School of CIVIL Engineering

The Optimisation of Slurry Separation Within Pipe Jacking

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DECLARATION

The candidate confirms that the work submitted is his own and that appropriate credit has been given where reference has been made to the work of others.

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ABSTRACT

Pipe jacking is an environmentally friendly technique for the installation of services and utilities which leads to minimum disturbance during installation. It is an important construction method for urban environments where disruption to transport is expensive. The need to tunnel through varying geologies requiring support during tunnelling has led to the increased use of slurry tunnel boring machines. The slurry is used to stabilise the tunnel face and transport the excavated spoil to the surface.

The slurry, which includes the excavated material, has to be separated into liquid and solids so that they can be transported off site and disposed of. Current legislation does not allow for liquid waste to be disposed of straight to landfill and transportation and offsite treatment of liquids is extremely costly. Therefore improving the separation process on site helps reduce the cost of disposal.

This thesis looks at issues seen on current pipe jacking sites and investigates the optimisation of the decanting centrifuge commonly used by contractors to separate the sub 63μm particles. The testing carried out using a decanting centrifuge showed that the separation plant operator (mud man) requires an in-depth knowledge of how to control the plant to gain maximum separation capabilities. The slurry feed rate to the centrifuge was found to affect the centrifuge outputs significantly. At high flow rates the water content of the cake was seen to decrease. However the clarity of the liquid discharge (centrate) deteriorates. This allows the mud man and site management to make decisions on centrifuge control depending on excavation rates, geology, site/disposal constraints and ability to control slurry density.

Other key findings related to the dosing of flocculants when using a centrifuge. Flocculants were clearly seen to increase the water content of the cake and the liquid limit of the cake, showing that although the use of flocculants is essential, careful dosing is required to control the quality of the centrate and reduce trapped water being taken off site in the solids.

Key words: pipe jacking, slurry separation, flocculation, decanting centrifuge, liquid waste.

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DEFINITIONS

For the purpose of this thesis the terms pipe jacking and tunnelling are interchangeable as the topics being dealt with are predominantly the surface plant that can be scaled up for tunnel contracts.

Arisings: Spoil produced from the excavation of the tunnel.

Coagulate: The coming together of particles due to the reduction in surface particle charge.

Cake: Separated solids being re-combined within a separation process to form a solid layer. This is often referred to during fine aperture shakers, decanting centrifuges, filter press or belt press.

Flocculate: The binding of particles with a flocculant by both charge attraction and chemical bonding.

Liquid arisings: Arisings that do not meet the following statement; "*Any waste that near instantaneously flows into a hollow in the surface of the waste*" or " *If the arisings containing more free liquid than 250litres or 10% of the arisings (which ever is less)"* (Potter. Jeffries, 2005)

Mud Man: Separation plant operator in charge of monitoring and operating the separation system.

Sludge: A material that has a water content beyond the liquid limit but does not "*near instantaneously flows into a hollow in the surface of the waste*" (Potter. Jeffries, 2005).

Slurry: Is a suspension of solids within a liquid. Within this document it refers to the water based transport medium used in slurry tunnelling. This is historically a water and bentonite mixture but in more recent years is often just water (plus cut solids) or water and a polymer additive.

TBM: Tunnel Boring Machine.

1.0 INTRODUCTION

1.1 Slurry tunnelling machines

Slurry tunnelling is a development of traditional tunnel boring machines (TBM) that allows a tunnel to be driven through challenging geology with minimal surface disruption and safe operation. This could be when a stratum is water bearing or when mixed ground is encountered along the tunnel alignment. Figure 1.1 shows a diagram of a slurry TBM which varies in size from 0.35m to 19m in diameter.

A slurry pipe jack uses a slurry TBM to excavate the tunnel with connected pipes being pushed from a starting drive shaft using large hydraulic jacks. This allows the TBM to progress the length of an individual pipe before stopping and whilst a new pipe is connected at the rear. This process continues until the TBM reaches the designed destination. This is the main difference between pipe jacking and tunnelling where segments are built directly behind the TBM and then pushed off of.

Slurry tunnel boring machines (STBM) utilise a water based slurry to help provide tunnel face stability, reduce the ingress of ground water and to act as a transport mechanism to carry the excavated material to the surface. They can be driven in a range of geologies, but are more suited to sands, gravels and weak rocks. Grading curves of the ground though which a STBM can be driven is shown in Figure 1.2. This does not necessarily apply when small diameter tunnels are being driven. This is due to earth pressure balance machines (EPBM) being limited at 1.6m OD and a shortage of availability below 2.5 meters. This could cause the ideal grading curve to move considerably into the silt and clays. An EPBM differs by using a air pocket behind the face to aid in support and a screw auger to remove the cutters. The reducing in auger pitch and the use of chemical treatments the tunnel face pressure is reduced to atmospheric pressure at the discharge point. This is limited without pre-treatment to the hydro-static pressure of the machine.

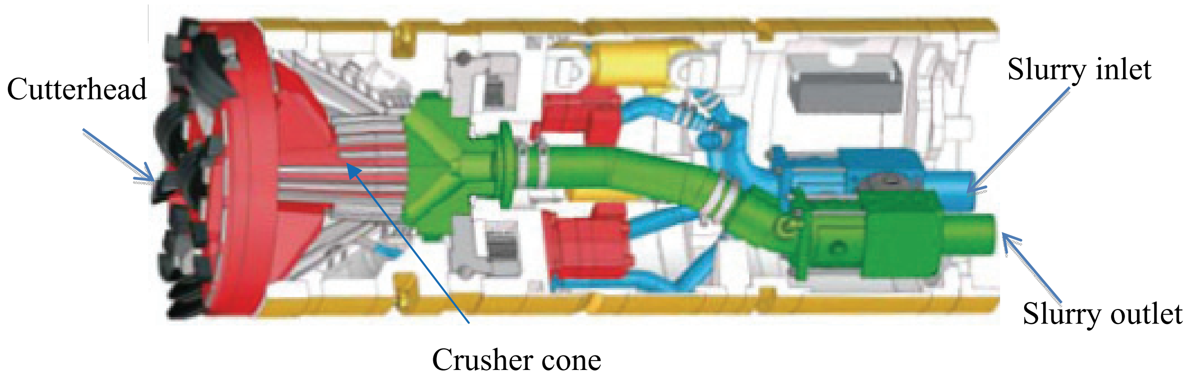

Figure 1.1 Diagram of a slurry tunnel boring machine

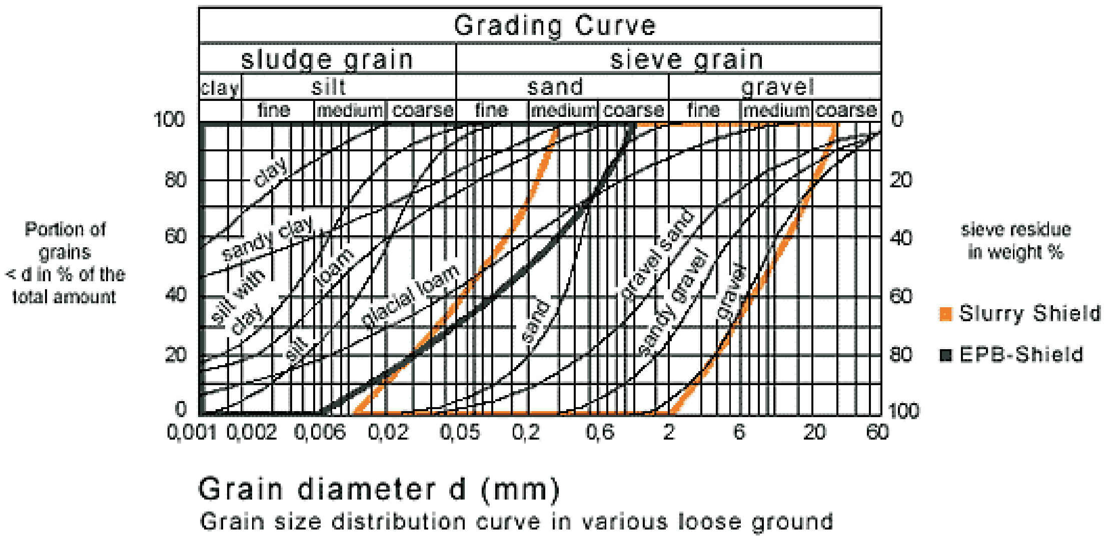

Figure 1.2 Grading curve for selection of Slurry and EPB shield tunnelling machines (Herrenknecht, 2010)

Both the ground conditions and the design requirements of the slurry will affect the composition of the slurry used. This can vary from often just pure water, to bentonite slurry or a gum based slurry using guar or xantham gum. Additives to the slurry are designed to prevent/reduce slurry loss within high permeability grounds or those with large fissures, help support the slurry face and prevent settling of solids within the transport pipes. The slurry pressure at the face of the STBM can be adjusted to ensure that the slurry pressure is equal to or in excess of the ground water pressure.

