at 14 rpm faster than the bowl. The fluid treatment rate was slightly lower at 5 m³/h. These speed settings generally follow the advice of the

(a)

(b)

Figure 6. Desilter SU300DP: (a) hydrocyclones; (b) vibrating dewatering screens

Figure 7. Centrifuge S3-01-H and solids discharge at the front

centrifuge supplier: for the removal of very fine solids, a high bowl speed is needed and the retention time for solids within the centrifuge is increased by running the scroll at a lower differential speed. It may be noted that the rate of 5–6 m³/h is very much lower than the return flow rate from a diaphragm wall excavation during concreting and thus the centrifuge was operated off-line from the main slurry circuit.

4. Fluid treatment for reuse

4.1 Removal of solids

The effectiveness of the fluid treatment process was first evaluated by studying the behaviour of the desander, desilter and centrifuge on a single occasion, examining the sizes of the soil particles in the treated fluids. To this end, samples of the treated slurries and solid discharges were taken from the desander (SM250DP), the desilter (SU300DP) and the centrifuge (S3-01-H) operating in slurry thinning mode. The samples

were oven dried and then examined under a scanning electron microscope (Hitachi S-3400N) with a magnification of 50×. Figures 8 and 9 show electron micrographs of the dried treated fluids (overflows) and solid discharges, respectively, from the three pieces of equipment. In these micrographs, the particles have different levels of brightness. This is due to the build-up of excess electrons on some particles during the imaging process and should not affect the interpretation of results. Together, Figures 8 and 9 show that the particle sizes in the treated fluids generally decreased with increasing treatment. It is interesting to note that the soil particles in the liquid discharges could be larger than the aperture sizes of the dewatering screens of the associated equipment. For example, the aperture sizes of the coarse and fine dewatering screens on the SU300DP desilter were 300 µm (upper screen) and 106 µm (lower screen) but the soil particles in the liquid discharge had dimensions up to about 300 µm (Figure 8(b)). At first sight, this may seem surprising but could be due to the following

Figure 8. Electron micrographs of dried treated fluids from: (a) desander SM250DP; (b) desilter SU300DP; (c) centrifuge S3-01-H

Figure 9. Electron micrographs of dried solid discharges from: (a) desander SM250DP; (b) desilter SU300DP; (c) centrifuge S3-01-H

three reasons: (a) As described previously, the liquid discharge from the desilter is from the overflow of the hydrocyclones. A hydrocyclone does not have a sharp cut like a perfect screen and, statistically, some coarser materials will report to the overflow, especially when the solids content (or density) of the feed slurry, and thus also the slurry viscosity, is high; hence the use of a recycle on the hydrocyclone unit which acts to minimise the amount of oversized particles in the overflow. (b) Dewatering screens often have rectangular slots so that the maximum particle dimension can be greater than the minimum screen opening. (c) Screens are easily damaged, in which case some oversize particles can slip through holes.

Further information on plant performance was obtained from moisture content and density measurements on a set of samples of treated fluids. These samples showed moisture contents of 287%, 442% and 538%, respectively, for the treated fluids from the desander, desilter and the centrifuge in slurry

thinning mode, corresponding to solids contents (defined as weight of solids/total weight) of 26%, 18% and 16%. The associated measured fluid densities were 1.20, 1.14 and 1.11 g/cm³, respectively. Thus, at the time of sampling, the combination of desander plus desilter was able to maintain the treated slurry to within the specified limit of 1.25 g/cm³ for slurry for reuse. On other occasions, it was necessary to blend the treated slurry with fresh slurry and overflow from the centrifuge to maintain its density below the 1.25 g/cm³ limit.

4.2 Properties of treated fluids at different locations

The effectiveness of the solids-separation process was also assessed by measuring the properties of the treated bentonite slurry at different sampling locations in the fluid circuit at a particular time; these samples were different from those discussed in the previous section. As an example of the slurry properties, Table 1 summarises the properties of samples taken from digging slurry from the excavation for a pile, after

Table 1. Properties of bentonite fluids at three sampling points on one sampling occasion and control values from BS EN 1538:2010 (BSI, 2010)

Property	Measured value				Control values from BS EN 1538:2010	
	Digging fluid	After desander and desilter treatment	After decanting centrifuge treatment	Freshly mixed	Ready for reuse	Freshly mixed
Density: g/cm ³	1.34	1.24	1.14	1.025	<1.25	<1.10
Fluid loss volume: ml	33	27	24	21	<50	<30
Filter cake thickness: mm	6	3	1.5	1	<6	<3
Marsh funnel time: s	47	36	34	34	32–60	32–50
pH	11.2	10.6	10.7	10.4	7–12	7–11

desander and desilter treatment, after centrifuge treatment and from the fresh slurry mixer. The measured properties were fluid density, Marsh funnel time, pH, fluid loss volume and filter cake thickness. These properties were measured according to the procedures given in FPS (2006) except that density was measured using a pycnometer instead of the conventional mud balance for improved accuracy (Jefferis and Lam, 2017; Lam, 2016). The control values given in BS EN 1538:2010 (BSI, 2010) for diaphragm walling are also included in Table 1 for comparison. BS EN 1538:2010 does not include any parameters for digging slurry. However, a possible upper density limit of 1.35 g/cm³ is given in ICE (2017) for digging slurry. Few tests were undertaken on the digging slurry on site as they were not required.

