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Analysis on bentonite support fluid recycling using desanders,
desilters and centrifuges for the Diaphragm-Wall excavation
in adverse geological conditions:
The Chilterns' Chalk

High Speed 2 Railway – ventilation shafts

Project carried out within VSL Systems (UK) Ltd.

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Abstract

As part of UK's High Speed 2 Project, a new railway line connecting London to Birmingham, the C1 section is composed of a 3 km viaduct and twin-bored 16 km tunnels. For these tunnels, four ventilation shafts using the diaphragm-wall technique must be constructed along their alignment in the Chiltern Hills area. These shafts are inserted in typical British chalk ground which represents a big challenge regarding the treatment of the support fluid used for the excavation of the diaphragm-walls' elements. While excavating, the support fluid based on a mix of water and bentonite powder, gets contaminated with the soil cuttings and a specific solid separation technique is necessary to achieve the fluid recycling. Chalk is composed of a very important portion of fine particles that can disintegrate down to 2 μm diameter and, by remaining in suspension, they cannot be removed from the support fluid by the conventional desanding/desilting treatment plant. This makes the bentonite support slurry unsuitable for reuse, compromising the diaphragm-wall final quality and production. To overcome this, a new process with specific machinery like centrifuges is implemented.

This *in-situ* study evaluates the effectiveness of the chosen treatment process, following-up the fluid parameters monitoring and the diaphragm-wall production. The project exposes the problems created by the chalk that dissolves into the bentonite fluid while excavating the ground by means of a trench cutter and then investigates the performance of the mud treatment plant with special attention to the influence of centrifuges on the system. After removing gravels, silts and sands from the fluid using vibrating screens and hydrocyclones, centrifuges are the last level of the process which are expected to remove the fine chalk particles and keep the fluid ready for reuse in the excavation.

The goal is to prove the need of including a centrifuge on site to handle such contamination and to compare this case scenario with another one which would not include this kind of plant. To achieve it, the analysis undertakes, on one hand, a technical approach by specifying the equipment's role and the soil particle management. For this, a close-up on the evolution of the key parameters of the mud while excavating is carried out, proving the centrifuge importance to keep them in conformity. On the other hand, a more practical approach is performed

concerning the site's organisation and costing, demonstrating that there is added value to the project brought by using the appropriate recycling unit and centrifuges.

Keywords: Bentonite, Chalk, Centrifuge, Diaphragm-Wall, Slurry, Support Fluid.

Résumé

Dans le cadre du projet britannique High Speed 2, une nouvelle ligne ferroviaire reliant Londres à Birmingham, la section C1 est composée d'un viaduc de 3 km et d'un pair de tunnels de 16 km. Pour ces tunnels, quatre puits de ventilation utilisant la technique des parois moulées doivent être construits le long de leur tracé dans la région des Chiltern Hills. Ces puits sont insérés dans un sol de craie typiquement britannique, ce qui représente un grand défi en ce qui concerne le traitement du fluide de support utilisé pour l'excavation des éléments des parois moulées. Lors de l'excavation, le fluide, composé d'un mélange d'eau et de poudre de bentonite, est contaminé par les déblais du sol et une technique spécifique de séparation des solides est nécessaire pour assurer le recyclage du fluide. La craie est composée d'une partie très importante de particules fines qui peuvent se désagréger jusqu'à 2 μm de diamètre et, en restant en suspension, elles ne peuvent pas être éliminées du fluide de support par la station de traitement classique de dessablage/délimonage. Cela rend la boue bentonitique impropre à la réutilisation, compromettant la qualité finale de la paroi moulée et sa production. Pour y remédier, un nouveau procédé avec des machines spécifiques comme des centrifugeuses est mis en œuvre.

Cette étude *in-situ* évalue l'efficacité du procédé choisi, en suivant le contrôle des paramètres du fluide et la production de la paroi moulée. Le projet expose les problèmes créés par la craie qui se dissout dans le fluide de bentonite lors de l'excavation du sol par moyen d'une hydrofraise, puis étudie les performances de l'installation de traitement de la boue en accordant une attention particulière à l'influence des centrifugeuses sur le système. Après avoir retiré les graviers, les limons et les sables du fluide à l'aide de tamis vibrants et d'hydrocyclones, les centrifugeuses constituent le dernier niveau du processus de traitement qui est censé éliminer les fines particules de craie et garder le fluide prêt à être réutilisé dans l'excavation.

L'objectif est de prouver la nécessité d'inclure une centrifugeuse sur le site pour traiter une telle contamination et de comparer ce scénario avec une autre configuration qui ne comprendrait pas ce type d'installation. Pour cela, l'analyse entreprend, d'une part, une approche technique en précisant le rôle de l'équipement et la gestion des particules de sol pendant le traitement. Pour

ce faire, un focus sur l'évolution des paramètres clés de la boue en cours d'excavation est réalisé, prouvant l'importance de la centrifugeuse pour les maintenir en conformité. D'autre part, une approche plus pratique est réalisée concernant l'organisation et le chiffrage du site, démontrant que l'utilisation d'une unité de recyclage appropriées et de centrifugeuses apporte une valeur ajoutée au projet.

Mots-clés : Bentonite, Boue, Centrifugeuse, Craie, Fluide de Support, Parois Moulées.

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List of Abbreviations

UK: United Kingdom

HS2: High Speed 2

D-Wall: Diaphragm-Wall

TBM: Tunnel Boring Machine

KVJV: Keller VSL Joint Venture

CSG: Chalfont Saint Giles (site)

PSD: Particle Size Distribution

ICE: Institution of Civil Engineers

BGS: British Geological Survey

1. Introduction

Diaphragm-walls using bentonite support fluids have been a constructive solution for special foundations for more than a half of a century and even though the fundamentals of its technique remain the same, the choice of the machinery involved is crucial to optimise the production process and to overcome today's limitations and challenges found in the field.

For ground conditions where the soil's particles size does not go below coarse silts, site plant like desanders and desilters have been employed to treat the slurry and remove the solids released from the ground during the excavation of the d-wall panels by means of grabs and trench cutters. This treatment is responsible for the maintenance of the slurry parameters that ensure its own management on site as well as the quality of the panel being constructed. However, when ground conditions are revealed to be rich in finer particles as in the case in chalk soils, the mud treatment becomes more challenging as its density increases up to a point where the slurry is unsuitable for reuse. Consequently, the maintenance of these properties is impossible with the standard plant, leading to the almost direct disposal of the bentonite fluid. Recently, with the goal of achieving the recycling of the support fluid in such ground conditions and to avoid the high cost of direct disposal, the use of centrifuges from the oil and gas industry have been an unconventional choice to ensure the separation of the finer particles from the slurry that only desanders and desilters cannot handle.

This study concerns the utilization of centrifuges to tackle the challenge provoked by the chalk from the Chiltern Hills in the UK, where four ventilation shafts are to be constructed using the diaphragm-wall technique for the High Speed 2 Project. The chalk in question is composed of a very important portion of fine particles that can disintegrate down to 2 μm diameter. As centrifuges are coming from another industry and being on an experimental phase in these construction sites, the study is aiming to bridge the gap between the two industries analysing the efficacy of centrifuges on treating the slurry, along with desanders and desilters, to make it reusable. The analysis exposes the problem of the chalk and seeks to conclude if the chosen plant is effectively suitable and capable of treating the chalk, and advantageous for the circumstances of the site. It focuses on the data collected from the Chalfont Saint Giles and Amersham sites and compares it against other possible solutions, trying to deduce if this

treatment is interesting to future projects. It is indeed a first approach of formal feedback for this kind of solution for a construction site like this.

The document begins by presenting the project and the ground conditions where it is inserted, followed by a description of the diaphragm-wall technique implemented. Then, it introduces both technical and practical points of view about the study with a discussion of the findings and finally, a conclusion.

2. Project

2.1. High Speed 2 Railway

The new High Speed 2 railway project is considered as one of biggest railway projects in Europe. High Speed Two Limited, funded by grant-in-aid from the government, is the company responsible for the development of the new line. The UK government believes that HS2 is essential for the modern and low-carbon growth of the country as it will stimulate the economy and facilitate the travel between lands, reducing the intensity of road traffic. HS2's first construction interventions commenced in the beginning of September 2020 and the project is expected to be delivered around 2040. [12,4]

Although the original budget was £32.7bn, the official price tag was revised and set in 2015 as just under £56bn. Later predictions suspect that the updated value has already raised double the original budget, but the scale of the project makes the task of total costing not obvious. [1,2]

“HS2 is a new high speed railway linking up London, the Midlands, the North and Scotland serving over 25 stations, including eight of Britain’s ten largest cities and connecting around 30 million people.” HS2 [9].

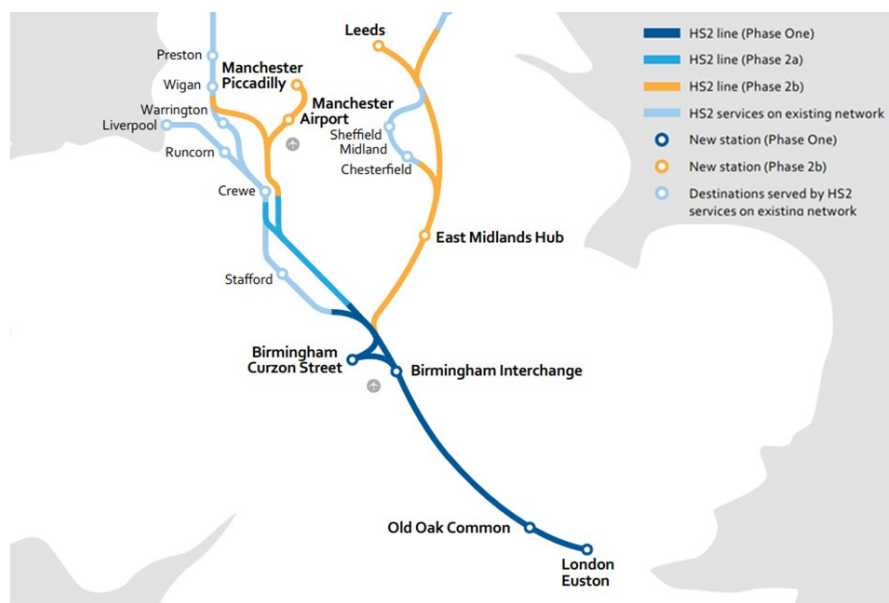


Figure 1: HS2 network map

The construction of this new railway route is split on the three phases:

- Phase One - linking London and the West Midlands
- Phase 2a - linking the West Midlands and the North via Crewe
- Phase 2b - completing the railway to Manchester and Leeds

Table 1 shows the key figures of the project presented to the public.

Table 1: HS2 public key figures [9,14]

Quantity	Unit
343 / 552	miles / kilometres of railway track
45 / 72	miles / kilometres of tunnels
37 / 60	miles / kilometres of viaducts
119 / 192	miles / kilometres of cutting
120 / 193	miles / kilometres of embankment
96,000,000	cubic meters of excavated material
19,700,000	tonnes of concrete (equivalent to 59 Empire State Buildings)
1,900,000	tonnes of steel (equivalent to 207 Eiffel Towers)
224 / 360	mph / km/h top speed of the trains
60	minutes of journey time saving between Manchester and London
300,000	passengers per day
30,000	workers (at the height of construction)

2.2. Host Organisation

Bouygues is large-scale industrial group present in several fields around the world, and its presence in construction is undoubtedly unavoidable. At the end of 2019, the group had 130,500 employees, a turnover of 37,929 M € and a net result of 1,184 M €. This French company has an impact in several countries around the world: among the European majors, in 2018, Bouygues was ranked third in the construction industry, behind Vinci and ACS, with a corresponding turnover of M € ([5,6]).

Of all the departments and sectors in which Bouygues has a large-scale presence, I had the privilege of joining VSL Systems (UK) Ltd, which is directly derived from Bouygues Construction.

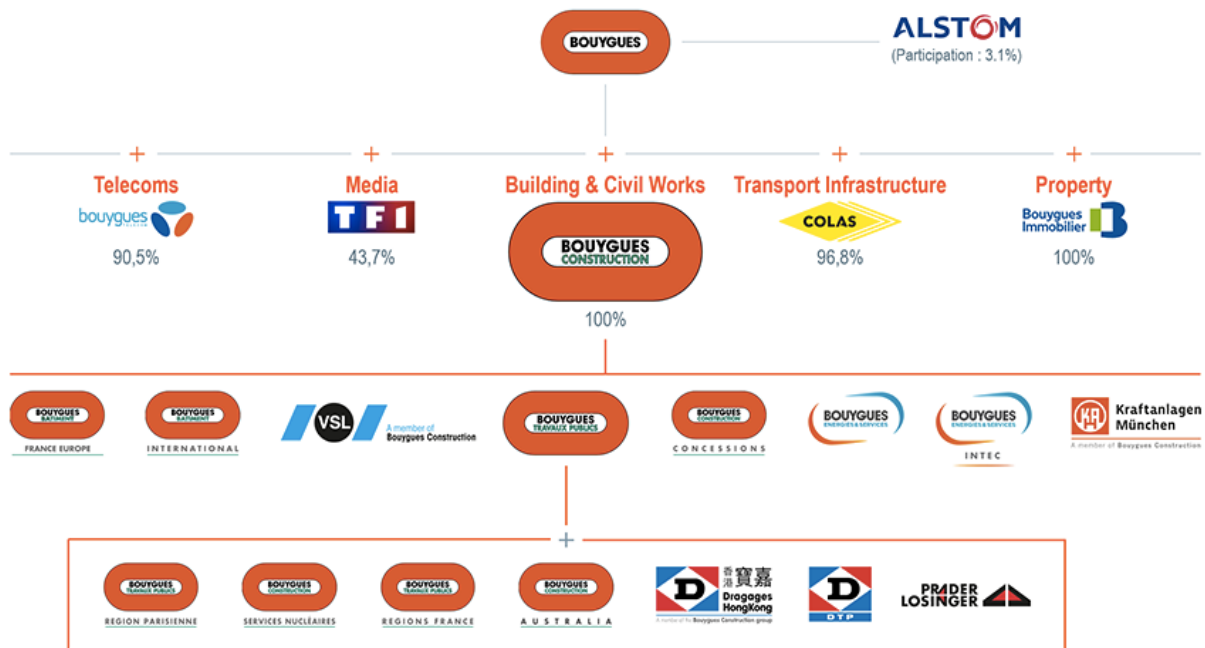


Figure 2: Bouygues' organisation chart [6]

VSL Systems (UK) Ltd is a Bouygues Construction's member operating in the UK and the Republic of Ireland. The company is part of the *Travaux Public*'s pole and is present in the civil engineering industry, specialised in post-tensioned, cable-stayed structures, foundations, and ground engineering. [15,16]

2.3. Personal Insertion

VSL Systems (UK) Ltd and Keller UK Ltd have formed a joint venture to execute the ground engineering works of the Lot C1, which is a section of the High Speed 2 Phase One and covers the main line through Colne Valley and the Chiltern Hills which includes the Colne Valley Viaduct and the Chiltern Tunnel. As Align JV as the main contractor, the client, the Lot C1 was awarded to Keller and VSL Joint Venture (KVJV) and mainly consists of diaphragm-wall, bored piling, grouting and CFA piling works.

2.4. Assigned Lot C1 project - Ventilation Shafts

The Chiltern tunnel consists in a TBM twin tunnel measuring 10 miles (16 kilometres) from Rickmansworth (South Portal), Chalfont line on its northern end to Great Missenden, South Heath (North portal) with five ventilations shafts.

KVJV is responsible for the supporting structure of four of those five ventilation shafts of a key section of HS2's Phase One, using the diaphragm-wall (d-wall) technique. It will construct 1,200 mm and 1,000 mm thickness elements of reinforced concrete diaphragm-walls serving as the retaining/supporting structure of the Chalfont St. Peter shaft, Chalfont St. Giles shaft, Amersham shaft and Little Missenden shaft.

Ventilation shafts are vertical openings connecting underground tunnels to the surface and open air. According to HS2 Ltd [9], the shafts to be constructed have the purpose to:

- Enable the smoke produced in the event of a fire to be extracted in a controlled manner and to provide fresh air in order to create smoke-free evacuation routes;
- Provide access for the emergency services;
- Meet the comfort requirements of passengers and staff in tunnels by keeping the air quality and temperature within prescribed limits.

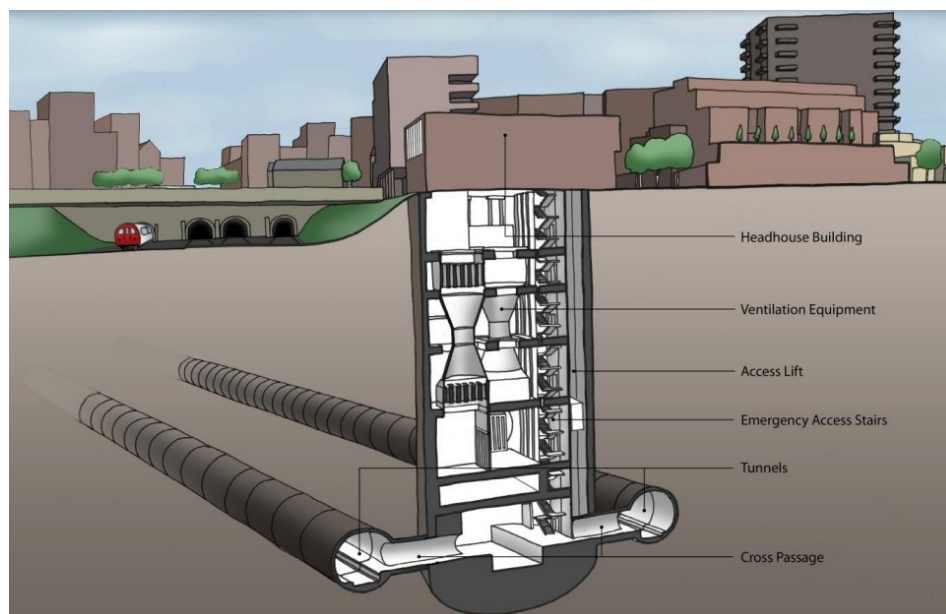


Figure 3: Tunnel shaft 3D model example

The four shafts are all inserted in rural areas which represents a great environmental management challenge, as they are being constructed in high sensitivity sites into an aquifer that is used for public water supply.