1.2 Separation plant

Technological advances and implementation of health and safety laws have resulted in an increase in the number of mechanical Tunnel Boring Machines. This has also coincided with an increase in the number of trenchless tunnels that have been needed to be laid to upgrade existing pipelines and lay new ones. Thus there is a increase in the quality of slurry being produced. During any one project the density of the slurry increases as more and more ground is removed. Some of these particles are removed during the site operations but at some point the slurry has to be deposed of. Recent changes to waste disposal legislation prohibit the discharge of liquids, other than potable water, to land fill. (Potter. Jeffries, 2005) Therefore, ideally, the slurry has to be separated into solids and water. The success of the separation depends on the plant available and the ground conditions. The success of the separation process also affects the progress of the slurry machines.

The cost of treating slurry so that it can be safely disposed of has proved to be high and those costs have increased as legislation has changed. It had been possible to pump the slurry to a lagoon and allow the water to evaporate leaving solids to be excavated and taken to landfill. This needs a large open area not commonly available in urban areas where the majority of the tunnelling takes place. This problem of disposed of slurry is not confined to the tunnelling industry. Slurry is used in a number of industries. Hence there has been a demand for an economical solution to treat slurry.

Meetings and interviews with the Pipe Jacking Association set criteria for choosing a preferred solution. The treatment of slurry had to:

- Be cost effective
- Occupy a small an area as possible
    - Be able to keep up with tunnel production rates, slurry flow rates and solid production
- Be energy efficient
- Produce an inert waste product

- Treat the slurry so it is suitable for landfill or if possible for another industry to use.
- Possible use of the solids in landscaping
- Minimum water content of the solids to reduce transportation costs
- Re-use of extracted water

This has been partially answered with current separation plants. Removal of particles is carried out in three stages, each decreasing in cut size or the minimum size of particle removed. The first two stages work in line with the slurry operation so particles are removed with the slurry continuously flowing around the system. The first stage removes particles approximately greater than 5mm in diameter (gravel, cobbles and clay balls), the second stage removes sand and silt size particles down to 30-75μm. This leaves fine particles in the slurry which are often removed using centrifuges working offline but in parallel with the tunnelling operation. The centrifuge operation has to be offline because of the time it takes to remove the fine particles. The specification of the slurry separation plant varies from site to site depending on the ground, the contractor's experiences and the availability of equipment. This three-stage separation process, as shown in Figure 1.3, is common in the UK.

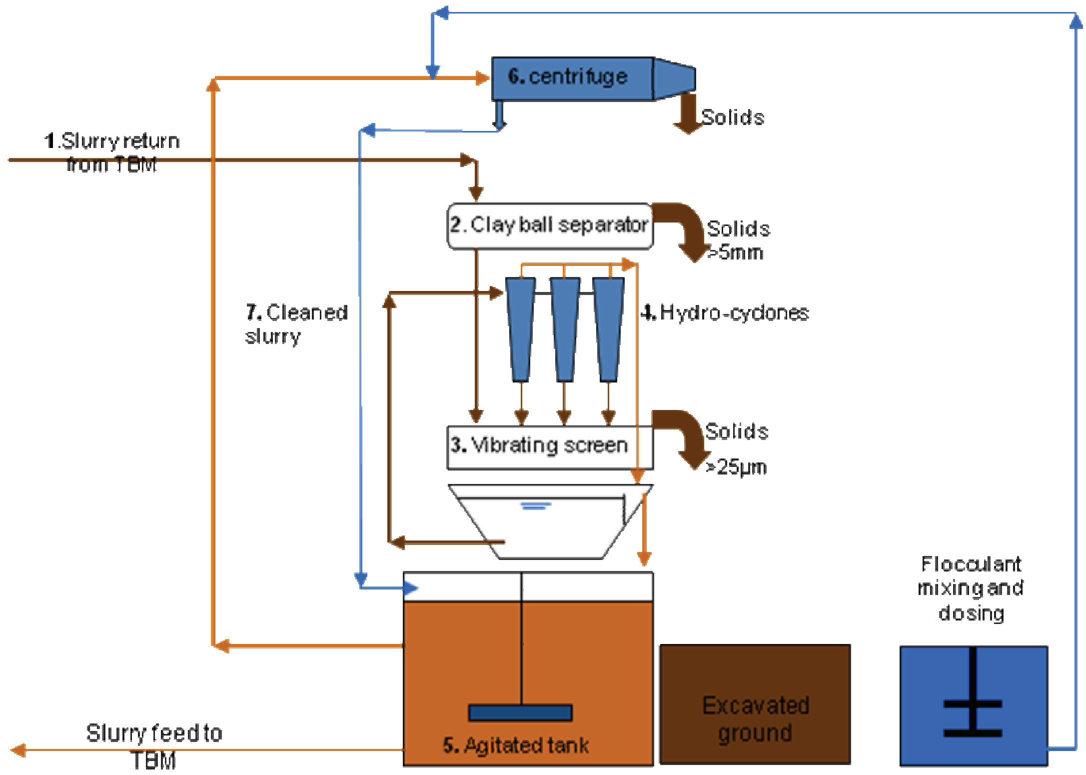

Figure 1.3 Systematic diagram of a typical three stage separation system (noted from site visits)

This set-up has been developed over the years from technology used within the oil and gas drilling industries to a configuration to suit the tunnelling and pipe jacking industry. The success of the separation plant is assessed against the speed of the pipe jack and the need to change the slurry if it becomes too dense. The success of the slurry separation system varies throughout the UK.

The percentage of solids removed at each stage of separation plant will be dependant on the geology of that is being tunnelled through and the exact equipment specifications.

1.2.1 Primary Separator

The first stage (2) of separation removes the large particles from the slurry such as gravel, clay balls and any large debris (unnatural cuttings) that the TBM tunnels through. The cut point for this section of plant would be approximately 5mm on a pipe jacking site. For larger tunnels this cut size may be increased and stepped down with extra shaker screens due to the larger cuttings and larger throughputs. The item of plant used can vary depending on the ground that is being tunnelled through. Plant includes primary shaker shakers or a clay ball belt separators. This allows for the most effective separation and ease of operation for the mud man.

1.2.1.1 Primary Shaker Screens

The primary shaker (Figure 1.4) consists of a dewatering screen vibrating at a high frequency by eccentrically weighted motors. This is an extremely effective method when tunnelling in granular material, producing a low water content, stackable spoil. In clay, silt rich soils it is not as effective and a clay ball separator may need to be considered instead.

The shakers can easily be altered depending on the ground conditions. The variables are inclination, aperture of screens and the type of vibratory motion. (Clarke, Lawson, 2004) The shakers can also be varied by adding multiple decks. This allows a wider range of material to be screened by using different aperture sizes. The disadvantages of a multi deck system are the increased stoppage time if maintenance work is required on the lower deck.

The design of most primary shakers is very robust and requires minimal maintenance. The two main wear components are the screens and bushes. If using polyurethane screens then the life span can be several months or years. If running in clay grounds then a considerable amount of time will be required to remove the clay that becomes trapped in the apertures. This is done using a flat scraper. This is a major disadvantage of a shaker as a primary screen.

If the most appropriate equipment is chosen for a particular ground condition and it is used correctly then very little operational time is required by the mud man and the main requirement is to check correct operation and wear. This allows the operator time to monitor the centrifuge which is working offline and much more sensitive to changes in slurry content. The noise level of the shaking screens is high because the movement of particles across the screens. It is above the health and safety limit of 80dB, so ear protection is a necessary.

1.2.1.2 Clay Ball Separator

Clay ball separators (Figure 1.5) are an alternative primary screen when tunnelling in fine grained soils. They consist of a rotating belt, which could be made from several materials. For robustness industry prefer a metal wire/link belt. The slurry from the machine is passed over the belt with the larger particles taken away from the flow area by the belt and the slurry and finer particles are allowed to pass through into the secondary stage of separation. Fans can also be used to further aid the dewatering of the arising, by blowing air over the cuttings prior to discharging of the end of the belt.

The clay ball separator minimises the disturbance to the clay cuttings keeping them intact. Compared with a vibrating screen this reduces the chance of the screens clogging and the amount of fines that enter the slurry, minimising the work that the centrifuge carries out. Clay cuttings are considered to be a dewatered spoil that can be removed straight from site.

When using a metal link belt the maintenance required is minimal, with the need to occasionally remove any wedged debris. Cloth belts generally have finer apertures and can require more maintenance due to likelihood of tearing. A minor benefit over a primary shaker screen is that whilst operating the noise level is low so the apparatus would not need encasing if in close proximity to housing.

Figure 1.4 Primary shaker screen

Figure 1.5 Clay ball belt separator

1.2.2 Secondary Separation

From the first stage the underflow then takes one of two courses to the secondary screen hopper depending on the system set-up. This can either be onto a finer vibrating screen for further scalping or directly into a hopper. From here the slurry is circulated up into the hydro-cyclones.

1.2.2.1 Hydro-cyclones

Hydro-cyclones can vary in size dependant on their use, either as desilters or desanders. They consist of a central cylinder with an open conical section at its base (Clarke, Lawson, 2004). The slurry is pumped in under pressure at the top of the cylinder through a tangential inlet. This causes a centrifugal force to be created and the heavier particles, sand and larger silts are pushed to the outside. These then pass through the under flow out of the conical section. Water and lighter particles rise through the vortex to the overflow. The underflow is usually passed over a vibrating screen for further dewatering (Figure 1.6).