Table 1 shows that the slurry density was as high as 1.34 g/cm³, which is a relatively challenging density for the soil–slurry separation plant. However, desanding and desilting reduced the density of the digging slurry to 1.24 g/cm³, which is just within the specification given in BS EN 1538:2010, which sets an upper limit of 1.25 g/cm³. The centrifuge in the slurry thinning mode (removing some but not all solids) further reduced the slurry density to 1.14 g/cm³, which is comfortably within the specification for the works. Ultimately, the slurry for reuse will have been a mix of desanded and desilted slurry, centrifuge-treated slurry and fresh slurry to make up for slurry losses to the ground and with the excavated soil. As the bulk fluid loss to the ground at this site was higher than typical for other areas of London, the volume of make-up fresh slurry was significant despite the prior grouting of the Bullhead Bed.

Typically, in clays and silty soils, the pH of bentonite slurry drops in use. It is interesting to note that the pH of the digging slurry was 11.2 compared with 10.4 for the fresh slurry. This increase in pH is unlikely to have been due to the chalk particles but rather to digging through the cement-grouted Bullhead Bed. In addition to raising the pH of the slurry, cement will flocculate bentonite particles, resulting in an increase in viscosity and fluid loss volume (FPS, 2006); these effects were also observed in this project (Table 1). Sodium

bicarbonate (NaHCO₃) can be used to reduce the pH of contaminated slurry, but this was not necessary in this project. It may be noted that chalk has no chemical effect on bentonite. Indeed, a sodium-activated bentonite will contain about 4% calcium carbonate (chalk) precipitated during the original conversion process from calcium bentonite to sodium bentonite.

4.3 Effects of density on fluid properties

To investigate the effects of slurry density on other fluid properties, Figures 10–14 respectively show plots of pH, fluid loss, Marsh funnel time, apparent viscosity and gel strength of fresh and treated fluids against density. The apparent viscosity and gel strength were determined with a direct-indicating viscometer (FPS, 2006; Lam and Jefferis, 2014, 2015). These results were obtained by the contractor's field technicians during the course of the project as part of the quality control work.

The increase in pH with density (Figure 10) was probably due to cement contamination as previously discussed – the higher density slurries had higher excavated soil contents and thus potentially higher degrees of cement contamination from the grouting of the Bullhead Bed. At this site, the fluid loss, which

Figure 10. Effect of fluid density on pH

Figure 11. Effect of fluid density on fluid loss

Figure 14. Effect of fluid density on gel strength

Figure 12. Effect of fluid density on Marsh funnel time

Figure 13. Effect of fluid density on apparent viscosity

was measured in a standard API cell (FPS, 2006), showed a trend of increasing loss with increasing density (Figure 11). However, data from other sites with Chalk have shown an inverse trend (i.e. decreasing fluid loss with increasing density). It would therefore seem that the cement from the grouted Bullhead Bed had a greater impact than the fines. The Marsh funnel data (Figure 12) showed a very narrow range of results, from 34 to 37 s. However, since the Marsh funnel test results were reported only to the nearest second, it would be unwise to suggest any correlation with slurry density. The apparent viscosity and gel strength showed considerable scatter and weak trends of increases with density (Figures 13 and 14).

Overall, the findings were very much as expected. Slurry density in excess of the fresh slurry density is an indicator of the amount of excavated soil (and associated cement grout on this site) in the slurry. For example, a slurry with a density of 1.25 g/cm³ will contain about 395 kg/m³ solids (assuming the solids are predominantly chalk with a density of 2.71 g/cm³), whereas the fresh bentonite slurry will have contained only 40 kg/m³ bentonite. Reducing slurry density after use will tend to return slurry properties to those of the fresh slurry but some non-bentonite fines will remain within the slurry. The concentration of bentonite by weight of water will also reduce with use as a result of the water released from the excavated soil (Jefferis, 2014). These effects will be partially compensated by fresh slurry added to the fluid circuit to make up for bulk fluid losses to the ground and with the excavated soil. Cement contamination will continue to impact on the slurry, tending to increase its gel strength, and this in turn will increase its solids-holding capacity – an adverse effect.

5. Fluid treatment for disposal

5.1 Methodology

In addition to treating bentonite slurry for reuse, the centrifuge was used to treat the unwanted bentonite slurry for disposal at

the end of the project. As previously described, the centrifuge was operated at a slightly higher bowl speed and a lower differential speed between the scroll and bowl than when operated in slurry thinning mode for slurry treatment prior to reuse. To improve the efficiency of solid–liquid separation, calcium chloride as a coagulant and an organic flocculant (Polyfloc 190CG) were added to the slurry prior to centrifugation. The supplier states that Polyfloc 190CG is an anionic polyacrylamide with a high molecular weight, which can be used in wastewater treatment. The divalent calcium cations compress the electrical double layer around the bentonite particles, so promoting aggregation of the particles. The charged long-chain polymer molecules can gather the destabilised bentonite particles together to form larger flocs, which settle more rapidly than individual particles. When used, the polymer and calcium chloride were first mixed with potable water at concentrations of 0.85 kg/m³ and 6.3 kg/m³, respectively, in separate mixing tanks. They were then added to the bentonite slurry in approximately equal amounts prior to centrifuging. Phillips (2016) gives details of procedures to optimise the flocculant dose for centrifugation.