2.5. Ground Conditions

The execution of diaphragm-walls for the ventilation shafts requires knowledge of the type of terrain in which the construction of the structural element will be carried out. A proper ground characterization is crucial for any type of engineering project like this which involves stability challenges for the final structure. In addition, and in this case study, for the purpose of the support fluid recycling here implemented, the geological and geotechnical surveys are important because only after the rock mass has been characterised will the equipment to be used for the recycling of the slurries be correctly selected.

Ground investigations were carried by HS2 Ltd., KJVJ's client Align JV and other subcontractors with the purpose of understanding and describing the ground conditions in the locations of the four shafts. Those investigations revealed that the ground conditions are very similar for all the shafts. A deep review was elaborated on multiple boreholes in the vicinity of Chalfont Saint Giles construction site where one of the future ventilation shafts will take place (Figure 4).

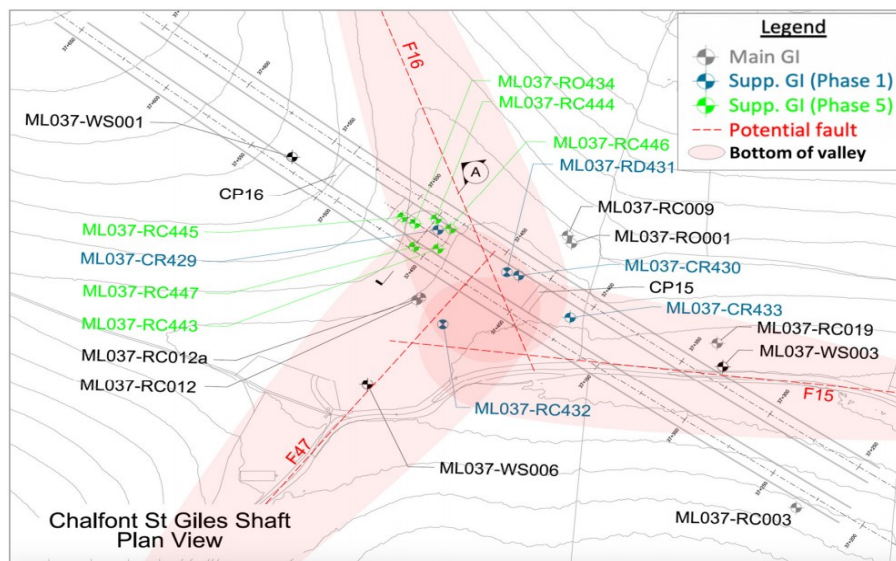


Figure 4: Location of boreholes in the vicinity of CSG shaft.

At first, the ground conditions at the CSG shaft area were only inferred from borehole ML037-CR429. After this borehole showing poor-quality cores, additional boreholes were taken into consideration and new boreholes were performed to provide a greater and better sampling of the ground conditions. At Chalfont Saint Giles, the groundwater level lies at around 16 m below ground level.

Figure 5 shows a sample from **Borehole ML037-RC445**, for a depth between 23.20 m and 26.20 m.



Figure 5: Borehole ML037-RC445 sample (Structural Soils ltd. for Align JV)

This ground investigation led to the conclusion that the four shafts are to be built within chalk ground conditions. Chalk is a soft, white, porous, sedimentary carbonate rock, a form of limestone composed of the mineral calcite. Its formation is mainly due to the accumulation of skeletons of organisms which have sunk or lived in the ancient waters. Calcite is an ionic salt called calcium carbonate or CaCO_3 .

Within the depth of the shaft, chalk is characterized as structureless, structured weathered or structured competent. Natural soils are a mixture of particles that can cover multiple categories according to their size. To represent the distribution of the grains in the various categories, a cumulative statistical distribution is generally used: the particle size distribution

curve is drawn by plotting the percentage of soil material smaller than a certain size, versus that particle size, on a logarithmic scale.

The average particle size distribution curve used as reference for the works is depicted in Figure 6.

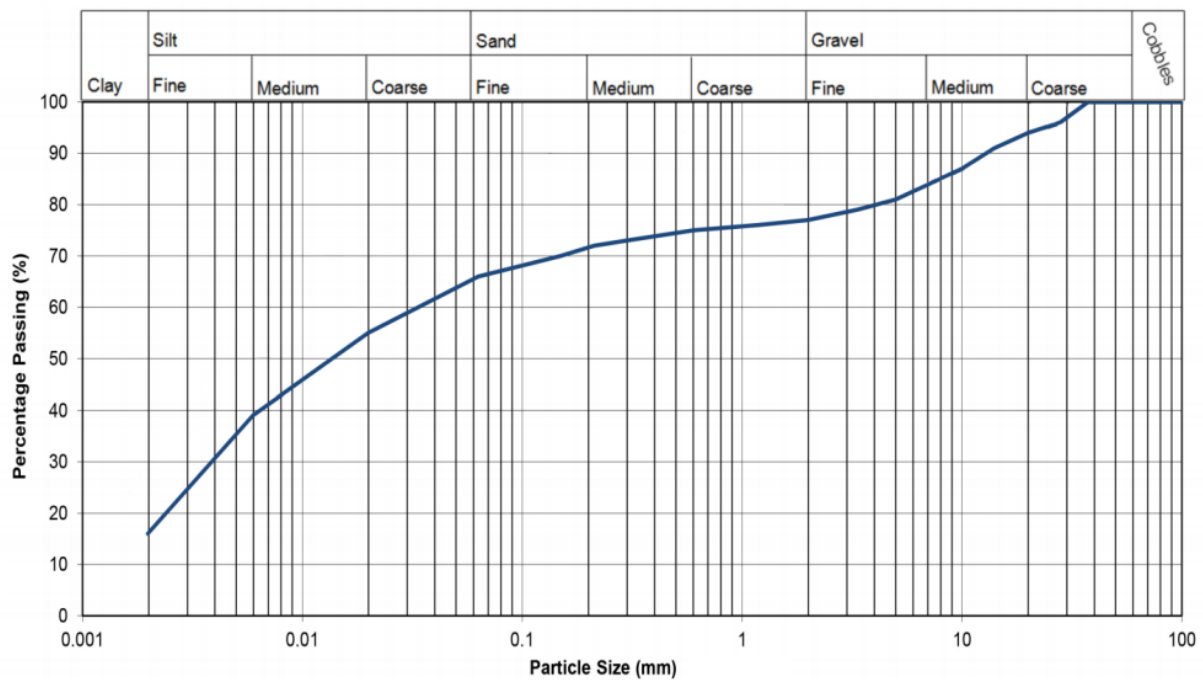


Figure 6: Average PSD curve for CSG site

In average, for Chalfont Saint Giles site, the percentage of material found is distributed for each soil size as per:

- Clays: $\cong 15\%$; Silts: $\cong 50\%$; Sands: $\cong 10\%$; Gravels: $\cong 25\%$
- The D_{50} of this distribution is between 0.01 and 0.02 millimetres

Nevertheless, as this PSD curve is based on samples recovered from the soil cores, gravel sized lumps can be found formed by fine down to $2\ \mu\text{m}$ particles bonded together.

Other geotechnical lab test results revealed the following parameters (Tables 2 & 3):

Table 2: Geotechnical testing results for borehole ML037-RC012A

Geotechnical Testing	
Borehole ML037-RC012A (GEOLABS project Nb. GEO/24973 Amersham Tunnel to Calvert 1G063-AAZ; date of test: February 2017; depth: 9.65 m)	
Water Content [%]	12.6
Liquid Limit (WL) [%]	42.0
Plastic Limit (PL) [%]	15.0
Plastic Index (PI) [%]	27.0

Table 3: Rock testing results for borehole ML037-RC009

Rock Testing	
Borehole ML037-RC009 (GEOLABS project GEO/25022 Amersham Tunnel to Calvert 1G063-AAZ; date of test: February 2017; depth: 39.88 m to 40.20 m)	
Water content [%]	23.0
Degree of saturation [%]	100.0
Bulk density [Mg/m ³]	2.09
Dry density [Mg/m ³]	1.70

Based on the consistency limits obtained for borehole ML037-RC012A and considering a D_{50} between 0.01 and 0.02 millimetres, smaller than 0.075 millimetres (No. 200 sieve), the soil is classified as fine-grained soil following the Unified Soil Classification and then as a lean clay following the Casagrande plasticity chart [8] (Figure 7).

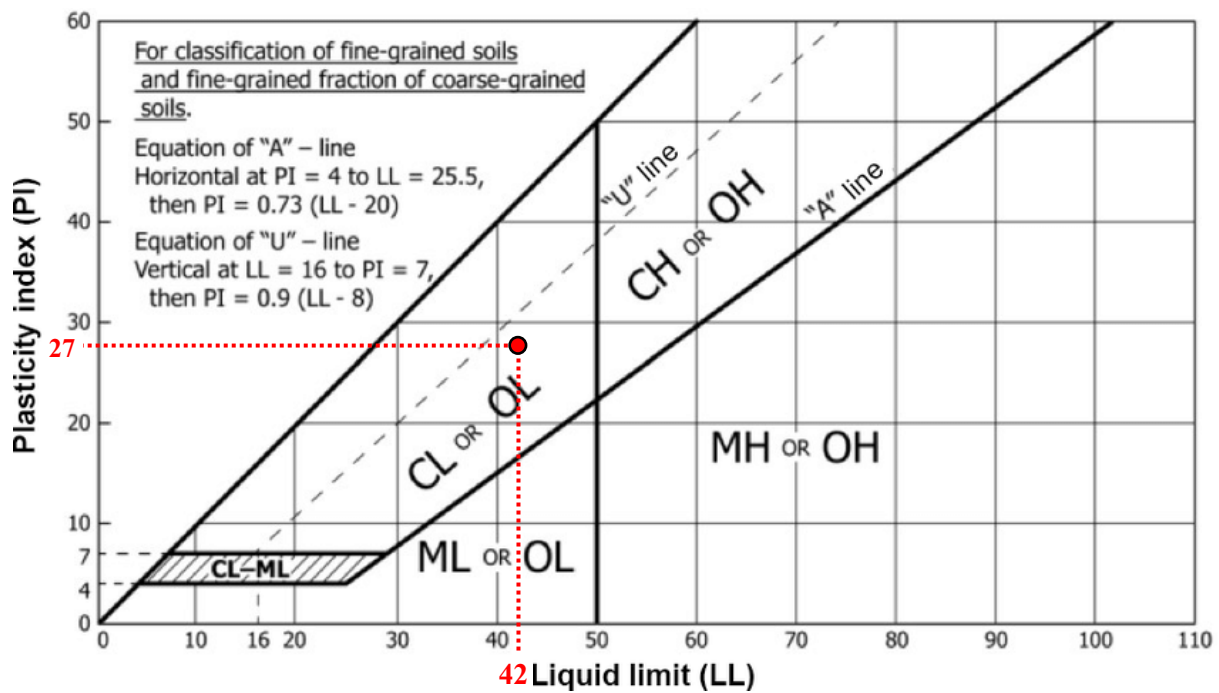


Figure 7: Fine grained soil classification on Casagrande plasticity chart according to ASTM D 2487-85. Point in question depicted on chart.

Finally, the main geological and geotechnical setting parameters for the shaft's design were considered as per Table 4. The future d-wall structure location is also illustrated.

Table 4: Geological/Geotechnical design setting and strata for CSG

Geological/Geotechnical setting			
Soil type	Superficial deposits	0 m	Superficial Deposits
Depth [m]	0 - 1.5		
Typical bulk density [Mg/m ³]	1.94		
K ₀	0.6		
Minimum stiffness E [MPa] (at 0,1% strain)	5	1.5 m	
Soil type	Structureless chalk		Structureless Chalk
Depth [m]	1.5 - 5.5		
Typical Bulk density [Mg/m ³]	1.94		
K ₀	0.6		
Minimum stiffness E [MPa] (at 0,1% strain)	15	5.5 m	
Soil type	Weathered/competent chalk intermixed		Weathered / Competent Chalk intermixed
Depth [m]	5.5 - 60		
Typical bulk density [Mg/m ³]	1.94		
K ₀	1.0		
Minimum stiffness E [MPa] (at 0,1% strain)	300 - 600	16 m	
		43.3 m	Competent Chalk
Soil type	Competent chalk		
Depth [m]	after 60		
Typical bulk density [Mg/m ³]	1.94		
K ₀	1.0		
Minimum stiffness E [MPa] (at 0,1% strain)	600	60 m	Competent Chalk
		60+ m	

3. Diaphragm-Wall technique fundamentals

Diaphragm-walls consists of elements executed in the ground that can provide the role of excavation support, foundation elements or containment structure for underground water flow. A d-wall is constructed by digging a trench in adjacent panels from the work platform to the required depth and thickness using a particular technique. The excavation of the trenches is dependent on specific machines and tools and the borehole walls are held in place by a stabilising thixotropic fluid based on bentonite or polymer slurries.

In this next section, the method applied to this project is presented. There are some variants in procedure within the d-wall technique. The purpose of using this technique on the four ventilation shafts is to bring forth to a peripheral system that will contain waterflow and support ground and water pressures during the excavation and the lifetime of the structure. In this case study, the support fluid is bentonite based.

The main phases of the construction of diaphragm-walls applied to the four shafts are:

1. Guide-Walls Construction;
2. Grab Excavation;
3. Trench Cutter Excavation;
4. Stop End Installation;
5. Cages Installation;
6. Concrete Pouring;

3.1. Guide-Walls Construction

The guide-walls are temporary works and aim to ensure the alignment of the diaphragm-wall, to guide the excavation tools, to avoid ground collapses in the fluctuation zone of the bentonite and to support the loads including the plant loads and the existing structures without excessive distortions and movements. Guide-walls are the first elements to be constructed as they will guide the d-wall sequence for the shaft.

The procedures of constructing the guide-wall are:

1. The surveyor will set out the alignment of the diaphragm-wall;
2. Excavate along the line of the diaphragm-wall;
3. Pour a blinding concrete at the bottom of the excavation;
4. Placement of reinforcement and formwork with the help of a crane, a telehandler or an excavator;
5. Concrete is poured directly from the ready-mix lorry;
6. Once the concrete has sufficiently set, the formwork is removed;
7. Before backfilling up to the ground level, wood props are put in place.

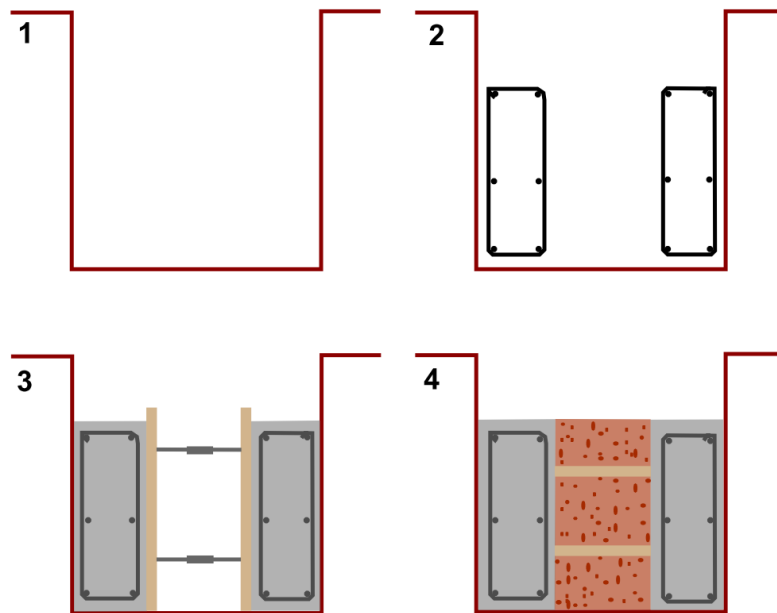


Figure 8: Main steps of the guide-wall construction

1 - Guide Wall trench; 2 - Placing of reinforcement bar cages; 3 - Placing of the frameworks and concrete pouring; 4 - Placing of timbers and backfilling



Figure 9: Guide wall before backfilling

3.2. Support fluid

A support fluid is a fluid that can be used to support an open excavation in the ground. The role of the fluid is primarily to keep the excavation trench open until a permanent element such as concrete is installed. In processes where the support fluid is also used to transport the cuttings back to the surface, the fluid may also be called a transport fluid as it does more than just support the excavation.

All support fluids work by exerting a hydrostatic fluid pressure on the base and the side walls of an excavation. In the presence of ground water, the stabilising pressure at all depths need to be greater than the free-field pore water pressure in order to stop flow of ground water into the excavation.