The size of the main cylinder and the taper angle partially dictate the particle cut. The size of the main cylinder also affects the flow rate required to operate. The smaller the cylinder and taper angle the smaller the cut, but more hydro-cyclones are needed to keep up with flow rates. (Figure 1.6) A desilting hydro-cyclone would typically be 100mm or 150mm and desanders 250mm to 500mm. Desanding hydro-cyclones would generally only be used in conjunction with desilting hydro-cyclones or when minimal silts and clays are present.

On larger tunnelling operations both desilters and desanders maybe used, but on smaller micro tunnelling operations the most appropriate type for the ground may be chosen. The cut off point for a desilter is generally around 20-50µm and a desander is 40-75 µm.

The hydro-cyclones can also be assisted by a vacuum that is attached to the overflow. This is reported to help produce a more consistent underflow (drier), reduce clogging and is virtually unaffected by changes in feed density. They also run at a lower feed rate reducing wear and power consumption. (Brandt, 2001)

This plant again requires minimal operation by the mud man if the correct cone size is selected and the plant set-up correctly. If the apexes are left visible then the mud man can monitor the hydro-cyclones performance and the variation in the solid content of the slurry. This is observed by the change in underflow shape, whilst it is 'roping' the solids content above the cut point is high and a 'fan /umbrella' shape the solids content is low. (Figure 1.7) Whilst 'fanning' and if excavation has paused the hydro-cyclone can be switched off saving energy and wear.

Figure 1.6 Bank of hydro-cyclones (150mm Ø)

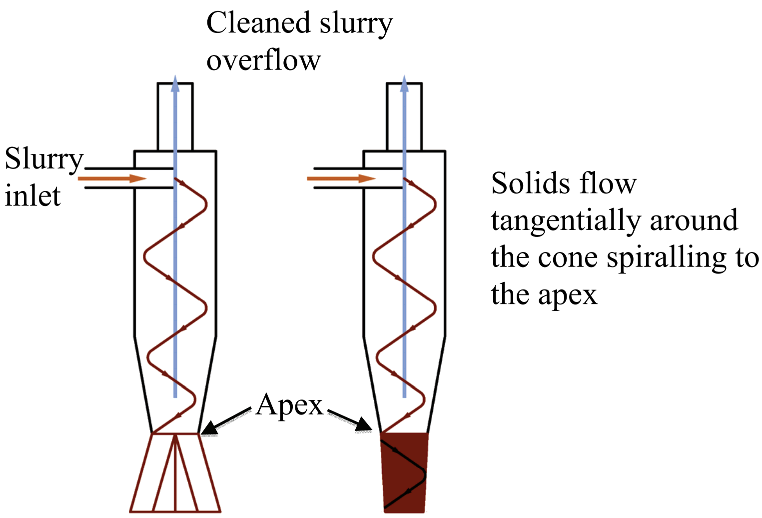

Figure 1.7 Two varying outputs of a hydro-cyclone

1.2.2.2 Vibrating Dewatering Screen

The underflow from the hydro-cyclones still contains a significant amount of water that requires further dewatering. This is carried out using fine aperture high frequency vibrating screens (Figure 1.8). The aperture of the screens can be varied depending on the size range being dewatered. This is generally around the 0.1-1mm range. The reason why the screens do not have a smaller opening is because the silt and fine sand particles can bridge and 'piggy back' over the openings thus not falling through the screens.

A wide range of screens are available and can be varied depending on the contractor's preferences for performance, wear, designed throughput and actual cut size. The popular choices are wire mesh, wire pyramid (Figure 1.9), polyurethane and wire cloth screens. The shaker angle can also be varied on the majority of shakers and is typically between -2° and +5°. The reason for this is to allow the operator to vary the cake depth (for improved dewatering) and the transport speed (maximise throughput).

When the shaker deck is set-up correctly effective dewatering can be achieved. The level of dewatering appears to decrease as the clay content of the under flow increases. This is because each particle is surrounded by a layer of water and as the particles get smaller a larger surface area is made available. This can produce a spoil that is close to saturation level.

The use of vibrating screens on site requires very little operative time by the mud man and limited maintenance. The main requirements of the mud man are to maintain a constant bed depth (which will be dependant on the equipment and tunnel arisings) and check for any abnormalities. The main points of maintenance are the replacing of worn screens (wire screens are more prone to wear), worn bushes and the regular greasing.

Due to the motion of the shaker, noise is an issue and they above the 85dB limit. This means that the mud man is required to wear ear protection and there is a potential need for sound proofing in sensitive areas.

Figure 1.8 Shaker screen looking at the side and the bed

Figure 1.9 Pyramid wire screen

The overflow from the hydro-cyclones returns to the main slurry tank via a weir system in the shaker hopper to maintain its slurry level. The partially cleaned slurry is then circulated back to the TBM or siphoned off for extra cleaning.

1.2.3 Third Stage: Decanting Centrifuge

Centrifuges are currently used to separate the fine particles, generally the sub 63µm particles (when desilting hydro-cyclones are used) from the slurry. They are used in conjunction with flocculants that are added to the slurry prior to it entering the centrifuge. This helps to remove the small neutrally buoyant particles by allowing them to form flocs. A pod system is common that combines both the centrifuge and flocculant system (Figure 1.10).

If flocculated correctly a clean centrate should be sent back into the main slurry tank and suitably dewatered spoil should go for disposal. The arisings are adequately dewatered so that they can be sent to landfill, without any further treatment. A centrifuge produces a much greater centrifugal force than a hydro-cyclone, between 1000g and 3000g because the centrifuge is mechanically operated as opposed to hydro-cyclones, which rely on fluid flow.

Due to restraints in space and money, centrifuges are run offline, continually cleaning the slurry, even between pipes when no excavating is occurring. Generally the flow rates through a centrifuge range from $6m^3$/hr to slightly over $70m^3$/hr (Clarke *et al*, 2004). The idea is to clean the slurry back to a target density before excavating re-starts. This is generally considered to be the most economical way to run the centrifuges. On occasions operatives may need to stay on site after the shift ends to continue to clean the slurry ready for the start of the next shift the next day.

When run correctly the centrifuge cake should be stackable and could have a water content in the region of 55-80% with the centrate clear with no trace of flocculant. The three main controls are the slurry throughput, flocculant dose rate and the centrifuge bowl speed. The most common adjustments would be the first two; keeping the centrifuge speed constant. The continuous running of the centrifuge allows the slurry to be maintained at the correct density. To do this it requires a mud man monitoring the centrifuge at all times. Due to the level of adjustment it should be relatively easy to maintain the centrifuge working at its optimum even with changes in the slurry composition.

Centrifuges have a high purchase and operating cost due to their energy and flocculant consumption. Based on a cost benefit analysis compared to dumping the slurry they are economical. They also operate around the noise exposure limit of 85 dB meaning that ear protection is required to operate and potentially the need for sound proofing whilst in close proximity to housing (www.alfalaval.com, 2012). Maintenance of a centrifuge is required to be carried out by an experienced fitter, which can result in a high maintenance cost.

Figure 1.10 Small decanting centrifuge

1.2.4 Storage Tank

Although the storage tank does not actually dewater or separate the solids, it does have an effect on the performance of the centrifuge and the easy of operating the TBM. This is caused by the agitation system that is used. There are two methods used to agitate the slurry. These are air agitation and vertical paddle agitators. From conversations with contractors and people within the industry it was reported that vertical paddle systems have the best performance. The reason for the agitation is to keep all of the solids within the slurry suspended and to ensure a homogeneous slurry. This reduces the variation of slurry characteristics sent to the centrifuge and the TBM.

1.3 Problems

Since the introduction of slurry tunnelling in 1959/1960, (Maidle *et al,* 1996) it has been used on countless projects around the world in different ground conditions. In this time there have been numerous problems encountered with the use of slurry and its separation. Many problems with the use of slurry have arisen over the years, only some of which have been resolved.

The major problems on site are the effective, efficient separation of the fine, naturally buoyant particles. There are particular problems when tunnelling through clays, chalks and rocks with a clay cementation. On many of these sites, larger and multiple centrifuges need to be deployed to keep the slurry at a suitable density. As the density increases a series of problems begin to occur through the system.

- Slow excavation rates
- Increased wear on the tunnelling head
- Increased wear of the pumps and pipes
- The possibility of the system not being able to pump the slurry because of the density and friction within the system
- Extra cost in potentially dumping and treating the slurry

An initial discussion regarding previous contracts suggested that there are a number of reasons for these potential problems. The reasons are listed below, with the key issues being the top four;

- Managerial
- Use of flocculants
- Site Investigation data
- Limited site space resulting in cut backs of plant
- Insufficient knowledge about the slurry separation, tunnelling and use of additives
- Large quantities of fine particles overwhelming the centrifuges
- Plant break downs
- Blockages in the pipe and the TBM

These points were taken from an initial study based on meeting discussions with members of the Pipe Jacking Association. The focus of this thesis is the process of separation identifying the issues providing recommendations as to how it can be improved. This allows for the greatest gain in efficiency and is also an area where the research can have the largest impact.