5.2 Effectiveness of treatment

The effectiveness of the solid–liquid separation process was evident on site as the centrate was near-clear water and the solid discharge had a soft paste-like consistency. For this project, the contractor had obtained prior consent from the local water authority to discharge the centrate directly to the site foul sewer. To confirm that the centrate complied with the discharge consent, chemical analyses were carried out by a commercial laboratory on two separate samples of the centrate. Table 2 summarises the consent limits and the associated test results. It can be seen that the centrate had the required low solids content. Of the other parameters, the chloride content was relatively high as a result of the use of calcium chloride as a coagulant.

The properties of dewatered bentonite sludge are also important since the disposal costs of liquid wastes are much higher than those for solid wastes. If dewatered bentonite sludge is classified as a solid waste, it can be disposed of with other soil arisings from the site by conventional means. According to

Defra (2010), liquid waste is defined as any waste that almost instantaneously flows into an indentation void made in the surface of the waste, or any waste load containing a free-draining liquid substance in excess of 250 l or 10% of the load volume, whichever represents the lesser amount. The first of these interpretations can be used to distinguish between liquid and sludge. A waste that flows only slowly, rather than nearly instantaneously, into an indentation void will be a sludge and a solid for waste regulation purposes. Figure 15 shows a photograph of the dewatered bentonite sludge. It can be seen that the sludge did not flow into an indentation on the surface made with a palette knife. Furthermore, the chalk–bentonite sludge did not release any free-flowing liquid.

6. Conclusions

The key findings of the slurry data and the soil–slurry separation plant from this study can be summarised as follows.

- (a) The solids-separation equipment used was effective in removing soil particles from the recycled bentonite slurry and thus reducing its density. However, the slurry after treatment in the desander and desilter could still contain significant amounts of chalk. Even after treatment in the desanders and desilter, slurry densities could be up to 1.27 g/cm³, which was too high for reuse without further management.
- (b) As expected, although not always appreciated, the slurry after treatment contained minor amounts of particles coarser than the aperture sizes of the finest dewatering screen. Among other reasons, this is because a hydrocyclone does not produce a sharp cut as with a perfect sieve but rather its behaviour can be described by a size-distributed efficiency curve where the D_{95} may be several times the cut size for 50% removal.
- (c) The use of a centrifuge in slurry thinning mode (i.e. the removal of some but not all the solids) was essential to prevent solids build-up in the slurry circuit on this project where disintegration of the chalk during excavation led to the release of fine particles that were finer than could be sufficiently removed by the desilter. The fresh make-up slurry required to compensate for bulk losses helped to reduce the recycled slurry density and keep it within

Table 2. Results of chemical analysis of centrate

Property	Consent limit	Sample 1	Sample 2
pH	6–11	8.3	8.6
Suspended solids: mg/l	<2000	38	111
Rapidly settleable solids: mg/l	<100	6	22
Settleable solids: mg/l	<1000	7	81
Chemical oxygen demand: mg/l	<1000	517	315
Chloride content: mg/l	<1500	1292	913
Sulphate content (as SO ₄): mg/l	<1800	230	300

Note: Analyses were also undertaken for chromium, copper, lead, nickel, iron, zinc, unsaponifiable oil and available chlorine. The results were all well below the consent limits

Figure 15. Dewatered bentonite sludge

specification. It is perhaps instructive to note that the third edition of the *ICE Specification for Piling and Embedded Retaining Walls* (ICE, 2017), which was published after completion of this project, suggests an upper density limit of 1.08 g/cm^3 for reuse. If such a density had been necessary on site, the centrifuge capacity would have had to be increased by using either more or larger centrifuges, or both.

- (d) The density of bentonite slurry in excess of that of fresh slurry is a direct indicator of the mass of excavated soil suspended in the slurry. Other properties such as fluid loss, apparent viscosity and gel strength often show some correlations with density but the trends depend very much on the nature of the soil dispersed in the slurry. Also, on this site, the slurry behaviour will have been influenced by cement from the grouted Bullhead Bed.
- (e) The apparent correlation of pH with density at this site was probably due to the grouting works carried out in the Bullhead Bed prior to the excavation works. The higher density of the slurry, the greater was its excavated soil content and thus the greater was the chance that it may contain grouted material from the Bullhead Bed. On sites without grouting, a reduction in pH with density or no correlation is more typical.
- (f) At the end of the project, the centrifuge was successfully used to separate the unwanted bentonite slurry into material that was classified as solid waste for disposal purposes and water that met the criteria for direct disposal to a foul sewer. This avoided any requirement to tanker liquid waste off site for treatment by others prior to disposal.

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