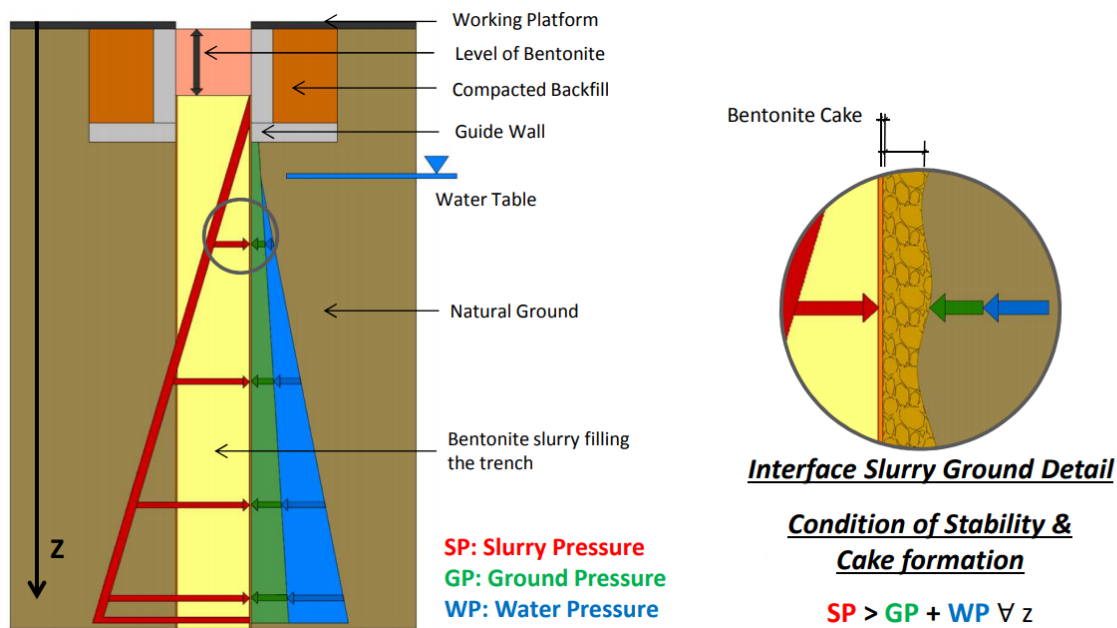


Figure 10: Pressures on an open trench, condition of stability and filter cake formation

A brief and simplified calculation can be performed using the earth pressure coefficient at-rest for natural soils in order to validate the condition of stability. At 5.5 and 60 meters depths as examples (boundaries of K_0 values provided) and considering the ground conditions and support fluid properties provided, the values required to verify the conditions are as per Table 5.

Table 5: Design values table for CSG site:

Design values assumed (CSG site)	
Gravitational acceleration [m/s^2]	9.81
Ground water table depth [m]	16
Ground unit weight [kN/m^3]	19.0
Fresh support fluid unit weight [kN/m^3]	20.11
Coefficient of earth pressure at rest [depth: 0 m to 5,5 m]	$K_0 (1) = 0.6$
Coefficient of earth pressure at rest [depth: 5.5 m to 60 m]	$K_0 (2) = 1.0$

Table 6 shows a verification of the stability condition applying the design values for calculation of the acting pressures for the depths corresponding to the boundary values of K_0 .

Table 6: Acting pressures calculation table

K ₀ boundary values stress calculation - condition of stability									
Depth	K ₀	Vertical stress σ_v	Pore pressure (from 16 m) u	Effective vertical stress σ'_v	Effective horizontal stress σ'_h	Support fluid pressure σ_x	SP (slurry pressure)	GP + WP (Ground and water pressure)	Condition of stability verification
[m]	-	[kPa]	[kPa]	[kPa]	[kPa]	[kPa]	[kPa]	[kPa]	OK/KO
5.5	0.6	104.5	0	104.5	62.7	110.6	110.6	62.7	OK
5.5	1.0	104.5	0	104.5	104.5	110.6	110.6	104.5	OK
60	1.0	1140.0	431.6	708.4	708.4	1206.6	1206.6	1140.0	OK

For the execution of the shafts, the fluid used for the d-wall construction is bentonite slurry, the most common excavation fluid for this type of technique. The definition for bentonite varies according to its applications. Bentonite provides specific physical properties such as strong colloidal interactions, high water absorption, high viscosity, and thixotropy [10]. In a general sense, bentonite can be said to refer to very fine clay particles with a high capacity to increase in volume in the presence of water.

In this special foundation works, bentonite clay (in powder form) and water are combined in a high turbulence colloidal mixer and clay particles bond to each other and set to form a gel when left to stand for a period of time. This period time is called hydration time, happens inside storage silos and its duration on site varies from 6 to 24 hours. When stocked or in standby in the trench, the mud quality and good hydration is maintained by circulation or agitation to avoid potential particle settling or water bleeding. When the bentonite is set in motion, it reverts to the fluid state rapidly due to its thixotropic properties. The bentonite fluid mix can vary depending on the ground conditions and the type of bentonite used: In this case, regarding the concentration, with one big bag (1 m³) of bentonite added with cellulosic polymers is possible to produce around 33 m³ of bentonite slurry.

The bentonite fluid is used to stabilise the excavation in any soil that demands stabilisation: usually non-cohesive soils. Even if the soil in question is considered as sufficiently cohesive, bentonite fluid can be implemented as a safety measure, preventing collapses whenever sandier soil faults are found. Having the properties referred above, a low-permeability filter cake will develop on the soil surface which will reduce the flow rate if there is fluid loss into the ground.

The cake is formed with the hydrostatic pressure of the fluid and its polymer content, creating a millimetric layer of thick fluid (solid residues) at the wall of the panel trench. For coarse soils, a rheological blocking process will first have to be established in the pore spaces before the filtration process can take place.

Bentonite levels and properties are frequently checked during the whole process and the mud needs to be treated or changed before cage installation and concrete pouring. The reasons why the mud is kept under control and why there is a recycling process are explained further down on this document (section 3.7).

3.3. Panel sequence

Regarding the construction sequence of the d-wall segments, the shaft is divided into multiple panels and there are two types of panels to ensure the final quality of the whole d-wall. For CSG site, panel depth is 43.3 m. Figure 11, from the general panel layout plan of a shaft, shows the panel numbering where the panels in grey represent the primary panels and the panels in white represent the closing panels. This overview of the sequence is important for further comprehension on how the support fluid is treated depending on the type of excavation and the excavation tool used.

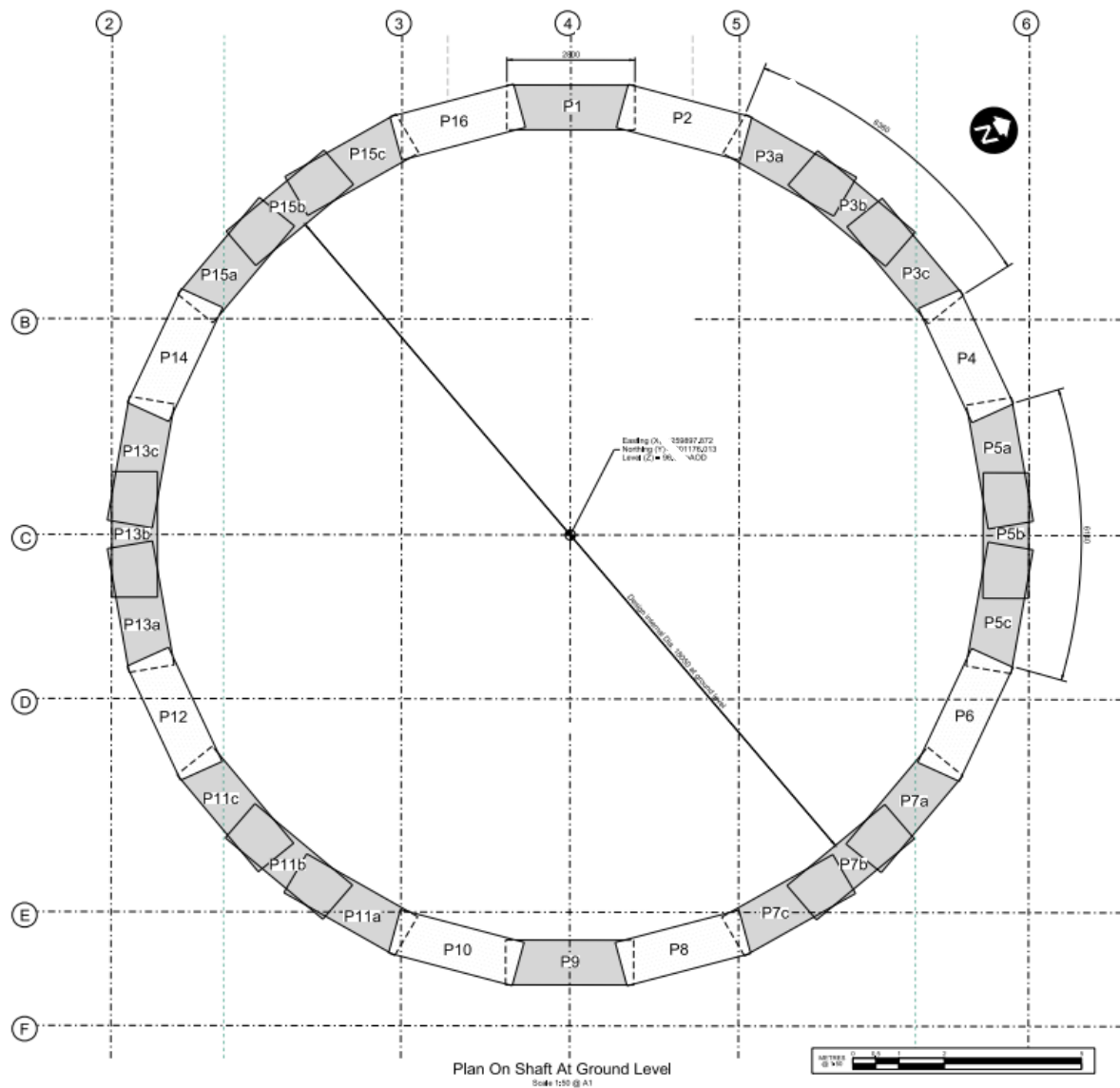


Figure 11: General panel plan layout at ground level

Primary panels are all excavated and poured before engaging to the secondary panels. This necessity is due to two main purposes. Firstly, as time passes after the completion of primary panels, the setting of the concrete will develop so the excavation of secondary panels can proceed without having the excavation area compromised by the fresh concrete nearby. Secondly, closing panels can only be excavated when the two adjacent primaries are completed, otherwise, the excavation tool is at risk of deviating while excavating between a virgin soil and a concrete panel.

The sequence then begins with the primary panels where the excavation takes place directly into the ground with no adjacent panels. Prior to the cage installation and concrete, the primary panels are equipped with stop ends on the first 6 m to, during the future closing panel excavation, make possible the placement of the cutter inside the trench and ensure the water-tightness between panels.

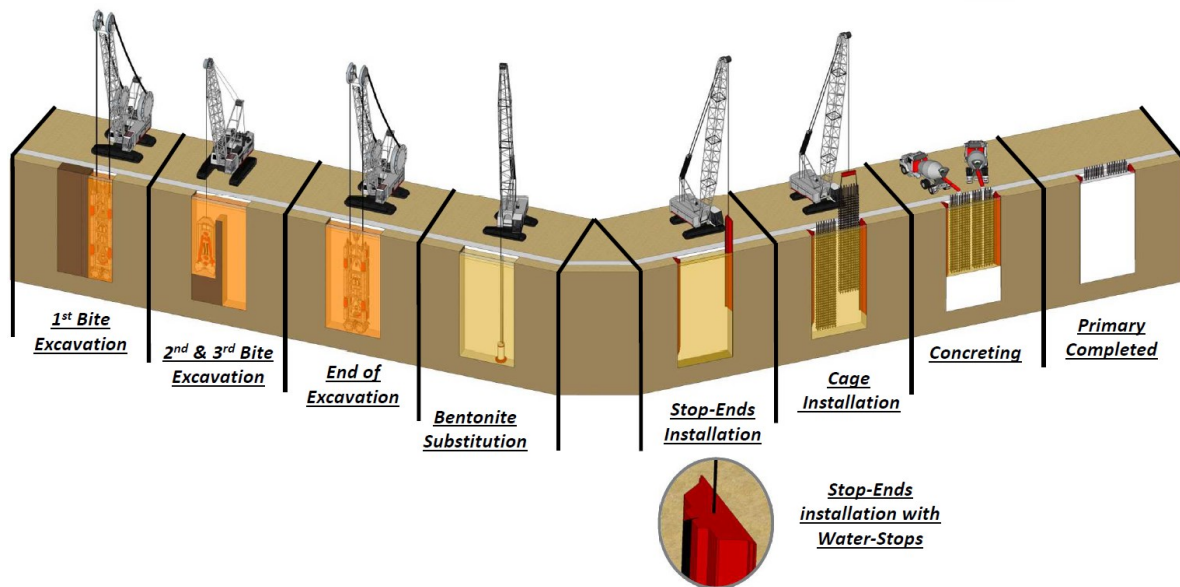
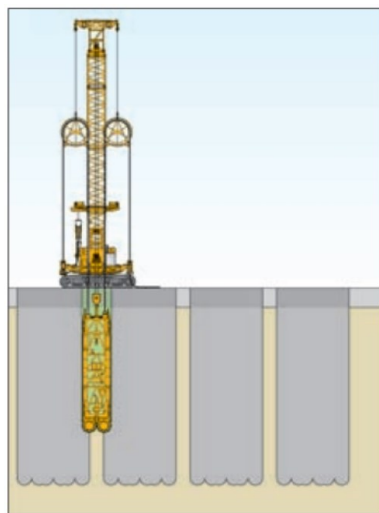


Figure 12: Diaphragm-wall primary sequence (three bite panels)

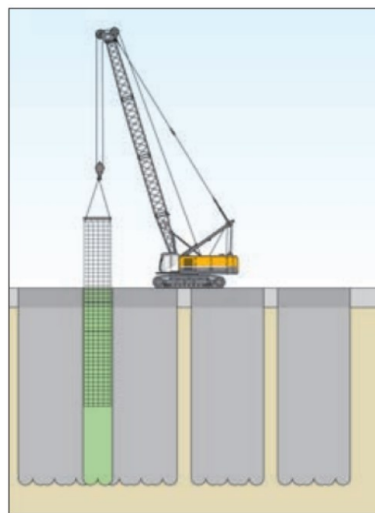
The closing panels are constructed lastly in the sequence. The first meters of excavation of a closing panel will be excavated by grab between the stop ends. The stop ends are elements that serve as a barrier on the top of primary panels and create a void on the interface between the two primary panels and the closing panel in the middle. Once the first 6 meters are excavated with a grab and the stop ends are removed, it is possible to descend the cutter and start the excavation until the toe of the panel by milling the hardened concrete from the previously casted primary panels. This overcut of the existing concrete will ensure the water-tightness and the good concrete joint between the primaries and closing panels (Figure 13).



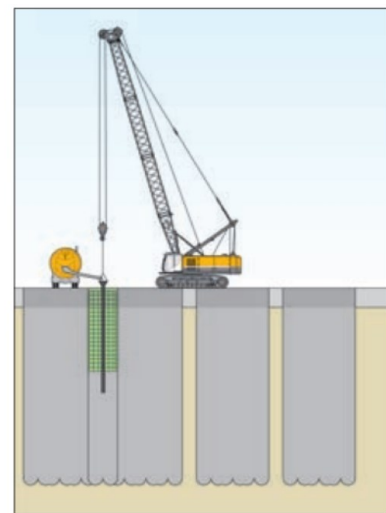
Figure 13: Concreted panel with stop ends installed



Cutting of closing panel



Reinforcement cage
installation



Concrete pouring of closing panel

Figure 14: Diaphragm-wall closing sequence (BAUER catalogue [3])

3.4. Excavation and machinery

Once the operation of the guide-walls is completed, the excavation of the d-wall begins. This operation consists in the extraction of the ground using three main excavation machines, designed to meet the needs of the project's sequence and the type of soil found.

3.4.1. Hydraulic Grab Excavation

The hydraulic Grab is mainly used for the excavation of primary panels unless a hard layer is found. The hydraulic grab can also be used to open closing panels before the excavation by means of a trench cutter and to clean the bottom of a panel. This excavation tool uses a hydraulic system that controls the opening and the closing of the bucket.



Figure 15: Start of hydraulic Grab excavation



Figure 16: Hydraulic Grab bucket full of material ready for evacuation

The Grab is suspended and operated by a base machine and is guided by the guide wall. The excavation proceeds bite after bite while the trench is continuously maintained full of bentonite slurry by the means of a mud pump.

During excavation, the deviation and inclination of the excavation are continuously monitored in the base-machine cabin by the grab operator using the built-in software and can as well be remotely monitored by the site engineers at the jobsite office. In the event of deviation, it is possible to make direct grab adjustments using corrective flaps for inclination.

3.4.2. Mechanical Grab Excavation

A mechanical Grab is used to begin and prepare (for the cutter) the excavation of closing panels and remove flints in the middle of them. Once the primary panels are completed, the hydraulic grab can be demobilised and transferred to the next shafts while the mechanical grab ensures the opening of the closing panels.



Figure 17: Mechanical Grab on standby

The mechanical Grab follows the same principle as the hydraulic one, but, in this case, it does not provide deviation and inclination monitoring. It is simple, raw, and cheaper excavation tool, as the opening and closing of the bucket is controlled by a cable system. However, it is the most demanding tool in terms of operation due to its working principles as only high-skilled operators can operate mechanical grabs. Operators need years of training and experience before being able to excavate with the required specifications.