Excavated material under 63μm is the main problem for the slurry handling process. It mainly occurs in silt and clay rich soils where a thickening of the slurry occurs if the separation process is not effective (Clarke *et al*, 2004). Removing fines from the slurry with a decanting centrifuge produces a cake with a higher than natural water content, meaning the spoil can be hard to handle and dispose of.

1.4 Aims and Objectives

The main aim of this project is to gain a greater understanding of the slurry separation system so that the variables that affect the final outcome (separated solids and cleaned slurry) can be identified. An analysis of the impact of these variables will allow recommendations to be made to improve the process.

The objectives of the research are as follows:

- Assess current separation plant against alternatives;
    - Compile a list of types of separation plant used in the pipe jacking industry and other sectors
    - Identify a set of parameters that can be used to characterise the separation plant
    - Compare the characteristics of the separation plant
- Identify current practice and where problems are occurring and how they are overcome;
    - Visit operational sites and interview contractors on what is used and current and historic problems
    - Assess current practice against that of other industries and literature.
- Collect and review slurry variation and pipe jacking drive data to identify areas of potential improvement;
    - Collect operation data from active slurry sites

    - Compare and analyse to find causes for problems and identify the best practice.
- Identify decanting centrifuge best practice and optimise desired outputs;
    - Test a decanting centrifuge by varying slurry inputs
    - Collect and analyse the effect of variation in operating parameters.
- Review the effects of flocculants of the slurry system and the desired outputs.
    - Test flocculants to see their effects on separation and soil properties
    - Look at previous work carried out and make suggestions for appropriate use

2.0 LITERATURE REVIEW

2.1 Introduction

One objective of the study has been deemed it necessary to assess current techniques of dewatering against possible alternatives that are on the market. Due to the size of the pipe jacking and tunnelling industry there are very few new products being directly developed and marketed to the industry. Dewatering and separation of slurries, however, is a large market that spans over many industries all trying to improve operations by both reducing cost and increasing performance. Thus it is possible to review the developments in other sectors and assess whether they could be applied to the pipe jacking industry

There are several key parameters that need to be assessed.

- Size (of total plant to achieve a set solids throughput)
- Cost
    - Purchase price
    - Operational cost
- Energy consumption (including cost and environmental impact assessed through carbon footprint)
- Range of solids throughputs (size and types)
- Ease of use
    - Operation
    - Maintenance
- Water content of arisings
- Clarity of liquid
- Pre treatment requirements

The size of the separation plant is a key issue because many sites are located within busy cities where space is a premium. This requires the plant to be easily configured in to a tight space. Whilst being relatively compact it must also be able to achieve the anticipated maximum solids throughput without causing delay to the tunnelling operations. This allows the operation to have minimal disruption to the public and efficient operation.

These criteria will be used to assess existing and alternative solid separating systems.

2.2 Possible Alternatives

Current separation plant is effective and economical when operated correctly. There is, however the scope for improvement and change if appropriate plant or techniques are found. The following section looks at potential plant from both inside and outside of the industry that could be adopted. This plant could be as an alternative to current systems or as an add-on.

The main areas that are concentrated on are fine particle separation, fine particle dewatering and additional dewatering techniques for the arisings produced. This would minimise transportation and disposal costs, along with avoiding distribution caused by landfills not excepting the spoil.

2.2.1 Clarification/Thickening

Whilst carrying out a literature review it was seen that many industries use clarification and thickening plant to help condense the solids prior to dewatering. This concept has also been developed by one tunnelling separation plant manufacturer ITE separation (ITE, 2010). For these reasons it was deemed necessary to explore this route further and see what benefits it could bring to current separation practice.

The idea of this type of plant is to produce concentrated slurry with significant solids content and remove clean water. This helps to reduce the quantity of fluid being passed through the fine particle dewatering stage which in the pipe jacking industry is the centrifuge. This is also said to reduce the water content of the final solid arisings.

This would require an extra piece of plant, adding to the footprint and pieces of plant that need to be operated by the mud man. (Figure 2.1) This however does not rule it out if it is deemed to have a significant benefit to the dewatering process.

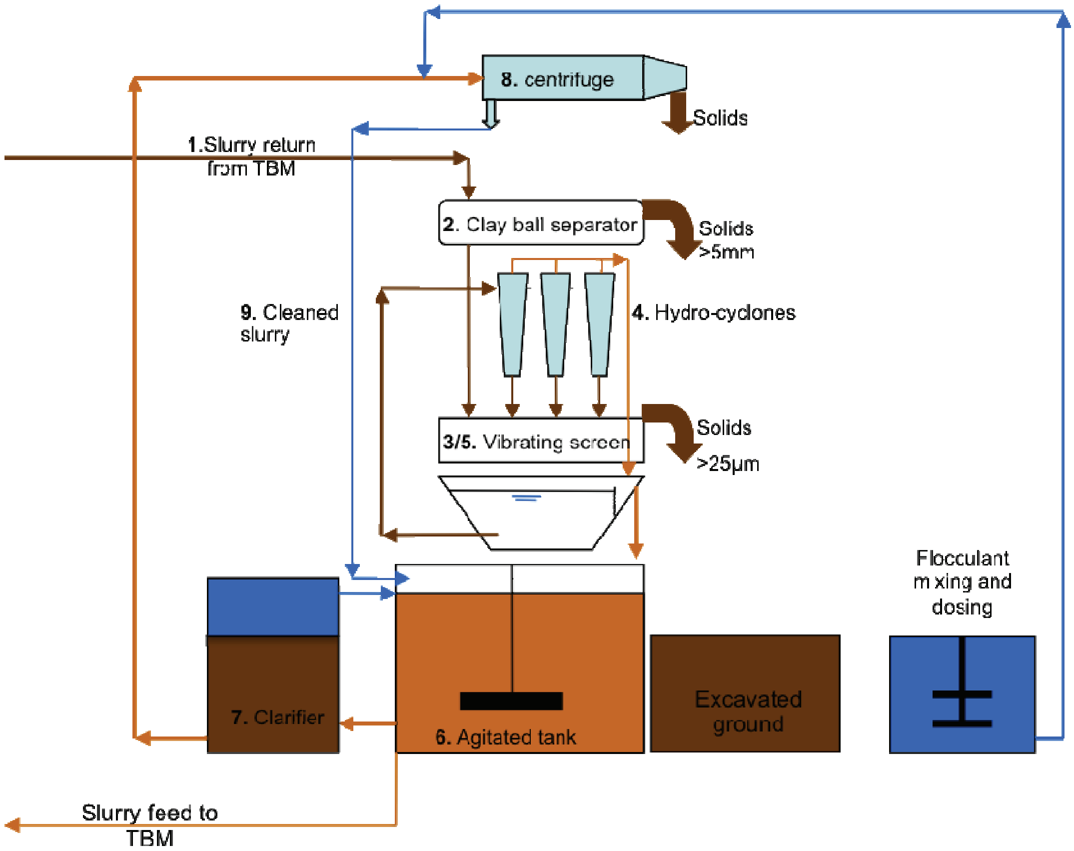

Figure 2.1 Systematic diagram of the slurry separation plant with a clarifier installed

2.2.1.1 Dissolved Air Flotation Separation

This process works by dispensing bubbles from the bottom of a tank. (Figure 2.2) The bubbles, approximately 20-50µm, attach themselves to the suspended particles within the liquid and make them buoyant. This produces foam on the surface of the tank that can be removed using a scraper (Beychok, 1967). This does not produce directly disposable arisings due to a very high water content, but it does remove the fines from the slurry economically. A belt press or similar dewatering technique could be used after this to produce a low moisture cake. This is commonly used within the waste water treatment industry with the aid of a coagulant. It is also used to in oil refineries and petrochemical industries. All of these industries have particles with low specific gravities.

The method is most effective for slurries with a low percentage of solids with a low specific gravity and could be an alternative to a clarifier. This is a major limitation due to the quantity of fines in tunnelling slurry and the specific gravity of the solids.

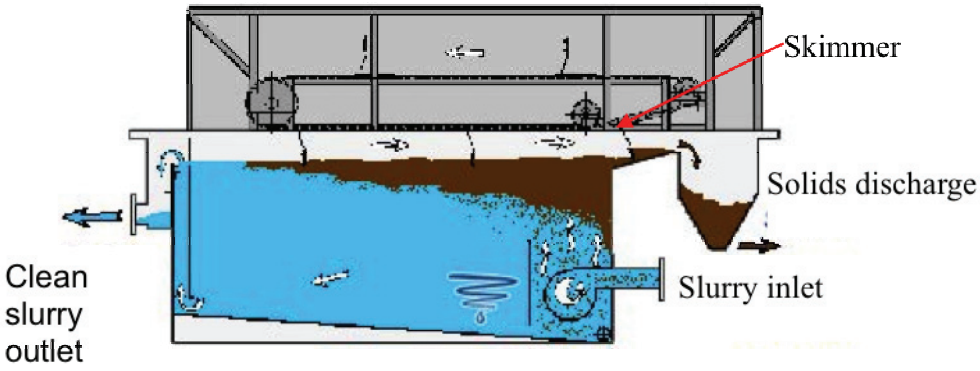

Figure 2.2 Dissolved air flotation

2.2.1.2 Continuously Self Cleaning Sand Filters

Continuous self-cleaning sand filters (Figure 2.3) are used to separate suspended fines from slurry. This method works by pumping the slurry in at the bottom of a chamber forcing it up through the sand. Clean water exits at the top after passing through the sand. The silts and some sand is then sucked up through a central pipe, where the sand settles back down into the tank due to its specific gravity and the fines leave through an outlet (Nordic Water, 2008).

This could be a very useful method as an initial stage of separating the fine particles from the slurry before it enters the centrifuge. This could increase the efficiency of the centrifuge and compared with other settlement techniques there is no need for flocculants. In principle it cleans itself and requires very little supervision or maintenance. It does however require a large gap in density between the sand and the particles within the slurry. This could require more hydro-cyclone separation to reduce the maximum particle size of the solids within the slurry.

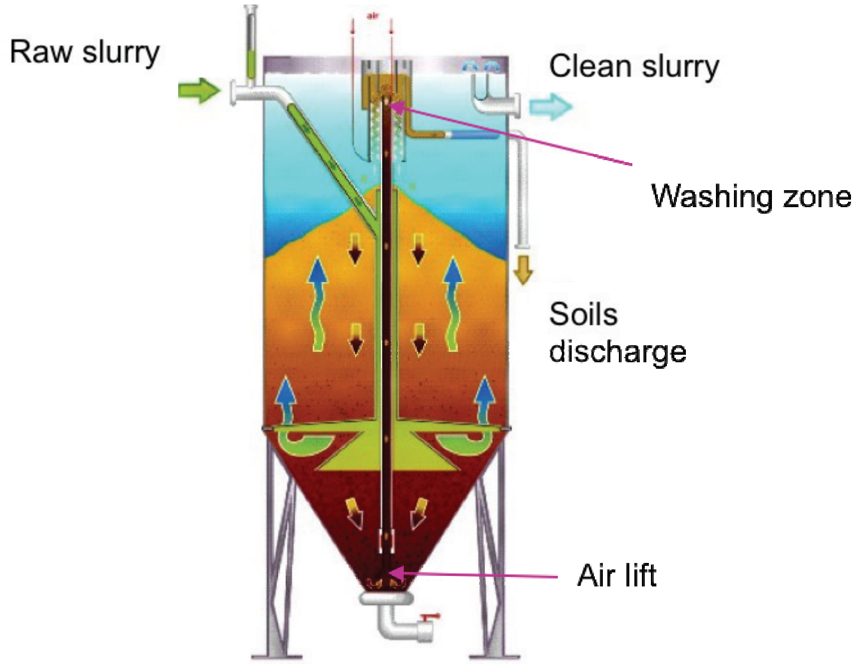

Figure 2.3 Continuous cleaning sand filter

2.2.1.3 Vertical Clarifier

A vertical clarifier is a method of thickening the slurry and separating the fine particles. The clarifier works by pumping flocculated slurry into the centre of the clarifier at the top. The flocculant creates agglomerates of particles which settle faster than the individual particles. The flocculated particles are then allowed to settle to the bottom of the clarifier forcing clean water to rise up and pass over the weir. This provides a concentrated sludge for offline dewatering. Using this method prior to treating with a centrifuge could increase the efficiency of the centrifuge. Herrenknecht quote that the efficiency could be improved by up to three times. (Herrenknecht, 2007)

With the floor plan being relatively small and no moving parts other than an extra pump, the vertical clarifier could be a beneficial piece of plant on site. The stated maximum flow rate is 160m^3/hr which is adequate to be run inline on a 1200mm tunnel and would provide adequate cleaning for larger tunnels and run off line.

Running offline would make it easier to control the solids build up so that the clarifier and centrifuge would be operating at the same solid throughput.

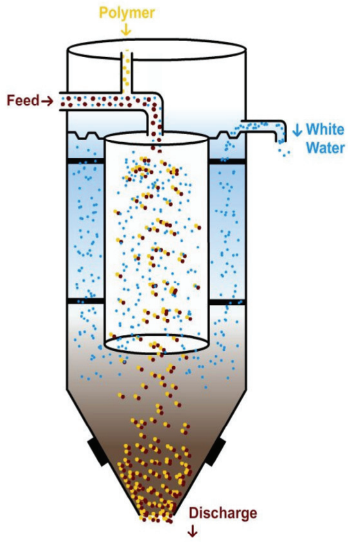

Figure 2.4 Vertical clarifier (ITE, 2010)

2.2.1.4 ACTIFLO® Micro sand Ballasted Clarifiers

This technique has been used in America for the treatment of river water prior to treatment for drinking water. Before the water enters the system it passes over an air burst cleaning filter screen, to remove the large particles. This is a self-cleaning filter where air is pushed back through the filter at set intervals to prevent the filter clogging. The water is then pumped into the treatment area, where a mixture of coagulant and sand is mixed into the water. The coagulant helps to produce flocs from the fine suspended solids in the water and bind them to the sand. This increases the specific gravity of the flocs allowing them to settle faster.

Slurry pumps then remove the solids from the bottom of the settling area and the sand is removed by hydro- cyclones for re-use. The overflow from the hydro-cyclones is then sent for further treatment. In many cases the overflow is dewatered using a centrifuge (Latker, 2008).

This appears to be very efficient at removing fine particles from the water. The main problem with the system is the size; it adds an extra component to what is already on site. It is also most beneficial to slurries with low quantities of suspended solids. This means that it would not be suitable for use with pipe jacking slurry used in fine grained soils.

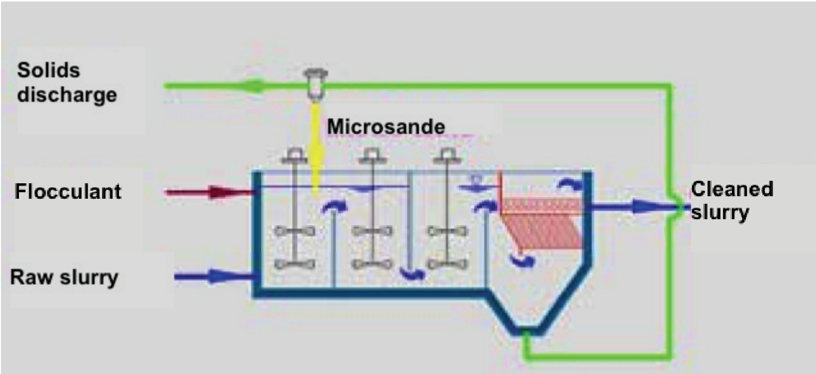

Figure 2.5 Micro sand ballasted clarifier (http://www.veoliawaterst.com, 2012)

2.2.1.5 Laminar plate settler

A laminar plate settler (Figure 2.6) is another form of separation/thickening system. It comprises of several inclined plates in the top half of the tank. These commonly vary from 45° to 60°, depending on the material. This maximises the area provided for the slurry to settle and flocculate (Siltbuster, 2010).

Depending on the manufacturer the position of the flocculant dosing and slurry input into the tank varies. This commonly happens at one of two locations. The first method is to flocculate with either a mixed flocculant or flocculation block and pump the slurry into the top of the tank. In the second method the pre-flocculated slurry is pumped into the bottom third of the tank. As it rises the fine particles hit and collect on the inclined plates. As the flocs increase in size they slide down the plates and fall to the bottom of the tank. The thickened sludge can then be pumped to a centrifuge. Clean water is released from the top of the tank back into the system.

This system has a larger footprint then the vertical clarifier but has a more effective method of separation. With the extra area provided by the inclined plates increased performance maybe possible. This could be a viable piece of plant if the throughputs, size and dosing of flocculant are correct.

Testing carried out by Liu (2010) showed that with only single flocculant dosing prior to the inclined plate settlement tank, the centrifuge centrate turbidity was increased when compared to similar flow rates with no prior sedimentation. This however is counteracted by the cleaner supernatant from the settlement tank. It was also shown that accurate flocculant dosing was extremely hard to control with supernatant often containing excess flocculant.