3.4.3. Trench Cutter Excavation

A cutter is mainly used on closing panels and in the existence of hard soil layers on primary panels (when the grab cannot be efficient).

The Cutter is the most expensive excavation machine on site. This excavation tool is suspended by a base machine and equipped with two wheels fitted with cutting teeth and a mud pump between those wheels. With the purpose of optimizing soil disintegration, the wheels rotate in opposite directions during the excavation. The cutter proves its efficiency on hard

layers, but when the soil is rich in clay, the wheels risk getting mud around them and losing its excavation capability.



Figure 18: Cutter ready after assembly

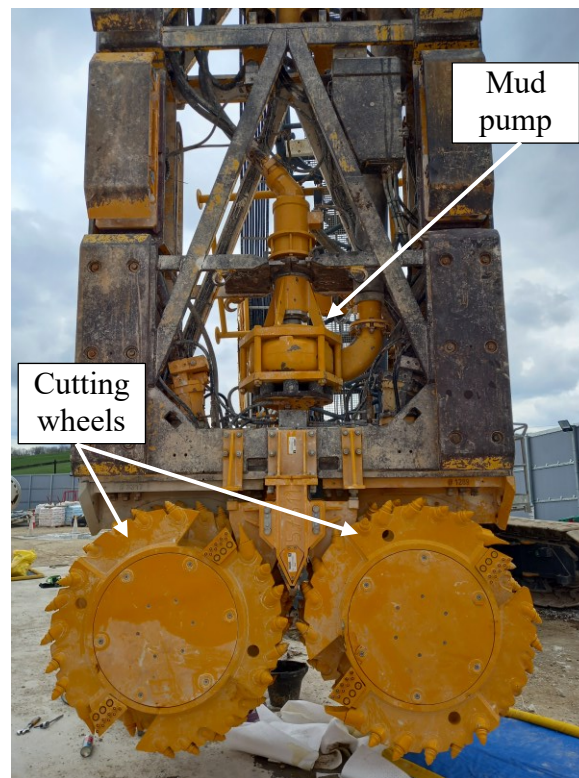


Figure 19: Cutter wheels and mud pump

The cutter needs a minimum depth of open trench so that the mud pump gets submersed. That is why a grab is needed to prepare the panel for the cutter. Once the cutter is submersed, the soil cuttings are then mixed with the slurry, which will work also as transport fluid, and sucked by the mud pump and sent directly to the bentonite recycler unit.

Like with the grab, the trench is continuously maintained full of bentonite slurry. In this case, the pump that feeds the trench needs to be capable of matching the mud flow rate of the cutter's mud pump, which, depending on the excavation rate, can reach $500 \text{ m}^3/\text{h}$.

Regarding the verticality control of an excavation by means of a cutter, deviation and inclination monitoring, the principle is the same as the hydraulic grab.

3.5. Cage Installation

With the help of a crane, this operation consists of lowering one or more reinforcement cages in the trench. Reinforcement cages are previously built and shaped by a steel manufacturer. Among all the technical requirements regarding the quality of the reinforcement and the respect of design drawings, these cages are equipped with two pairs of sonic tubes in all their length for future concrete continuity testing. These tubes will allow the installation of a sonic auscultation device that will send and receive sound signals which will make possible the relation of the speed of propagation of the signal waves with the structural continuity of the concrete.



Figure 20: D-wall reinforcement cage installation (3 bite primary panel)

Before the installation, the panel bottom base must be cleaned with the excavation tool to prevent the settle of debris and the bentonite slurry needs to be recycled and substituted with fresh mud. Then, the slurry properties must be checked, as well as the depth of the panel. If there are no suspected collapses and the deviation is satisfactory, the panel is ready to embrace the reinforcement.



Figure 21: D-wall reinforcement cage installation (1 bite primary panel, stop ends on the sides)

3.6. Concrete Pouring

After the reinforcement cages are installed, concrete is poured into the trench, under the support fluid, through a set or two of tremie pipes depending on the width and length of the panel. The tremie pipes are extended down to the bottom of the trench and as the level of the concrete in the panel rises using an upward motion from the bottom to the top, the tremie pipes are withdrawn in sections. Before concrete pouring, the tremie pipes are lowered to the bottom of the trench and then lifted 10 to 30 cm to ensure the good concrete distribution at the bottom of the trench. The displacement of bentonite slurry until the top will take place by specific gravity gradient with the fresh concrete.

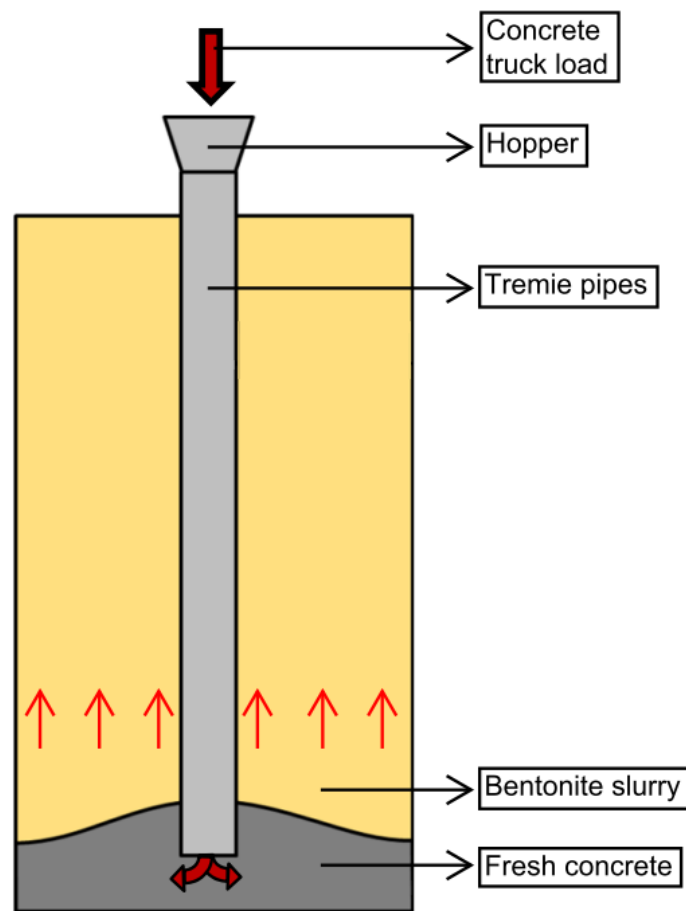


Figure 22: Tremie pipe concrete pouring

The first trucks unloading in the hopper must be quick and simultaneous with all the tremie pipes so that the first volumes of concrete strongly push up the bentonite through the tremies. To avoid an unwanted mixture between concrete and the slurry (bentonite pollution) and to minimise the risk of concrete washout by the mud, a plastic bag full of vermiculite is inserted into the pipe to create a proper interface between the two materials inside the tremie pipes. The aim is to push the slurry with the concrete to the bottom of the panel and then let the slurry naturally come up in the panel. It is ensured that a minimum of 3 m embedment into the concrete is maintained at all times for the same reason.

With the rise of concrete, the tremie pipes will be shortened to maintain a good setting up of the concrete.



Figure 23: Tremie pipes installation



Figure 24: Panel concrete pouring

After each truck is unloaded, the level of casted concrete is measured with a weighted measuring tape and recorded in real time on the concrete curve.

The concrete curve is a good quality inspection factor regarding the panel excavation. The monitoring of the difference between the theoretical curve and the real concrete curve recorded on site during the pouring gives to the engineer evidence of under or over concreting of the panel.

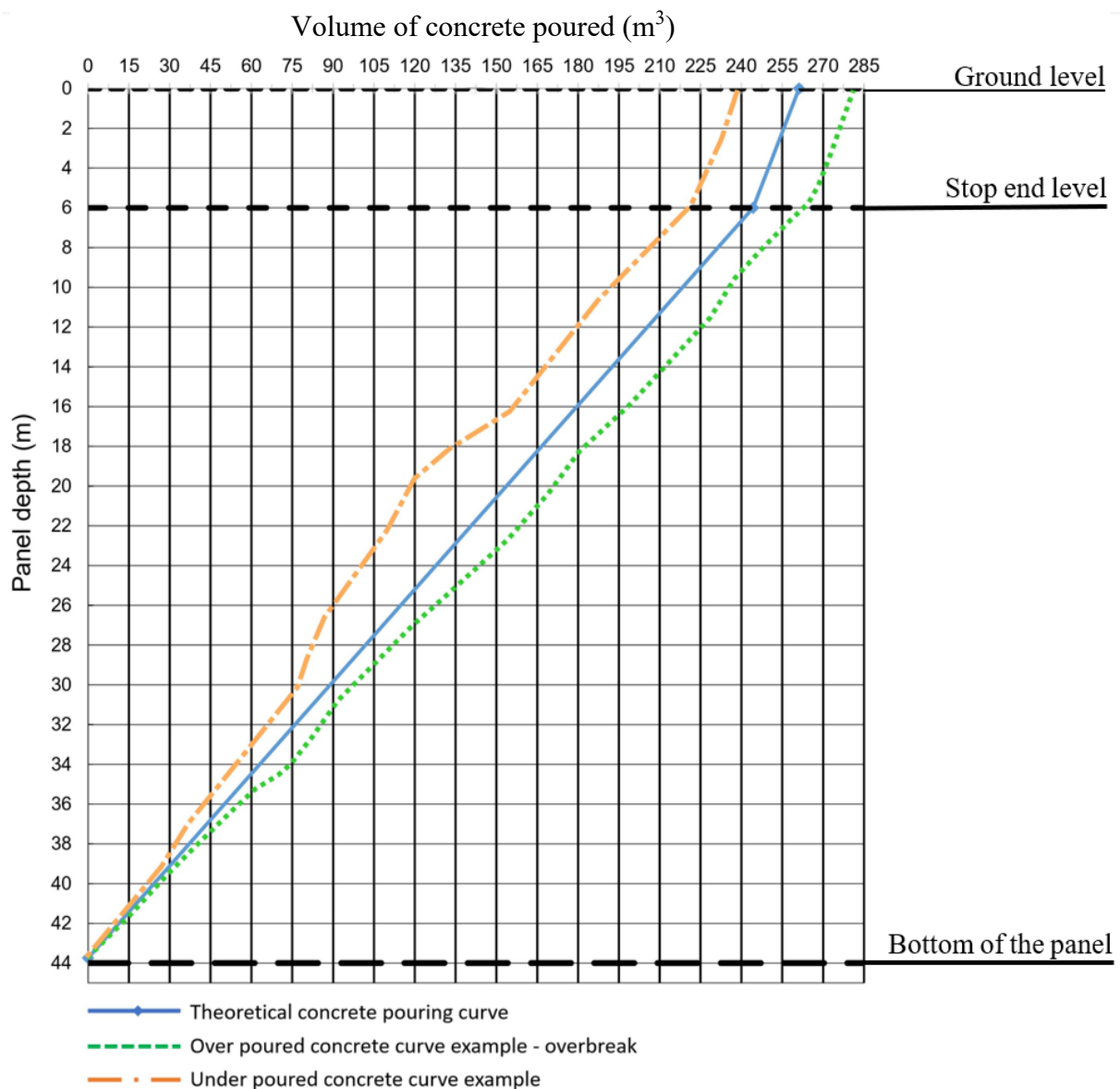


Figure 25: Example of a concrete curve of a primary panel

The “overbreak”, when the real curve tends to follow the green curve of Figure 25, is interpreted as the volume of poured concrete exceeding the theoretical one. This can happen quite frequently as it can be explained by an over excavation: with the raising and lowering of the grab and cutter, the side extremities of the panel can be over excavated. Thus, with soil cohesion irregularities along the depth of the panel, the pressure exerted by the bentonite fluid - which can be enhanced with a piston effect with the lowering of the grab and cutter - can push in less cohesive layers of soil and result in over excavation and transportation of material. If there is indeed an over excavation, an over “belly” shaped d-wall can be seen during the shaft excavation. Inaccurate information about the concrete volume provided by the batching plant can also cause this in the case when trucks come to site with less concrete than what was communicated.

The source of the second phenomenon, however, can be more problematic: when the real curve tends to follow the orange curve of Figure 25, it can be an indicator for ground collapses inside the panel during the pouring. This can happen when the behaviour of the soil is not what was expected or that the support fluid was not as effective as it should be. When panel collapses are detected, the pouring must not stop until the contaminated concrete reaches the top and is taken out. Nevertheless, the risk for slurry mixing with the concrete and slurry deposition at the lateral extremities of the panel rises. This may lead to remedial works for the shaft such as injection grouting.

3.7. Control of the bentonite slurry properties

The support fluid follows some rigorous standard quality values that need to be checked frequently during all the d-wall works, especially before cage installation and concrete pouring to ensure good quality d-wall panels. As a support fluid, when in contact with the liquified soil during excavation, bentonite slurry gets contaminated with soil particles which will make the bentonite slurry gradually lose its quality and ability to work with as d-wall support fluid. This contamination intensifies during the excavation by the trench cutter since the fluid is also used as transport fluid and continuously mixed with loosened and broken soil material. The use of the trench cutter proves therefore to be a critical criterion when it comes to the loss of bentonite properties.

With the slurry quality varying depending on the stage of the d-wall works, it is characterized in four different quality levels:

- Freshly mixed: virgin fabricated bentonite slurry
- During excavation/digging: already partially contaminated bentonite slurry from the excavation
- Ready for reuse: treated excavation bentonite slurry ready for use in the next panel
- Prior to concreting: freshly mixed bentonite slurry ready to use prior concrete pouring (can be treated and reuse for the same purpose)

Table 7 presents the main quality compliance requirements established for the shafts' works for each type of fluid, following the Institution of Civil Engineers (ICE):

Table 7: ICE Typical tests and compliance values for sodium activated bentonite support fluids [11]

Property to be measured	Test method and apparatus	Compliance values			
		Freshly mixed	Ready for reuse	During digging	Prior to concreting
Density: g/ml	Mud balance	<1.05 g/ml	<1.08	<1.35	<1.10
Fluid loss: ml at 30 minutes	Low temperature fluid loss test	<30	<50	n/a	n/a
Filter cake thickness: mm at 30 minutes	Low temperature fluid loss test	<3	<6	<15	<3
Marsh funnel flow time: seconds	Marsh cone	30–50	30–60	n/a	30–50
Shear strength (10 min gel strength): N/m ²	Fann viscometer	4–40	4–40	n/a	4–40
Sand content, per cent by bulk volume	Sand content set	n/a	n/a	n/a	<2*%
pH	Electrical pH meter to BS 3445; range pH 7 to 14	7.5–11	7.5–12	7.5–12	7.5–12
Notes: * A 4% limit on sand content prior to concreting maybe permitted where the cleanliness of the base and end bearing performance is not critical. A 'during digging' column has been included in the table. The compliance limits are provisional pending the development of a database of results. Control of cake thickness is the key parameter as excess cake may not be removed during excavation cleaning. Slurry densities have been reduced from those of BS EN 1538 which are more permissive than is useful for most UK work. The density limit of 1.05 g/ml for freshly mixed slurry limits bentonite concentration to 8%. The density limit of 1.08 g/ml for ready for reuse slurry limits soil contamination of slurry to about 90 kg/m³ in addition to the bentonite. The density limit of 1.35 g/ml for digging slurry allows soil contamination of slurry up to 530 kg/m³. The density limit of 1.10 g/ml for ready for concreting slurry limits soil contamination of slurry to 120 kg/m³. The requirement for a minimum gel strength should be applied only when there is a specific requirement for gel strength such as limitation of slurry penetration into coarse ground.					

On one hand, a denser slurry means being on the side of safety regarding its hydrostatic capability of supporting the ground. On the other hand, the mud needs to comply with the above parameters in Table 7 because such particle contamination notably leads to density and filter cake related problems. Those problems can be structural and visual regarding the d-wall panel or even of pumping nature:

- A denser slurry containing soil fines will result in a thicker and excessive filter cake which can lead to: inclusions of mud on the lateral extremities of the panel (causing reinforcement-bar exposure); inclusions of mud stuck to the cages' reinforcement bars compromising the good marriage between the concrete and the steel; inclusions into the concrete during the pouring as the separation between the two fluids becomes more complicated.
- A denser slurry gives rise to particle settling, which means increasing the quantity of cuttings at the bottom of the panel.
- Too dense excavation mud will reduce the performance of the many pumps and equipment on site required for the process. The wear of the equipment will also increase equipment maintenance related costs; It also increases the floatability of the tools and thus decreases their "weight when excavation" by reducing the penetration speed. Consequently, it will reduce the general production rate.
- The pH is also important to maintain between acceptable values, as very high pH values can break and "burn" the polymers added to the treatment cycle in the slurry and neutralized their actions.

Therefore, bentonite slurry properties, especially the density as main indicator, will be the key elements affecting the definition and election of treatment procedure and plant of the support fluid during the works.

To maintain the desired properties of the mud and use the trench cutter as excavation tool, the use of desanders and desilters are typically effective for bentonite recycling as they remove soil particles down to 30 μm . This equipment is developed to separate solids from a fluid by running it through screens, shakers, decanters and hydrocyclones. The recycling of bentonite fluid in soils composed down to medium silts is therefore a common part of the process for d-wall excavation and the treatment of the fluid is often call "desanding".