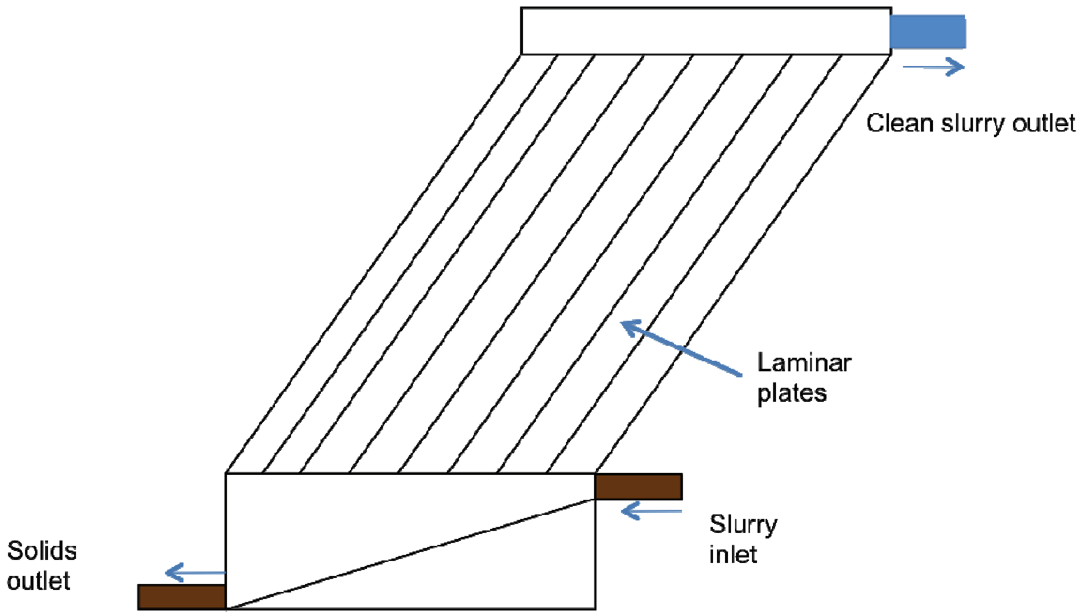

Figure 2.6 Laminar Plate Separator

2.2.1.6 Tangential Separator

This is another form of separation tank that uses flocculants. It is very similar to the vertical clarifier, but a shorter, wider version. The water runs into a header tank first which contains flocculation blocks. This is used predominately by Barhale Ltd and generally when pumping out shafts and disposing of site water (Mudtech, 2012). The flocculant blocks allow for easy dosing and minimal monitoring by the mud man.

This could also be used in the same way as the other settling systems to enhance the performance of the centrifuges. It would also significantly increase the quantity of slurry that could be cleaned removing almost all particles from the slurry. Exact data are not available but it would not be unrealistic to assume a cleaning capability of +100m^3/hour within the small footprint. This would be capable of removing all the suspended solids from a 1200mm ID pipe jack as an inline piece of plant.

The use of flocculant blocks requires no input from the mud man other than variation of the flow rate. Time will be required at the start to adjust the flow rate of the solids pump to achieve a clear centrate.

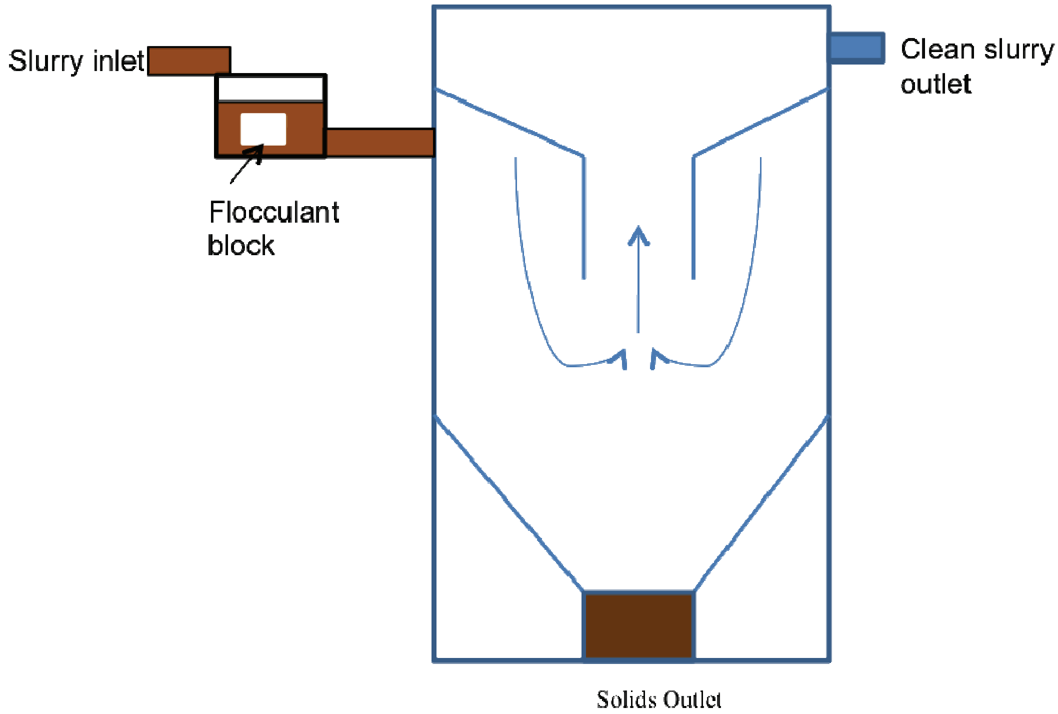

Figure 2.7 Tangential Separator

2.2.1.7 Paddle Thickener

Paddle thickeners are a traditional form of slurry separation and thickening. They have been used within many process industries for over one century. They can vary in size from a diameter of 5m up to diameters of 200 meters with a low height to diameter ratio (Poole (a), 2009). They work by flocculating the slurry and pumping it into the central level. This should be below the top of the settled solids.

The clean water is allowed to rise up due to its lighter specific gravity and feed over a weir to the discharge section. The solids are continuously stirred by a low rotational paddle speed. This condenses the flocs that have formed and releases extra water from the slurry. At the bottom of the tank a pump removes the thickened solids. This requires very little operational time by the mud man. There may be a problem of the accuracy of flocculating dose and the possibility of amounts of excess floc entering the active system.

With the level of the solids kept above that of the inlet, this means that the rising liquid is filtered by the solids. This creates a clean over flow in the weir section. The agitation helps to shear the flocs making them strong and more compact. (Poole (a), 2009)

With the low height to diameter ratio means the footprint hinders the suitability on pipe jacking sites. The dosing of flocculant is also difficult to control correctly and avoid over dosing. This is due to the long delay time between seeing the flocculant effects and change in dose levels.

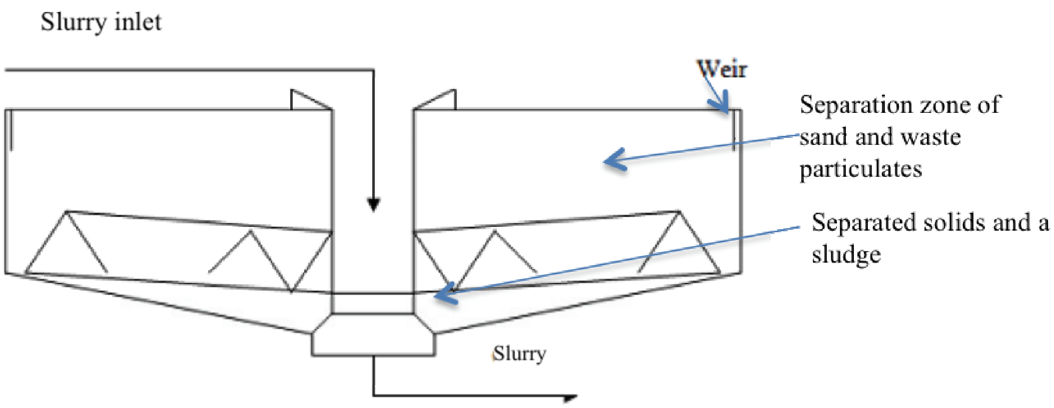

Figure 2.8 Paddle Thickener (Poole (a), 2009)

2.2.1.8 Summary of Methods

Separation Technique	Advantages	Disadvantages
Bubble Flotation Separation	-No need for flocculants -Cost effective to run -Works Continuously	-Most effective in low solid slurries -Large foot print
Continuously Self Cleaning Sand Filters	-No need for flocculants -Works on continuously -Small footprint	-Could become clogged when slurry is heavily laden with solids -Set-up and cleaning at the start and end of each pipe jack -Effective for light suspended solids
Vertical Clarifier	-Small footprint -Can clean large quantities of slurry -Can keep up with a 1200mm ID TBM	-Needs to be flocculated -Hard to control the -flocculant dosing
ACTIFLO® Micro sand Ballasted High Rate Clarifiers	-Cleans Light suspended solids from the slurry -Can produce very low turbidity's in the centrate	-Large footprint -Several extra pieces of plant required -Most effective on low solid slurries
Inclined Plate Settlers	-Effective cleaning -Could possibly keep up with tunnelling rates -Could be combined with electro kinetics	-Large foot print -Needs to be flocculated -No method of accurately dosing the flocculant

Tangential Separator	-Small foot print -Can be dosed using a floc block -Low hire cost	-No method of accurately dosing the flocculant -Added footprint
Paddle Thickener	Concentrated solids Clean centrate	Large footprint Need for flocculant Moving parts

Table 2.1 Advantages and disadvantages of clarification and thickening plant

The effect of the above selection of plant on the efficiency of a separation system is unknown. All of the above plant would be additional to the current plant used and would increase the size of the overall footprint. Sources (ITE, 2010)(SNF, 2011) have pointed towards an increased solids throughput capacity of the centrifuge. There are several unknowns that could be a disadvantage to using a thickener on site which requires investigation. These issues are:

- An extra piece of plant and larger footprint; does the benefit outweigh the size and inconvenience?
- What is the increase in separation rates by the centrifuge?
- Can it be run independently with minimal operator's time?
- Can the solids level be maintained with ease?
- What is the effect of using flocculants and coagulants, and the effect this has on the centrifuge separation?
- Can the dosing rate be easily controlled to avoid over or under flocculation?