However, in ground conditions that release a larger quantity of fines into the slurry, such as chalk, the recycling can get more difficult and other types of separation technology and equipment not so conventional may be necessary. (Lam C, Jefferis SA and Suckling TP (2008). [13]).



Figure 26: Freshly mixed bentonite in mixing tank



Figure 27: Cutter partially submersed in bentonite fluid during panel excavation

4. Study on bentonite support fluid recycling for excavation into the Chilterns Chalk

4.1. Chiltern Hills Chalk

Chalk is considered as the one of largest geological features in Britain. With its unavoidable presence from a geological point of view and recalling the massive White Cliffs of Dover, it makes part of England's cultural history. Figure 28 illustrates the distribution of soluble rock types in Great Britain, where the strong presence of chalk is clear.

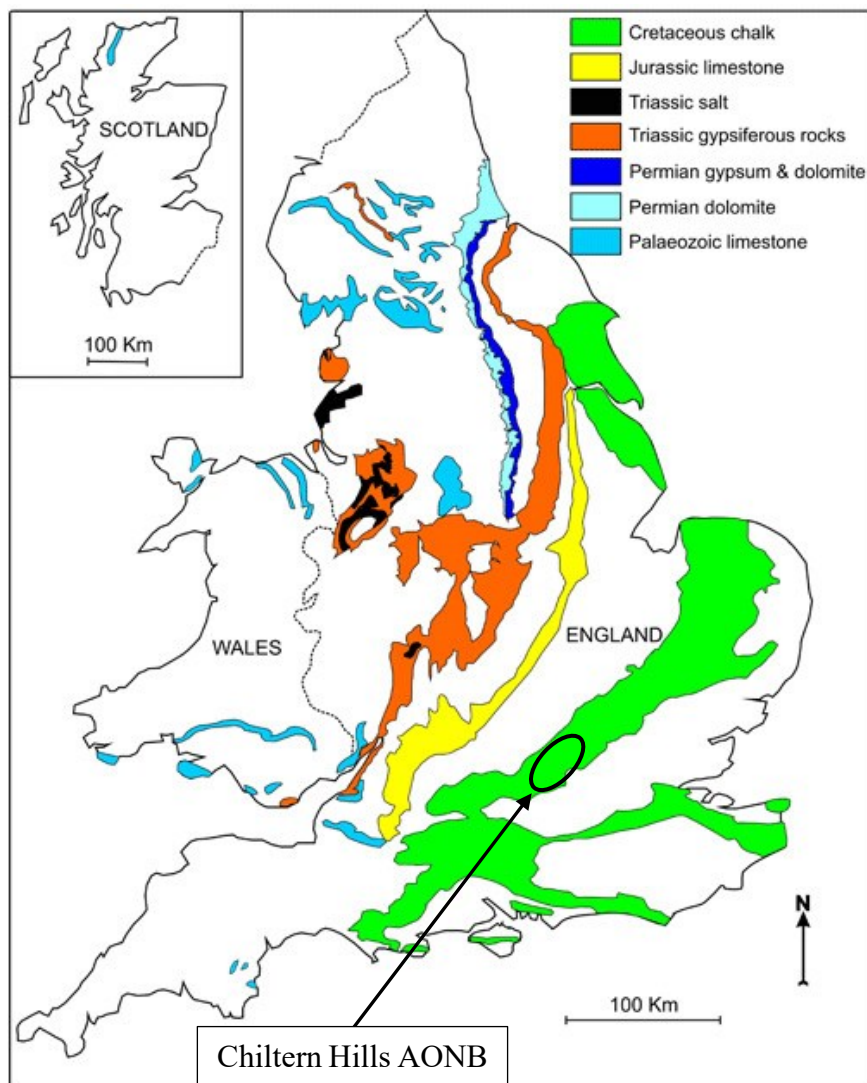


Figure 28: Soluble rock types and their distribution in Great Britain. Based on the BGS 1:625 000 scale Bedrock Geology map of the UK. BGS © UKRI.

Chalk is an important element to take on consideration for foundations works as it can bring many challenges due to its often structureless, permeable and soluble characteristics, leading to risk of cavities and even sinkholes (BGS [7]). However, cohesive weathered and competent chalk can be found depending on the depth and layers reached during the works.

Picture in Figure 29 shows a nodule of competent very cohesive chalk collected at CSG site during the excavation.



Figure 29: CSG chalk sample

Although chalk can bring obstacles in the foundation engineering industry, this study focusses on how the different chalk structures (like the nodule shown in Figure 29) will deteriorate and contaminate the support fluid during the works.

4.2. Chalk contamination in the slurry

The chalk present on the case history area creates challenges regarding the management of the bentonite slurry used for the excavation. As presented in section 2.5., a great portion of the

chalk can be considered as “fine” and therefore possibly finer than what a desander or a desilter could handle in terms of particle separation.

Chalk is suspected to release a great amount of fine particles during excavation while it disintegrates as it will get mixed and diluted into the bentonite slurry. Before considering what type of equipment to use for the recycling procedures, studies have been carried out by MS SAS on behalf of Align JV to prove the phenomenon of chalk dilution in the slurry. For this study, the tests consisted of observing the evolution over time of the chalk’s dilution in bentonite slurry by putting a chalk sample in a cement mixer full of bentonite slurry (the same slurry later used during the works of the ventilations shafts). Results on Table 8 and Figure 30 clearly show the high increase of the concentration of fine particles below 63 μm in bentonite slurry. Thus, the concentration of particles between 6 mm and 63 μm also increases. Finally, concentration of the coarser particles above 6 mm decreases. This happens as chalk deteriorates in correlation with the time spent on a cement mixer. The cement mixer can simulate the mixing of soil and fluid happening during the excavation by means of a cutter and the transportation of fluid by the site pipelines and pumps.

Table 8: Chalk dilution in bentonite slurry test results (data provided by Align JV)

Chalk dilution in bentonite slurry test			
Time in cement mixer [min]	% > 6 mm	% 6 mm to 63 μm	% < 63 μm
5	68,0%	3,2%	28,8%
10	53,0%	7,0%	40,0%
20	36,0%	14,4%	49,6%
30	27,5%	18,1%	54,4%
60	15,5%	23,7%	60,8%

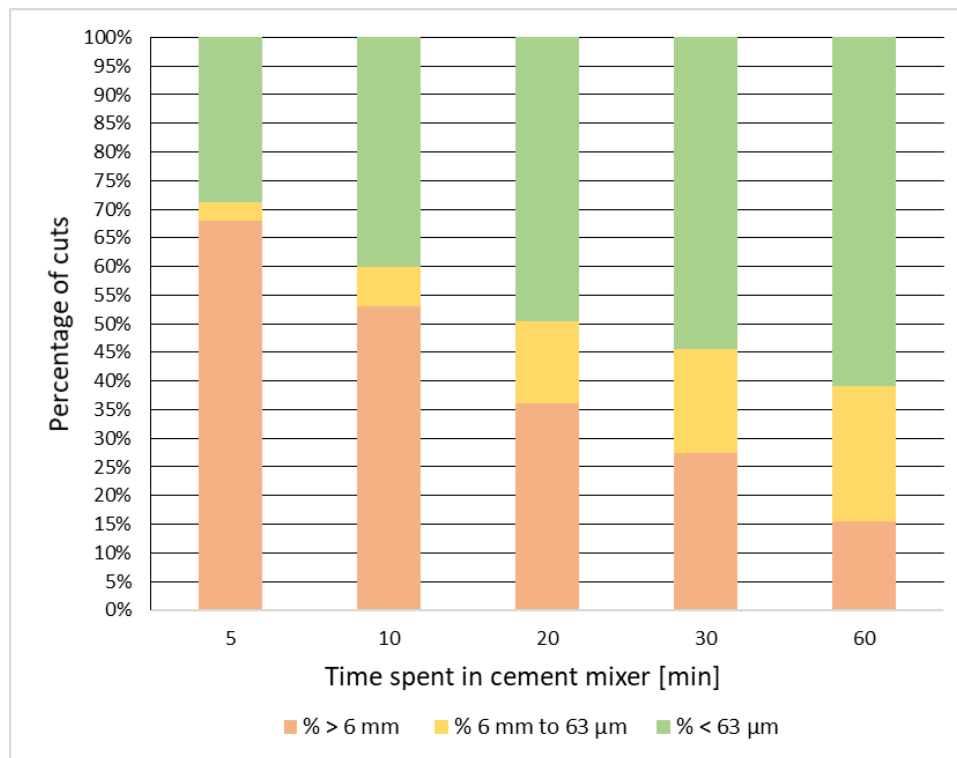


Figure 30: Chalk dilution in slurry graph (data provided by Align JV)

The chalk contamination is therefore a factual phenomenon that will bring constraints to the bentonite recycling. The longer the chalk remains in the slurry and goes through mechanical equipment, the more particles of finer chalk are released in the slurry because of particle breaking with time in the system. Additionally, with the breaking of particles and the increase of the finer portion, the specific surface area of the mass will also increase. This leads to a greater water adsorption and apparent viscosity.

The extraction the fine chalk from the slurry will not be possible if only desanders and desilters are used. Consequently, the properties of the bentonite slurry will not be maintained during the works if a proper recycling system is not implemented.

4.3. Bentonite recycling system procedure for excavation with trench cutter: set up and main components

To excavate a d-wall panel with a cutter, a great pipeline set up is required for the works regarding the bentonite fluid management and there is a need for a recycling unit (desander and desilter) and a centrifuge. Before lowering the cutter into the trench, the panel is already opened

and full of bentonite until the first meters excavated by the mechanical grab. Then, two phases of the works must be distinguished for the understanding of the bentonite management:

- Panel excavation and cleaning of the support fluid
- Bentonite fluid substitution and panel concrete pouring

Firstly, when the cutting begins, the cutter's mud pump operates on a closed cycle with the main 20ft Desanding/Desilter Unit also known as 20ft Recycling Unit. The contaminated bentonite fluid transporting the soil material from the bottom of the panel is sent to this 20ft Recycling Unit which will desand and desilt the bentonite fluid and then send the recycled bentonite fluid back into the panel. This happens all along the excavation of the panel and a constant production of solids, considered as waste, comes out of the 20ft Recycling Unit. These solids are only a portion of the particles coming from the soil disintegration provoked by the excavation. Connected in parallel with the 20ft Recycling Unit, two centrifuges are required to assist the recycling process and remove the remaining finer portion of the contaminant particles, which will also end up as waste. Despite the good effectiveness of both types of machines, the solid disposal always contains some liquid waste as well. The sum of this liquid losses, the bentonite fluid losses in the panel due to ground infiltrations and the added volume to fulfil and follow the excavation forces the adding of excavation bentonite in the system, provided by working bentonite stockage pool. When the excavation of the panel is completed to the target depth, the whole volume of the bentonite fluid is treated in the system until the values of the mud are as good as per the required parameters for a ready to reuse excavation bentonite.

Secondly, the preparation of the panel for the concrete pouring takes place. After verifying the mud values, the fluid is ready to be stocked back in the excavation bentonite pool. The next step is then the bentonite substitution where the excavation bentonite is sent to the pool and the panel is fed with fresh bentonite. Even if the excavation bentonite parameters are as good as the fresh one, the substitution, as well as the separated stockage on site of both qualities, is an internal requirement to insure perfectly good and thin bentonite fluid prior to the concrete pouring. This thin bentonite fluid should not be used for excavation, as its density is low and close to the limit of what the slurry should be for a support fluid behaviour. Finally, the concrete pouring starts, and the fresh bentonite is pumped out of the panel as its level rises due to the concrete at the bottom of the panel. The bentonite contaminated with soil particles from the

walls and possibly with the cement rising from the concrete is treated with a smaller recycler, the 10ft Desanding/Desilting Unit, and then again stocked in the fresh bentonite silos.

Figures 31 and 32 & 33 characterize a simplified bentonite set up plan based on what was implemented for the above-mentioned phases of the panel work.

A recipe of products in the form of powder or liquid are also included in the system (added in the mixing unit or directly in the ready for reuse mud tank or centrifuge pipelines) when necessary. Table 9 resumes the products to be added and their role in the mud maintenance.

Table 9: Additive products to improve the mud properties

Additive products to improve the mud properties	
Product	Effect
PAC LV (polymer)	To reduce filtrate and control viscosity (long polymer chains)
PAC HV (polymer)	To reduce filtrate control viscosity (short polymer chains)
Sodium bicarbonate	To adjust the pH and unflocculate mud in case of cement contamination (for closing panels)
Soda Ash	To soften water and adjust pH
Citric Acid	To correct quickly and efficiently the pH of a cement contaminated mud
Flocculant polymer	To flocculate the particles
Coagulant polymer	To coagulate the particles

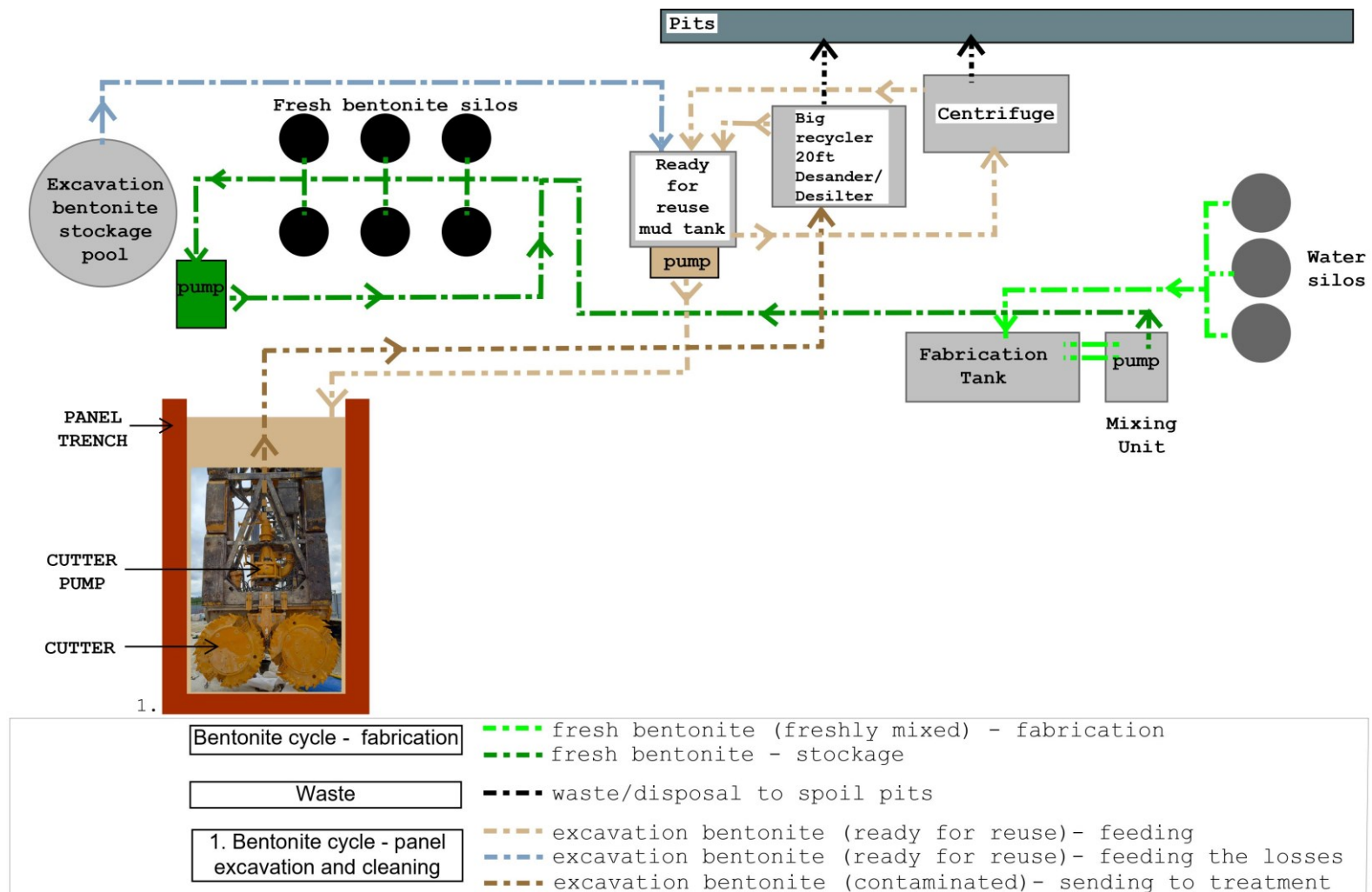


Figure 31: Simplified bentonite fluid cycle - Panel excavation and cleaning of the support fluid