These questions cannot be fully answered without more field experiments undertaken and are beyond the literature review undertaken. The rate of dosing had been found to be extremely hard to control (Lui, 2010) at a level where excess flocculant was not being discharged with the centrate. Field tests are required on operational plant to check if this can be controlled.

2.2.2 Dewatering: Centrifuge Alternative

Clarifiers and thickeners are most effective with particles greater than 65μm. Current practice for separating and dewatering the sub 65μm is with a decanting centrifuge. This is very effective but has a high capital cost and still produces a cake with a water content in excess of 55%. It is known that other practices are being used in large scale tunnelling contracts and other industries.

2.2.2.1 Electro coagulation/ Electrophoresis

The water/ slurry separation technique of electro coagulation was looked at as a possible solution for separating and dewatering the slurry. A typical unit was only found to be able to treat $11m^3$ in a relatively compact area (Clarke and Lawson, 2004); this would not be to dissimilar to a medium sized centrifuge currently used. The system passes a current through the slurry to separate the water from the excavated material. (Powell Water, 2002) state that 98% of clays can be removed from the slurry in one pass. The principal benefit over chemical coagulation is that it does not trap water in the sludge, producing a drier product (Clarke and Lawson, 2004).

One initial problem from this technique may be that it is too effective when using a bentonite slurry and whether it is cost effective to continually add bentonite (For bentonite refer to 2.4.1.1). Safety issues about passing a current through a liquid have been raised but the voltage levels are low so it is a safe practice for site conditions. A large area is needed for the plant. The sludge from the process may still be too wet to be disposed of so a centrifuge may still be required to dewater the sludge. More research is required to find out if the water content of the arisings can be low enough, if another dewatering process is required to produce a waste product suitable for landfill.

The sacrificial anodes break down with time and that breakdown leads to potential contamination of the sludge (Figure 2.9). This also affects the treated slurry by dramatically increasing its pH which can rise above 12.

One method of using this could be within a clarifier system. A research project on this was carried out at the University of Leeds (Poole (b), 2009). This produced exceptional results with the solids settling and dewatering in the bottom of the tank to an extent that they could not be removed. Further developments could be made in order to remove this material, using a high torque auger.

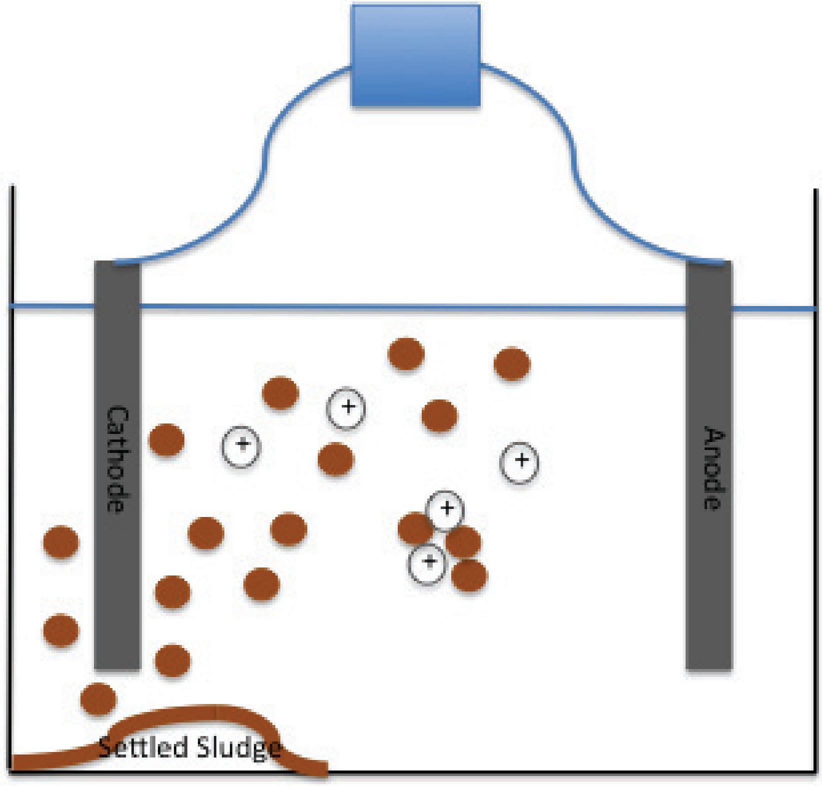

Figure 2.9 Simplified diagram of Electro-coagulation

2.2.2.2 Geotextile Bags

A method used in the mining industry for the dewatering of tailing fines and the mine water sludge is geotextile bags or on a larger scale tubes (Figure 2.10). This uses either a finely perforated or woven material to allow the water to drain away. On initial tests carried out in Greece on the Stratoni mine complex (Newman *et al,* 2003) within 20 hours the slurries were dewatered to 50%wc. With the use of additives the speed of this process could possibly be increased.

A continuous water supply for tunnelling would be necessary to keep up with demand because of the relatively slow dewatering time. The bags would need to be placed in a carefully constructed sump so that the water could be pumped back into the system. The bags could also be used with the electro kinetic geosynthetics (EKG) (Electrokinetic, 2010) to speed up the time of separation. This would work on the principle of electro osmosis drawing the water to the edge of the bag.

Problems with this process are the time and space needed for this method to work and remove enough water to allow the material to be sent to landfill.

Figure 2.10 Bank of geotextile bags being filled (Hi-Tech Speciality Fabrics (exports) PLC, 2012)

2.2.2.3 Belt Press

Belt presses work by forcing the slurry or sludge through two porous belts with a decreasing size gap between them. (Figure 2.11) This in turn squeezes out the excess water. This technique is used in many industries including tunnelling. Commonly a dry solids content of around 60% is achievable (Electrokinetics, 2010). The cost to run and maintain is also relatively low compared to a centrifuge.

Belt presses are used in many industries with similar function to that used in pipe jacking and tunnelling. It was witnessed on the Olympic Park in Stratford as part of a soil washing plant. The plant footprint was larger than that of a decanting centrifuge when producing similar quantities of solid cake (EFLO, 2012). The moisture content was not checked but literature states that it is similar to that of a decanting centrifuge.

There is the possibility of replacing the centrifuge with a belt press or to reduce the water content of the waste material by placing the belt press after the centrifuge in the production line. A belt press can be used to continually process slurry unlike a filter press which works on a batch basis. A draw back with a belt press is the size of plant needed and to get a dry cake a thickener is also needed inline. This adds to the plant on site and the foot print. Typical sizing would be for a small belt press in approximately 1m by 2.5m, up to several meters in width and length.

A development to the traditional belt press mentioned above is the incorporation of electrokinetics. The use of anodes and cathodes has been developed so that they can be woven into geosynthetics (EKG). This has allowed Electrokinetic Ltd to combine the technology with a belt press. With the aid of the EKG the belt press can dewater through electro osmosis as well as pressure producing a significantly drier cake (Electrokinetics, 2010).

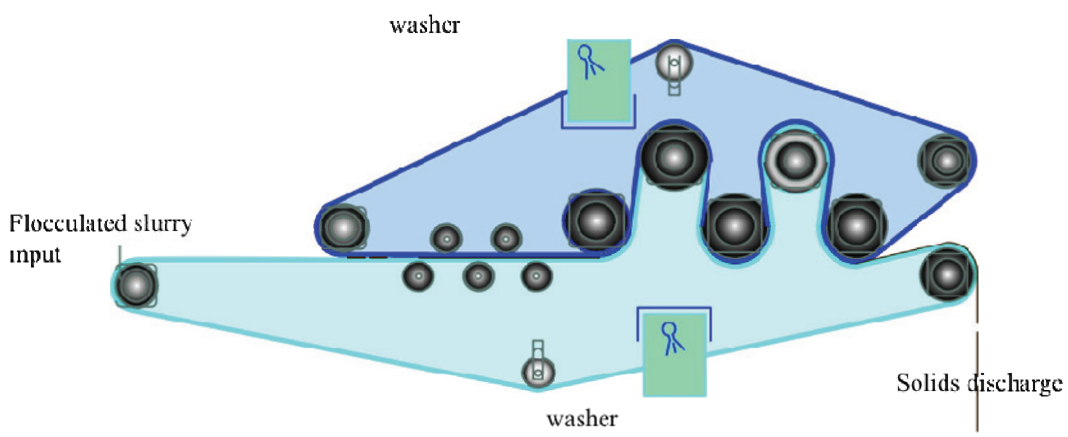

Figure 2.11 Diagram of a typical belt press

2.2.2.4 Filter plate Press

A filter press consists of a series of vertically hung filters plates on a horizontal frame. Each filter plate is covered with a filter medium that seals together when closed. Hydraulic cylinders on the frame push the plates together. Slurry is then fed into the cavity producing a hydrostatic pressure that causes the liquid to pass through the filter medium in to the discharge system. The solids remain between the plates building up a filter cake. Slurry is continuously fed under pressure between the plates until the solid content reaches its maximum and a solid cake is formed. Once this is achieved the plates are pulled apart and a dry cake falls out into a disposal area. The filters are then automatically washed.