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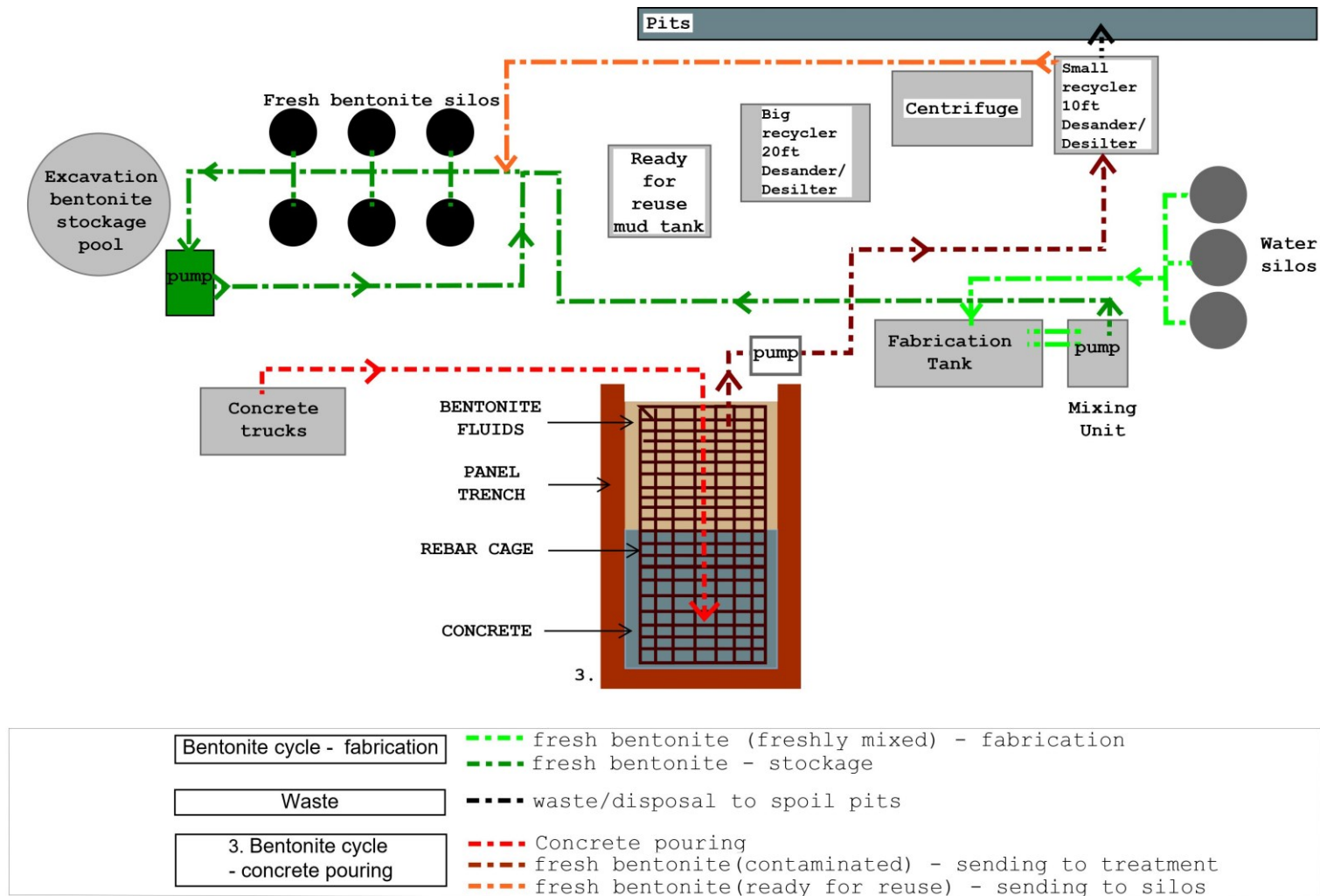


Figure 33: Simplified bentonite fluid cycle - panel concrete pouring

4.4. The role of desanders, desilters and centrifuges

The chosen equipment for the bentonite slurry recycling consists of a 20ft Desanding/Desilting Unit (Derrick Stepoiltools 20ft Recycling Unit), a SOBB55 Centrifuge (Derrick Stepoiltools) and a Flotwegg Z92 Centrifuge – Figure 34. This kind of equipment is well known in oil and gas rigs where water/solids/oil separation is a key factor for the drillings. The proposal for the use of this plant installation to manage the fluid for this d-wall project is therefore inspired from that industry, especially regarding the centrifuge which is not so common compared with desanders or desilters.



Figure 34: 20ft Recycling Unit and Centrifuges.

The 20ft Recycling unit is a three-level unit composed by multiple vibrating screens and hydrocyclones. Each one of these components are particle separation systems for different particle size targets. This equipment can remove big soil lumps, desand and partially desilt particles from the excavation bentonite fluid until around 10 μm . Below 10 μm sized particles, the 20ft Recycling Unit is not capable of removing the chalk's finer particles in the system that can go down to 2 μm . To remove the chalk below this range, the SOBB55 centrifuge is used as the last step of the recycling process. In purely mechanical mode (decanting mode), the centrifuge can remove particles sized down to 8 μm and if polymer flocculant is added to the system (decanting + polymer mode), the centrifuge is capable of removing particles sized down to 2 μm . The distribution of particle size targets for each equipment are depicted in Figure 35. The Flotwegg Z92 Centrifuge follows the same functioning principle as the SOBB55 but can run at higher flowrates and is essential for the bentonite fluid breakdown at the end of the jobsite which involves decanting the mud with added flocculant and coagulant polymer to almost completely separate all the solid matter from the water.

A sketch of the complete recycling installation as well as the path the fluid takes between the machinery during installation is depicted in Figure 36. To reduce the exposure of the fluid to additional pumps that increase the breaking of the chalk particles, the 20ft Recycling Unit is designed in such a way that there is only one main pump that sends the flow to the top floor. The flow then arrives to the first top set of screens where the fluid passes through a vibrating screen separating the first coarser particles. Then, the fluid continues to the second set of screens following the same methodology but now filling with its underflow the first chamber of the intermedial mud tank inside the 20ft Recycler Unit. From this chamber, the flow is pumped into the hydrocyclones which will, by centrifugal force, concentrate the coarse particles into the underflow and make them pass again through the second set of screens while the treated upper flow by the hydrocyclones is reinjected into the second chamber decanted by overflow from the first one. Finally, a third chamber filled by overflow of the second one is the last step of the 20ft Recycling Unit leading to the ready to reuse mud tank. The flow capacity of the 20ft Recycling Unit is around 400 m^3/h . From the ready to reuse mud tank, the SOBB55 Centrifuge collects a flowrate of around 50 m^3/h in pure decanting mode and around 30 m^3/h in decanting mode with added polymer flocculant, treats the mud by separating the finer particles of chalk and sends back the recycled mud back to the tank. While excavating, the complete system

keeps up with the trench cutter mud pump that runs between 250 m³/h and 450 m³/h and can reach the 500 m³/h.

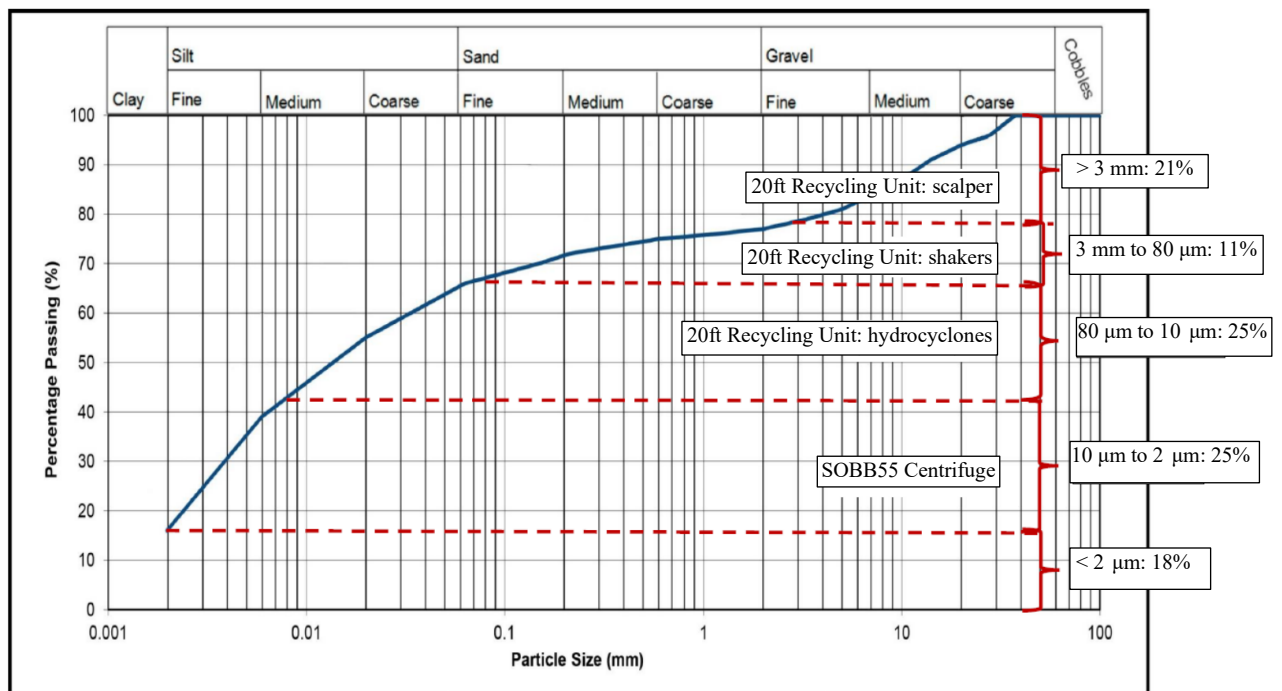


Figure 35: Equipment cut off points distribution on PSD

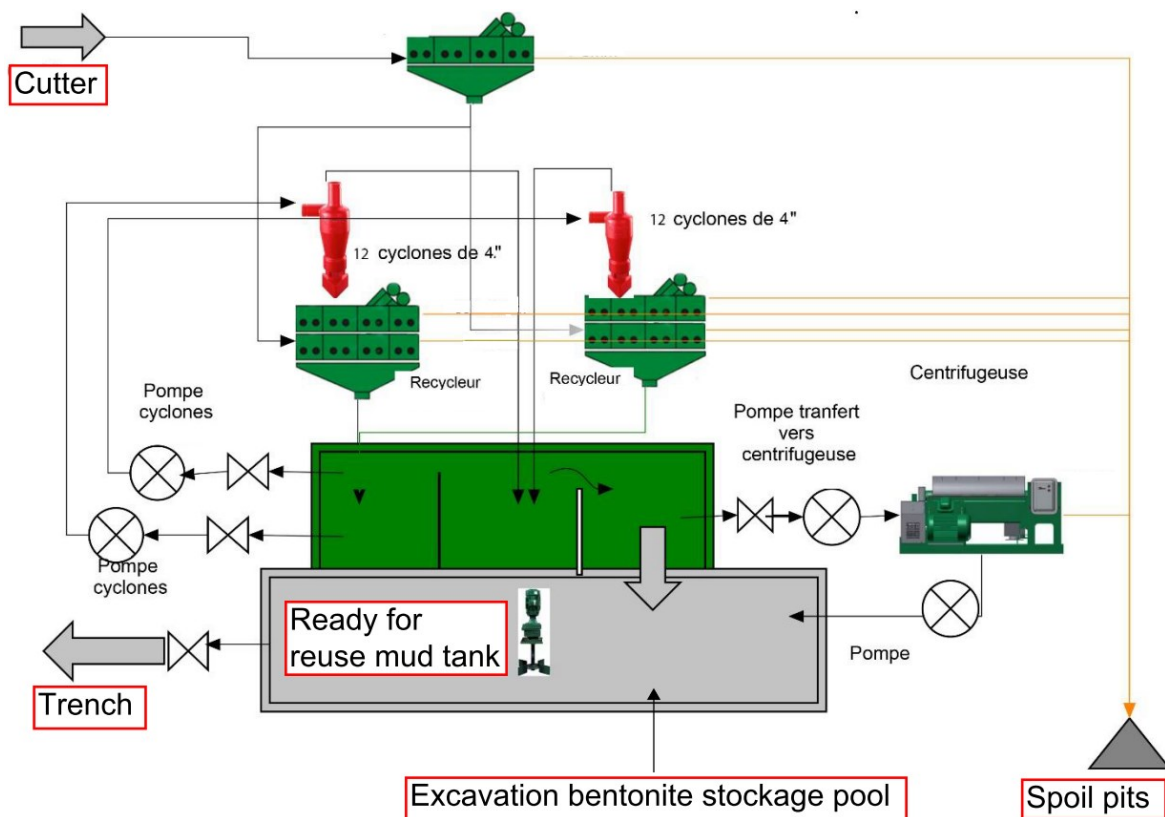


Figure 36: Bentonite fluid recycling path (20ft Recycling Unit + SOBB55 Centrifuge)



Figure 37: Recycling set up component: 1-Vibrating screens (first set); 2-Vibrating screens (second set); 3- Hydrocyclones; 4- SOBB55 Centrifuge

The key elements for the recycling system effectiveness are therefore:

- A recycling unit with shakers, screens and hydrocyclones adapted to the problems encountered
- The contribution of the centrifuge
- The reduced number of pumps in the process
- The chemical treatment

Hence, having a centrifuge is essential for the recycling system, as it removes the finer particles of chalk soil that contaminate the slurry. It is predicted that without it, those finer particles would accumulate in the system and the mud properties would reach a state where it would not be possible to handle and to be considered as fluid to achieve good quality d-walls.

A SOBB55 Centrifuge sketch is depicted in Figure 38. Performing centrifugation in the system is a way to speed up the phenomenon of decantation. The slurry enters the centrifuge chamber through a centre pipe, and this chamber called bowl will spin at high speed and deposit the solid particles, which are denser, on the walls of bowl. Then, a spinning conveyor composed by permeable blades transports and discharges the solids to an extremity of the bowl while the liquid will overflow and send back to the 20ft Recycling Unit by the opposite extremity of the bowl.

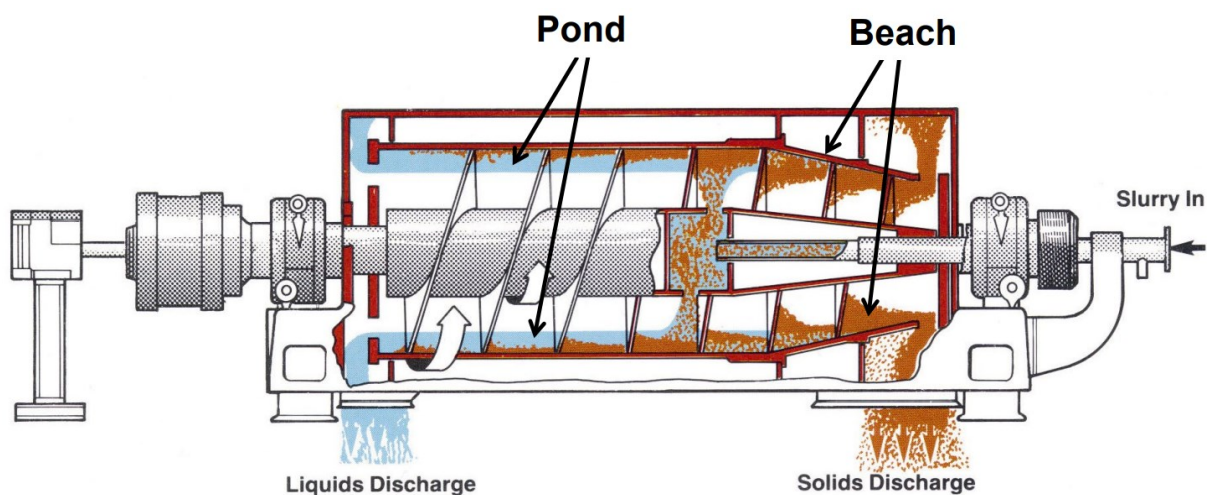


Figure 38: Centrifuge operative sketch (Derrick Equipment Company)

Picture in Figure 39 shows the discharge point of the centrifuge solid waste. What looks like a fluid and wet liquid due to its very fine composition, it actually feels like dry clay at touch.



Figure 39: Centrifuge decanting solid waste discharging point during excavation

4.5. The influence and need of a centrifuge as part of the bentonite fluid treatment process during excavation

As mentioned earlier, the density of the fluid is the most important property to be maintained between proper values to secure the management of the mud and to ensure the quality of the d-wall. With the aim of profiling the results obtained for the density of the bentonite support fluid during the excavation, a data analysis of multiple samples taken from the ready for reuse mud tank was carried out. To isolate the effect on the mud contamination using the cutter, the sampling period consists of 29 working days which represents the period when only the trench cutter was used as excavation tool at CSG jobsite. These mud tests are part of the everyday

basis quality control tests of the operating bentonite management team on site. The filter cake thickness and the pH were also analysed since they are also limited in value for an excavation mud according to the Institution of Civil Engineers. Figures 40 to 42 plot the day average results obtained, as well as the average of the total sample period and the maximum compliance value (ICE).

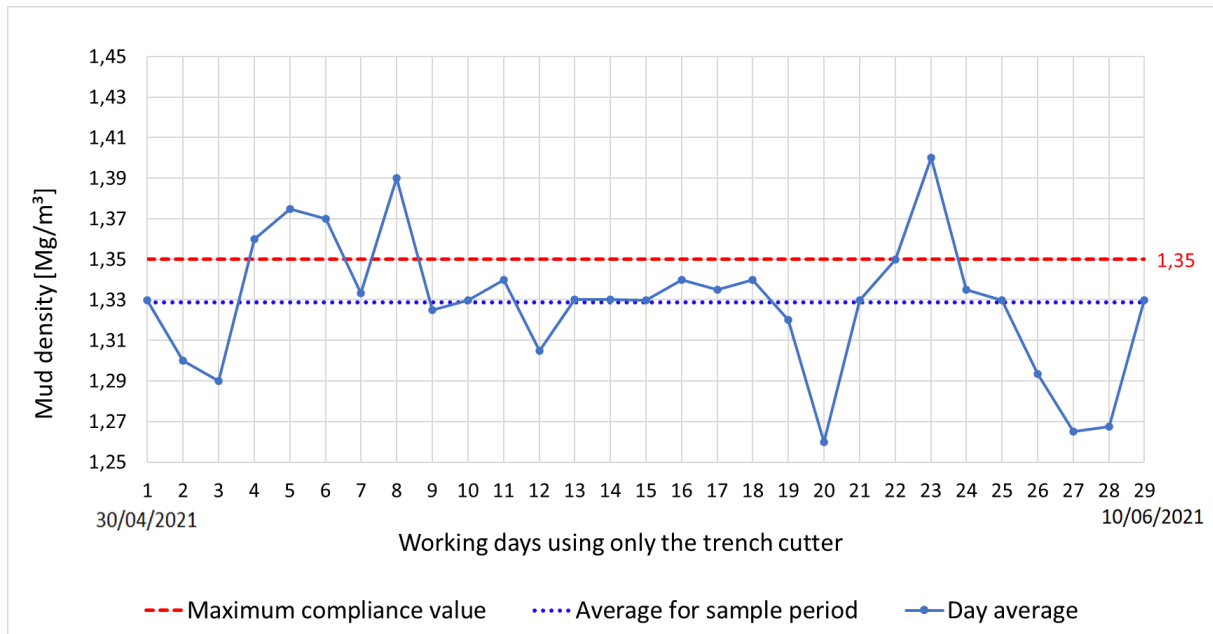


Figure 40: Mud density records for period of excavation with cutter using the 20ft Recycling Unit + SOBB55 centrifuge

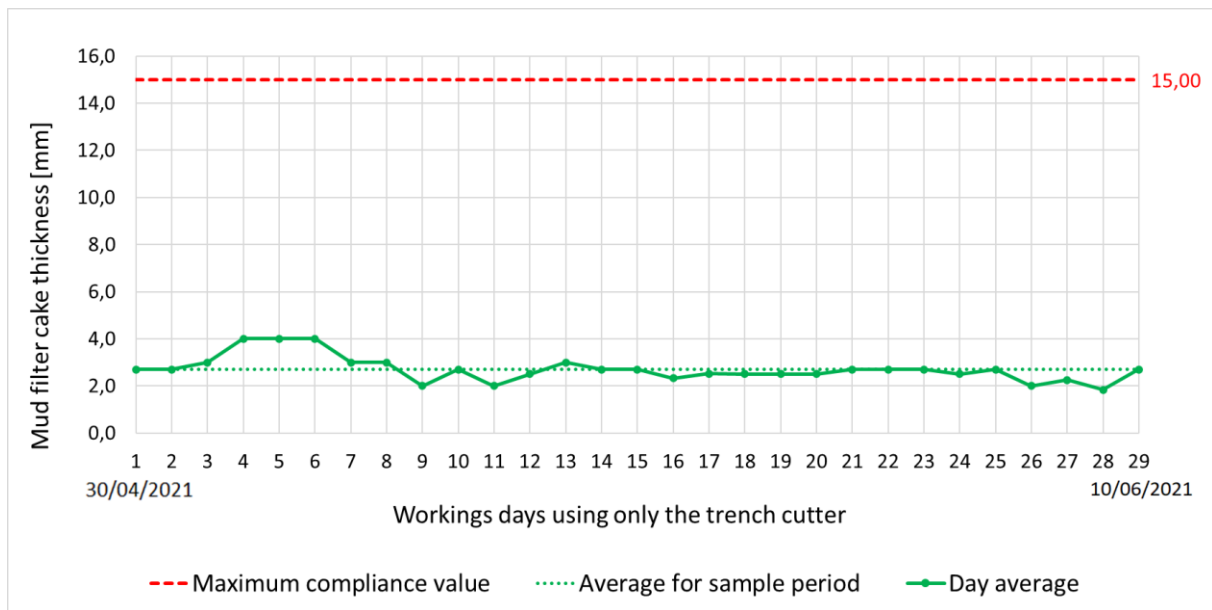


Figure 41: Mud filter cake thickness records for period of excavation with Cutter using the 20ft Recycling Unit + centrifuge

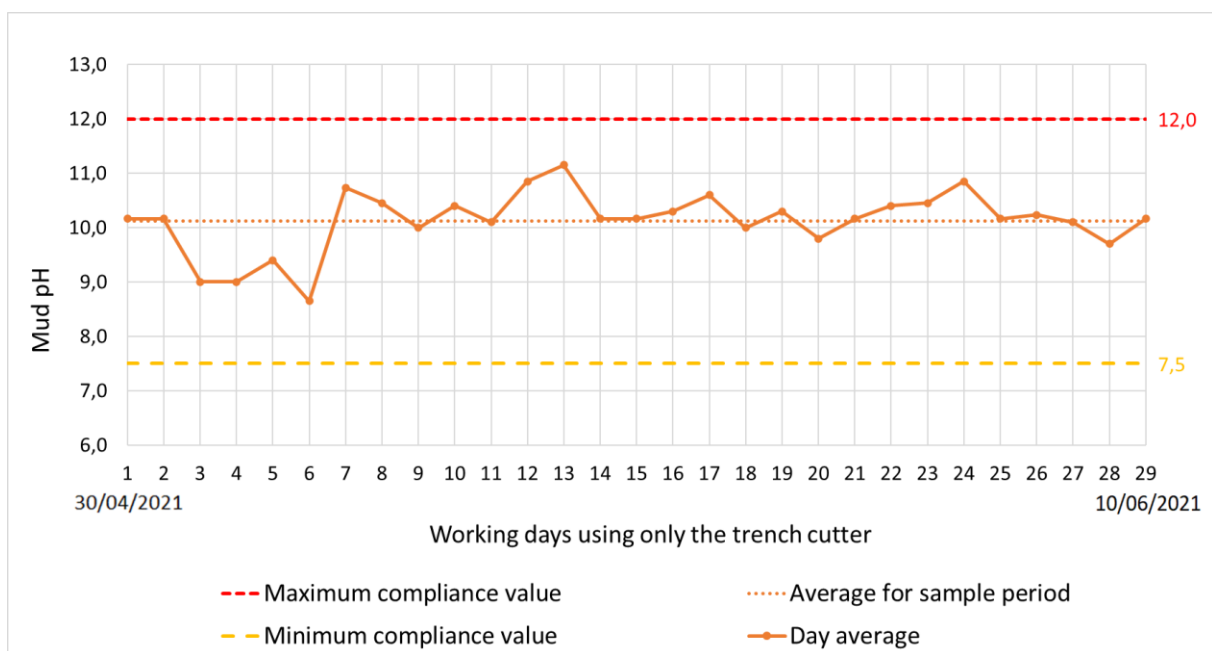


Figure 42: Mud pH records for period of excavation with Cutter using the 20ft Recycling Unit + centrifuge

The results obtained indicate that, in average, the density of the mud is kept under the compliance value which is 1.35 Mg/m^3 . Surprisingly, the bentonite slurry density exceeded the

maximum compliance value on days 4, 5, 6, 8 and 23. After investigation alongside the operators on site and analysing the daily records, the flaws on days 4, 5, 6 and 8 could be explained by several breakdowns of the centrifuge during those same days. Regarding the peak on day 23, a breakdown of one of the shaker's motors on the 20ft Recycling Unit was recorded and can be admitted as root cause, since the non-functioning of this important element of the recycling unit strongly reduces the ability of the desander to remove sand particles from the mud. On the other hand, the high drops in density recorded, like for example on day 20, are usually related with the fabrication of fresh bentonite that is added to the system. On the previous day, around 90 m³ of fresh bentonite slurry with a density of around 1.05 Mg/m³ was added to the pool, leading to a drop in density caused by fresh mud dilution on an excavation mud stock with a density of around 1.27 Mg/m³.

The filter cake thickness is kept under compliance during the whole sampling period and its evolution reveals to be quite stable on time.

The pH is also kept under compliance during the whole sample period and its unstable evolution on time can be explained by the cement contamination provoked by the excavation of closing panels. Since the excavation of closing panels includes the overcut of concrete coming from the adjacent primary panels, the cement brings an alkaline contribution to the system, neutralizing the action of the polymers and compromising the quality of the support fluid. Although products like sodium bicarbonate, soda ash and citric acid are used to tackle this phenomenon, the rise of the pH is unavoidable and can be clearly observed, for example, between days 12 and 13, when panels P16 and P2, both closing panels, were being excavated.

This first results confirm the ability of the recycling system to keep the bentonite support fluid in good conditions during the excavation with the trench cutter.

To reveal the importance of the centrifuge's presence in the treatment system, a closer investigation was carried out: the exercise consisted of taking samples every hour of the mud during the excavation of panel P10 at Amersham site, using the 20ft Recycling Unit and the SOBB55 Centrifuge as treatment set up. The collection of data started at a panel depth of 11.80 m and finished at the depth of 50.85 m which represents a total of 39.05 m excavated panel depth, 107.15 m³ excavated panel volume and 9900,8 m³ of mud pumped through the recycling

system. The reason why the observation did not start at the panel depth of 6 m (when the cutter starts excavating the panel) was because during the first 5.8 m, the site pipelines, as well as the pumps involved, were being tested like they usually are before starting the excavation at “full power”. Since this testing period contains both breaks and a significant variation of flow rates that could influence and confuse the results, it was discarded from the analysis. The observation could not be carried out until the end of the panel excavation (final depth of 59.2 m) due to the lack of available operators to carry the bentonite fluid tests at that time.

It is important to mention the great amount of work done for the collection of the following data, where the operators have substantially increased their rate of testing of the mud to participate on this study. Furthermore, with the goal of analysing the density evolution versus the excavation volume and the mud pumped into the recycling system, an exhaustive collection of data from the cutter’s software which records depths and flow rates of the mud pump was also necessary to make the analysis independent of time and only dependent of the fluid flow treated.

Figures 43 and 44 display the evolution of the density that comes out of the recycling system versus the excavation volume and versus the mud pumped into the recycling system of P10. It is depicted as well on each figure when the centrifuge is turned OFF and ON.

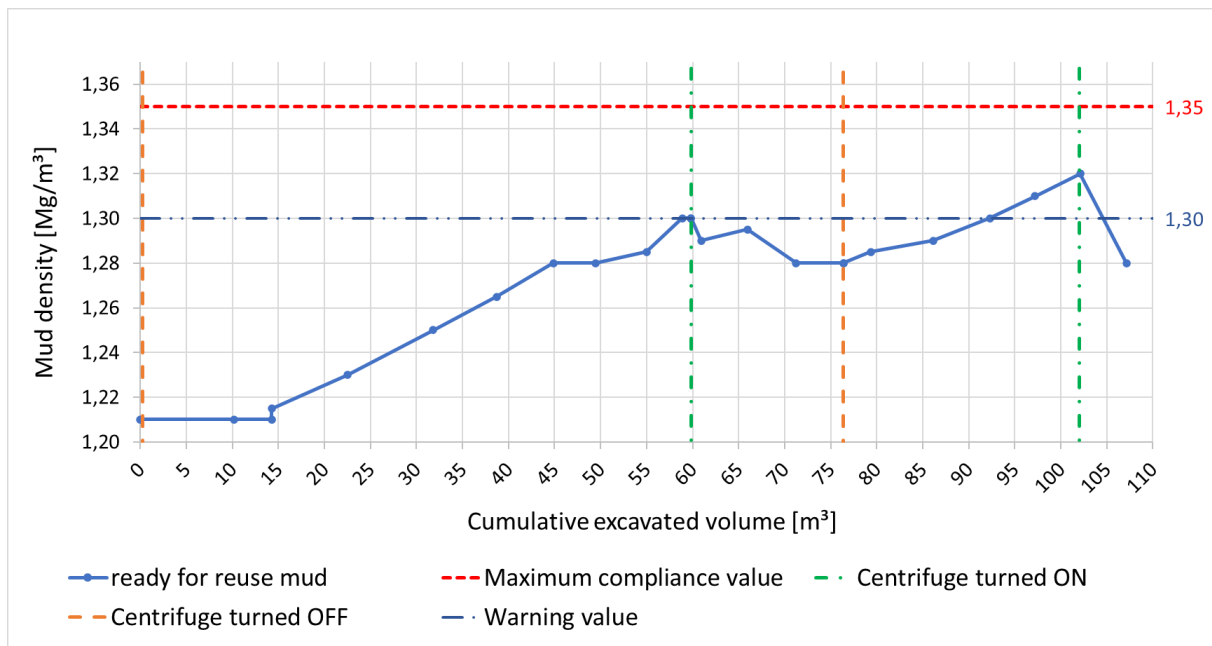


Figure 43: P10 ready for reuse mud density evolution on panel excavation volume

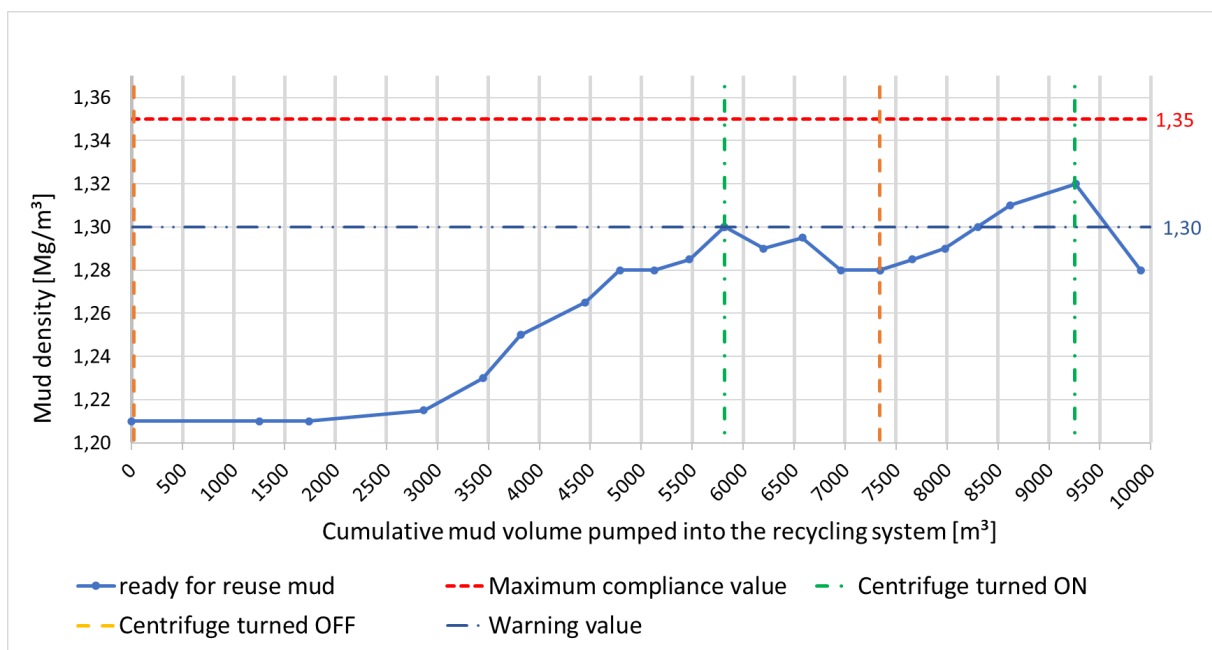


Figure 44: P10 ready for reuse mud density evolution on mud pumped into the recycling system

Looking at both curves, the rise of the density from the start of the excavation is clear. It is important to refer that this first increase in density is not only because of particle contamination from the panel, but also from the excavation bentonite pool storage from where

a continuous addition of 1.27 Mg/m^3 mud is added to the system to assist the excavation. After that, the rise in density can only be due to particles coming from the excavation.

Pertinent results are observed when paying extra attention on when the centrifuge was whether in functioning or switched off. In these two figures, the influence of the centrifuge on the treatment system can be well highlighted. In fact, the excavation started with the centrifuge switched off, that is, with only the 20ft Recycling Unit in functioning. The bentonite fluid plant team usually switches on the centrifuge when the mud density starts reaching 1.30 Mg/m^3 (warning value) and, when they do it, a drop in density can be perceived until the centrifuge is switched to off again. The density would otherwise continue to increase out of the constant breaking of the particles in the system while the centrifuge is switched on, its power to remove fine particles and consequently drop the density is greater than the trend for the fluid to increase in density. If the contamination intensifies and if an even greater drop in density is required, the Flotwegg centrifuge can also be switched on to assist the main one. The centrifuge utilisation is therefore delicate and needs to be continuously monitored because the use of the centrifuge for the whole duration of the excavation could treat the mud to a point where it would become too thin to behave as a support fluid.

4.6. Recycling process versus bentonite disposal and replacement

As part of the analyses of the choice of having a centrifuge on site which can turn the bentonite fluid recycling possible on such ground conditions, a comparison with other possible choices for the project must also be carried out. An alternative case scenario would be the use of the standard BAUER recycling unit which uses less specified desanders and desilters, and no centrifuges. This standard system is familiar to VSL and a d-wall project in Dubai within similar ground conditions revealed the obligation to proceed with direct disposal to waste of the bentonite fluid when its parameters did not comply with the attended. The aftermath indicates that, if this system was applied to HS2, the standard system with no centrifuge would represent a hypothesis that would correspond to an estimated volume of bentonite fluid equivalent to 150% of excavation volume to be disposed at the end of the production. Evidently, even if the two situations share common important circumstances, this hypothesis comes from experience feedback from another project facing also other obstacles that are not taken in consideration in this study. This only represents an approximation of what would be necessary

if the system was used in HS2. Nevertheless, with data internally collected from the company's records, this perspective can be a starting point for comparison between two different approaches.

Assumptions and considerations for the same excavated volume with cutter – 1,315 m³:

1. Regarding the system implemented, the data sample is collected from the 30th of April to the 10th of June at CSG site, corresponding to the period when the cutter started working fully operational on site as the main excavation tool (no hydraulic grab).
2. The non-recycling case scenario represents a hypothesis that would correspond to an estimated volume of bentonite fluid equivalent to 150% of excavation volume to be disposed.
3. The bentonite fluid losses motivated by ground infiltration through the panel are estimated as 5% per day of the excavated volume. This is an average from the information collected during the sampling period.

4.6.1. Bentonite fluid volumes

The first comparison is based on how much volume of bentonite fluid has been used on site compared to how much it would be used if the recycling process with a centrifuge was not implemented.

Following the assumptions mentioned, chart in Figure 45 shows the volumes for the two scenarios for 1,315 m³. The volume used with a standard treatment system would be of approximately 2,306 m³ and the volume actually used for the on the case study was approximately 569 m³ which represents a decrease of 83%.

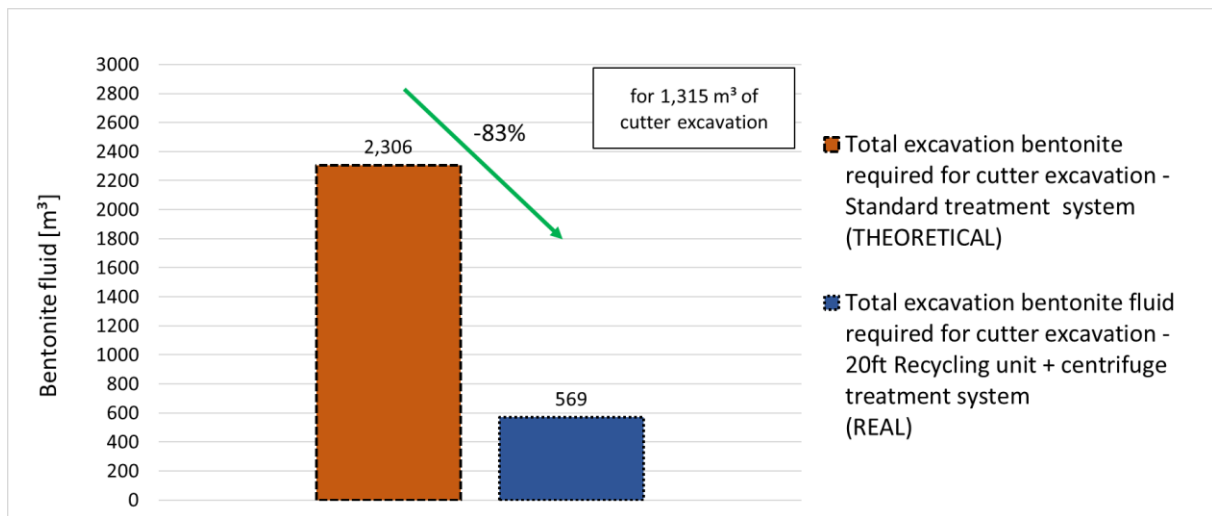


Figure 45: Required excavation bentonite fluid volume - comparison between two treatment systems for 1,315 m³ of cutter excavation

This contrast indicates that it is possible to significantly reduce the volume of fluid used during excavation with cutter. By adopting a recycling system with centrifuges, the recycling reveals much more effective.

By reverting to the standard system, it would lead to a bigger storage on site of good quality excavation bentonite fluid in order to inject in the system and maintain the properties of the mud. This would be the main physical limitations on site, as it would cause the necessity of a greater space to install more storage pools and mixers.

4.6.2. Overall costs analysis

Also, a cost analysis can be undertaken considering the cost of the plant to be used on each case scenario, the personnel implicated, the bentonite fluid plant consumables and finally, the disposal trucks required. The goal here is to point out the key variables between the two scenarios.

Table 10: List of variables to consider on cost comparison between two treatment systems

Standard treatment system - THEORETICAL	20ft Recycling Unit + centrifuge treatment system - REAL
Mobilisation	Mobilisation
	Extra transport trucks
Pool assembly	
Pool agitator assembly	
	Treatment plant supervisor
Pool disassembly	
Pool agitator disassembly	
Demobilisation	Demobilisation
	Supervisor
	20ft Recycling unit
	Derrick Stepoil tools Centrifuge incl. floc station
	Flotwegg centrifuge unit incl. floc station
BE500 Cutter desander	
BDS220 add-on to cutter desander	
Desilting unit BD90 + flocculation FA5000 or equivalent	
Extra Bentonite Pool	
Extra bentonite Pool agitator	
Plant and equipment	Plant and equipment
	20ft Recycling unit
	Derrick Stepoil tools Centrifuge incl. floc station
	Centrifuge unit incl. floc station
BE500 Cutter desander	
BDS220 add-on to cutter desander	
Desilting unit BD90 + flocculation FA5000 or equivalent	
Extra Bentonite Pool	
Extra bentonite Pool agitator	
Personnel	Personnel
	Plant supervisor
	Centrifuge operator 1
	Centrifuge operator 1
Plant perator 1	Plant operator 1
Plant perator 2	
Consumables	Consumables
Bentonite	Bentonite
Sodium bicarbonate	Sodium bicarbonate
	Soda Ash
	Citric acid
PAC LV	PAC LV
PAC HV	PAC HV
	Flocculant
	Coagulant
Waste trucks	Waste trucks
BE500 Cutter desander solids disposal	20ft Recycling unit solids disposal
	Centrifuge decanting mode solids disposal
	Centrifuge polymer mode solids disposal
	Centrifuge polymer mode water disposal
Bentonite mixed with concrete disposal	Bentonite fluid mixed with concrete disposal
Liquid bentonite disposal	

Chart in Figure 46 demonstrates the cost of these four group of variables regarding the two systems. The cost variation here calculated by the difference between the cost of each system divided by the cost of the standard system.

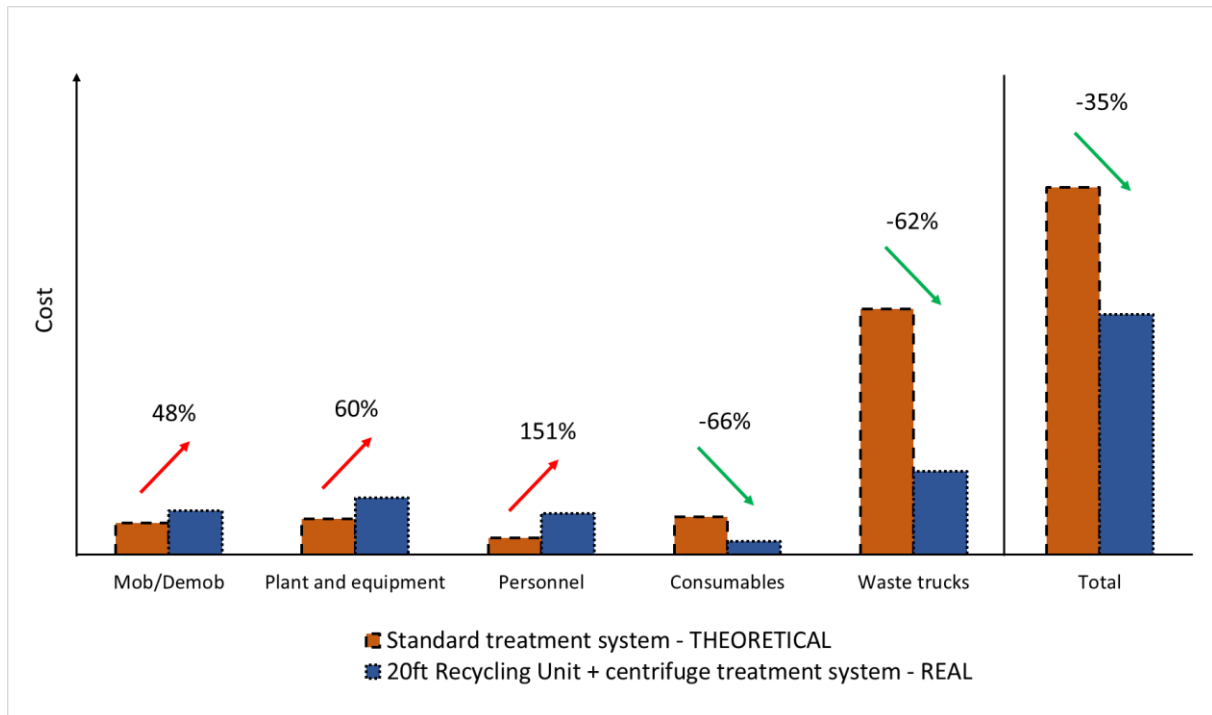


Figure 46: Cost comparison between two treatment systems

In fact, it is observable that in the implemented system at HS2, there is an increase in cost concerning the mobilisation/demobilisation, the plant, and personnel of 48%, 60% and 151% respectively, which is expected since there is a clear need for investment in machinery and qualified personnel to operate it. The operators are familiarised with this kind of plant because they also have experience from the oil and gas industry. The supply of trained operators for this kind of task in the construction industry is close to inexistent.

However, regarding consumables and waste trucks, there is a decrease of 66% and 62% respectively. Although the need for a great recipe of mud treatment products that follow the recycling procedure in place, the standard system would require a great mass of bentonite powder in big bags for the constant fluid mixing. Additionally, a much greater amount of sodium bicarbonate would be necessary without the mixing system here used. On the other

hand, the decrease in truck load cost is mainly due to the high price of evacuating liquid bentonite fluid from the site. This is the variable with greater influence on the overall cost.

Considering the gains and losses of this group of variables, the total indicates that, for this period of 29 working days and under the CSG site's circumstances, the system in place can generate a decrease of cost down to 35%, which represents an order of magnitude around £8,000 per working day.

Chart in Figure 47 predicts the evolution of the total cost for the two situations by volume excavated with the cutter, following the case situation at CSG site, i.e., considering a rate of excavation of approximately 50 m³/day (15 hours shift).

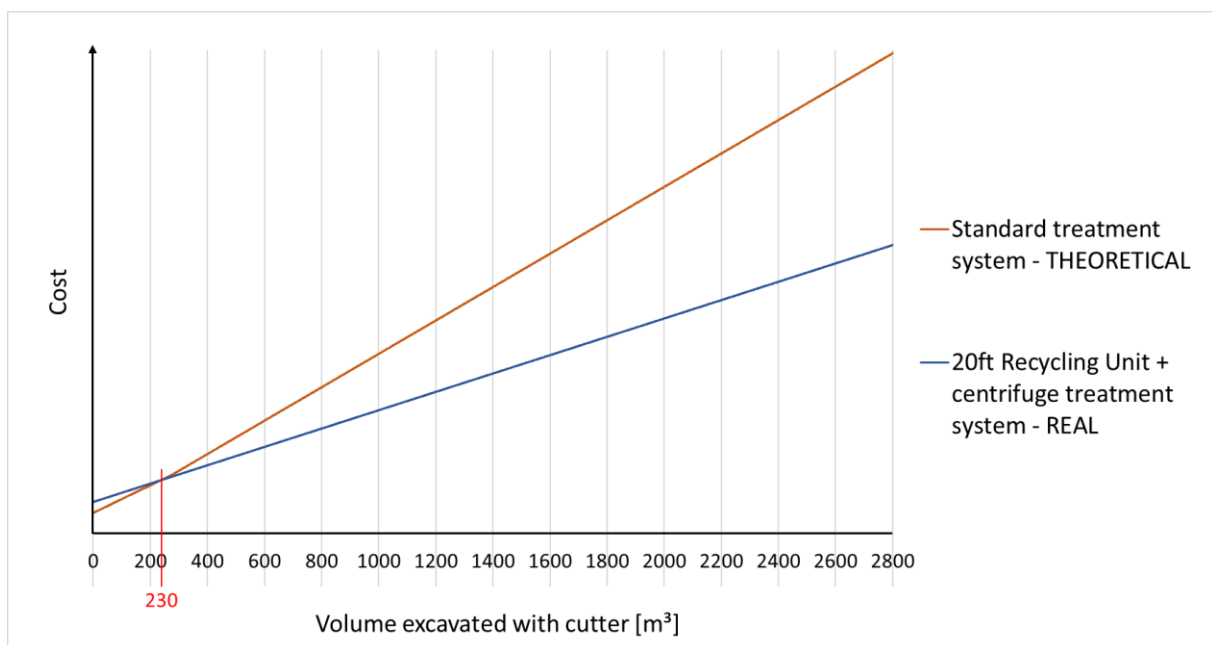


Figure 47: Cost evolution comparison between two treatment systems

Looking to the first 400 m³ of total volume excavated, it is observable that the implemented system proves to be more expensive until approximately 230 m³ of cutter excavation. This can be explained by the higher cost on plant and personnel during the mobilisation of the site, including extra transport trucks and the bentonite plant specific supervisor needed to attend the installation of the 20ft Recycling Unit and the centrifuges.

Additionally, the impact of the liquid bentonite disposal, and consequently bentonite fluid fabrication regarding the theoretical case scenario is not yet taken in full consideration as it is assumed that the first CSG 3-bite primary panel (excavation volume of approximately 275 m³) can be excavated without bentonite fluid disposal as its parameters can be maintained until the second panel.

However, results suggest an overall slower rate of cost increase for the system implement, which indicates that, the larger the scale of the project by resorting to the use of a cutter on these conditions, the greater the cost saved.

4.7. Discussion of the above results

Being an *in-situ* study, this project contains vital and rich interpretations of the results, as they are collected directly from the source and discussed with the main actors involved without any intermediate parties. The results presented also serve as a communication bridge between the civil engineering and the mud engineering.

Having a strong presence in the UK, especially in England, chalk will bring a great challenge when it comes to bentonite support fluid contamination for the diaphragm-wall excavation by means of a cutter. To get control of this obstacle, the setup and the plant used for the construction of the diaphragm-walls has proven to be ambitious and complex, but if well-engineered and executed by the personnel involved, it is capable of achieving the required performance. Each component has its important role on the treatment system and the analysis of the data collected at both Chalfont Saint Giles and Amersham sites proves that use of centrifuges plays indispensable function on keeping the good parameters of the slurry. Apart from the undertaken analysis on the mud parameters, tests using scanning electron microscopes to depict the precise particle sized distribution or a simpler retort analysis (moisture content) could enrich this study.

Results also suggest that the recycling system here observed can save in costs almost from the beginning of the site and that, most importantly, this save will increase with the size of the project. Nonetheless, the cost gap between this solution and more traditional ones can still be improved. In fact, this solution still depends very much on the oil and gas industry expertise as

it is faced with even more complex challenges not applicable to special foundations (including other variables to the fluid such as temperature and considering depths of some kilometres instead of some dozens of meters). The company is therefore forced to hire competent subcontracted staff and machinery from outside the construction industry. An investment on proper training and familiarisation of the company's own staff with this kind of problematic and respective equipment applied to the special foundations challenges could lead to even profitable long-term results for future sites with similar challenges.

5. Conclusion

In the field of special foundations, the civil engineering industry has been looking for new solutions adapted to the challenges faced when delivering diaphragm-wall projects. For the excavation of the d-wall panels, thinking through the management of the support fluids is today indispensable to achieve the expected final quality while keeping the control of the site's resources.

This study has explored the challenges brought about the cretaceous chalk of England on the management of the bentonite slurry which plays the role of support fluid for the excavation of the d-wall panels. The contamination provoked by the chalk's very fine particles that are released into the mud while excavating the ground with a cutter tool reveals to be extremely demanding in terms of recycling plant if quality is to be assured and if the direct disposal of contaminated liquid bentonite fluid is to be prevented. The expertise and equipment, including custom-made desanders and desilters plus centrifuges, to deal with such problems is brought by the oil and gas industry, but is it really effective on this type of construction site? And is it worth it cost-wise?

After an analysis on the effectiveness of the chosen process by looking closely to the evolution of the key parameters of the slurry used for excavation, results suggest that, during excavation: in normal circumstances, the density is kept under the compliance value of 1.35 Mg/m³ (average: 1.33 Mg/m³); the filter cake thickness is largely kept under the compliance value of 15 mm (average: 2.7 mm); the pH is kept between the compliance values of 7.5 and 12.0 (average: 10.1). Furthermore, a focus on the performance of the centrifuge revealed its indispensability to the system, preventing solids build-up in the mud when the desanders and desilter could not separate the finer particles.

Findings and interpretation of the data collected show that the solution is justifiable regarding the cost invested and motivates the company to implement it in even larger projects. This is especially due to the cost avoided concerning the direct disposal of contaminated slurry.

During the study, the collection of data was constantly dependent on the production rate of the site, which is naturally susceptible to plant breakdowns, bad weather conditions or even the

waiting for subcontractors that can force the jobsite to stop. For instance, an analysis on the moisture content of the mud at different stages of excavation using a retort test was planned, but due to a breakdown of the cutter during the period when the testing equipment was available, it was not possible to collect and analyse the necessary samples. This retort analysis as well as the mud scanning by an electron microscope are tests to considerate to determinate the particle size distribution of the muds.

This work proves its relevance on establishing a preliminary bridge of knowledge between the two industries involved when dealing with this kind of challenges, allowing to improve the language between specialities. Nonetheless, a great dependence of external know-how is observed. With the aim for a constant optimisation, it is suggested a greater familiarisation of the construction sector with such technical approaches for the purpose of applying the portion of knowledge needed to tackle the foundations challenges.

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