A typical cycle time is 20min-5hours (Clarke and Lawson, 2004), although recent developments have suggested that times as little as 10 minutes (Siemens, 2011) can be achieved with certain slurry parameters. This process does work on a batching system, resulting in a large press to keep up with tunnelling. The longer the batching cycle the larger the machine that is needed. The slurry will also need to be flocculated prior to entering the press.

The foot print of a filter plate press is also larger than that of a centrifuge that produces equivalent solids throughput. This is its main disadvantage. It does however produce a drier cake and it extremely cheap to maintain.

Electrodes can be woven into the filter medium to improve the dewatering capabilities and potentially speed up the process using electrokinetics (Electrokinetic, 2010).

2.2.2.5 Vacuum Beds

Vacuum beds are extensively used by the US army to dewater sludge (Kim *et al*, 1992). The system works by applying a vacuum to the underside of a rigid container with a porous base. This helps to aid the process of drying by gravity and draw the water through the porous base.

This method is carried out on a batch basis which is not ideal for the pipe jacking industry. Although it is faster than open lagoons it is still too slow to get to a suitable product for disposal. A large area is also needed for this solution to be able to keep up with tunnelling requirements. In an urban area there would be no room for this method and the set-up costs would not be viable on a rural site. Another drawback is the effective porosity of the tunnelling arisings. If a large amount of clay sized particles are encountered then the dewatering time will be increased significantly and could even stop the dewatering process by blocking the porous base.

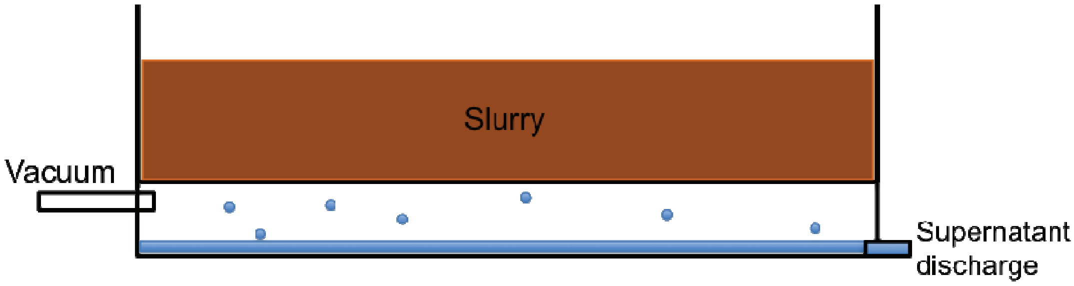

Figure 2.12 Simplified diagram of a slurry vacuum bed

2.2.2.6 Screw Press

This form of plant is used extensively in the food waste and paper industries. They work by a gradually reducing pitched auger rotating inside a perforated cylindrical screen. This compresses the material entering the press, squeezing out the water. It appears that there is a limitation to the size of particles that can be pressed; 375µm according to the Vincent Corporation (2008). A smaller filter would be needed for dewatering slurry. This plant has been seen to be used with mine tailings and would be more suitable as a desander. A belt press could be more effective in the pipe jacking industry.

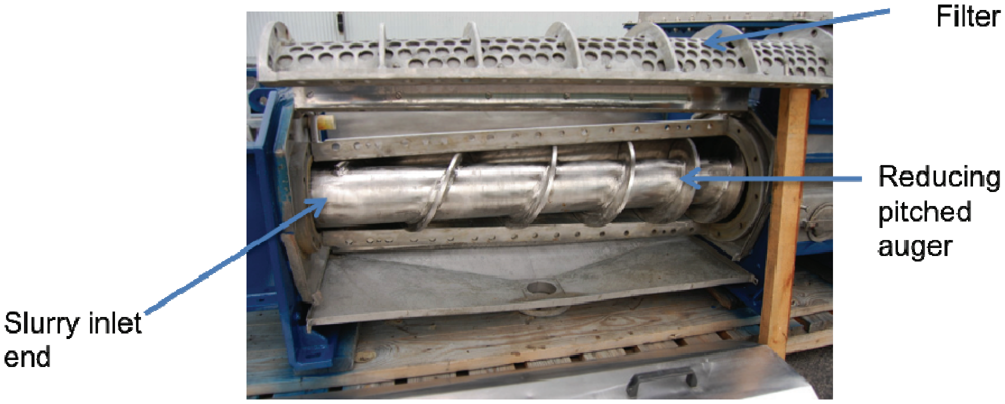

Figure 2.13 Internal workings of a screw press (Vincent Corp, 2008)

2.2.2.7 Rotary Vacuum Filters

Commonly used in the chemical processing and mining industries, they work by a rotating vertical drum through a pool of slurry (Figure 2.14). A vacuum is applied to the internal section that sucks the suspending particles onto filter that surrounds the drum. As the drum rotates the water is sucked through the filter and the cake falls off as it passes over a scraper (Komline, 2011). The material is stopped from settling in the tank by a paddle continuously moving the liquid.

This technique could be an alternative to centrifuges. If the output could be high enough, they could sit within the mixing tank and continuously remove the fines. This could allow the vibrating sieves to sit above them minimising the surface area used on site. It can only be presumed that the energy consumption would be less than that of the centrifuges because the speed of the rotating drum is much slower.

The limitations of this technique would be that it would require high solids concentrations to produce a good filter cake, the cake would require a high permeability to allow the cake to dewater. It may also lead to the finer silts and clays passing through the filter back in to the system.

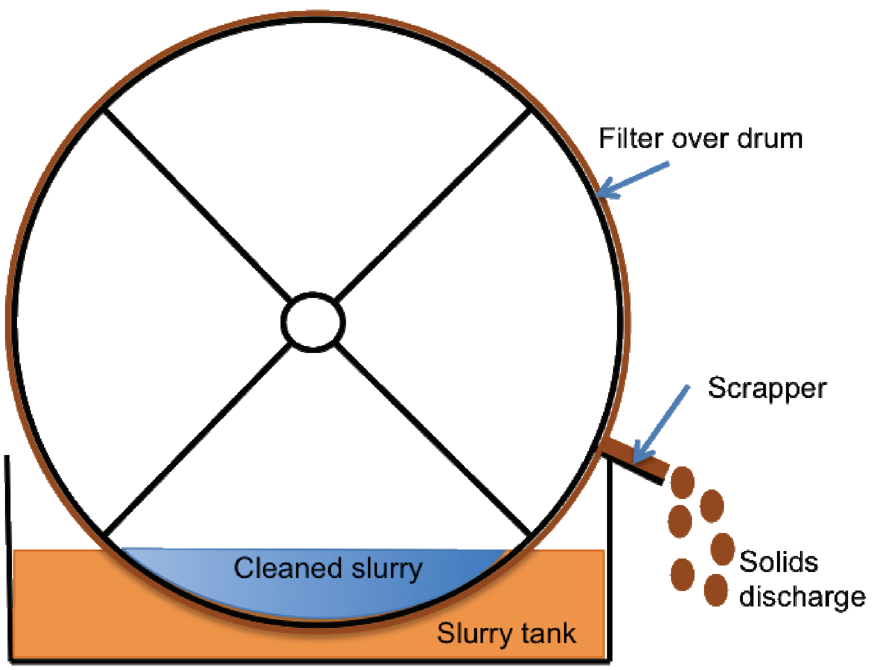

Figure 2.14 Vertical drum filter

2.2.2.8 Summary of Fine Particle Dewatering Methods

Separation Technique	Advantages	Disadvantages
Centrifuge	-Small foot print -Fast separation -Easy to monitor (when set-up correctly)	-Power Consumption -Capital Cost -Noise
Belt Press	-Dry cake -Ease of operation -Low power consumption	-Large plant -Requires wash water -Requires thickening in low solid slurries
Filter Press	-Very low moisture cake -Low operator requirements	-Batch process -Large plant -Slow process
Geotextile Bags	-Simple to operate -Cheap	-Large space required -Hard to control
Electro kinetics	-When incorporated a belt press can improve operation -Cheap to operate -Drier cake	-Size of plant required -Extra cost
Electro coagulation (lagoon dewatering)	-Very effective -Cheap to set-up	-Large footprint -Slow dewatering times -Increased pH of separated slurry
Vacuum Beds	-Cheap when used on a large scale -Easy operation	-Large area required -Slow to dewater
Screw Press	-Continuous operations -Low running costs	-Limited to larger particles mainly organics -Can have a large footprint -Does not always produce a clean centrate
Rotary Vacuum Filters	-Continuous operation -Easy of running -Relatively low operating cost	-Possibly wouldn't produce a clean centrate -Low throughput with a typical pipe jacking slurry

Table 2.2 Advantages and disadvantages of dewatering plant

2.2.3 Further Dewatering/Drying

There are methods that reduce the water content of the arisings from the separation process. Some of these have yet to be used in practice and would require pilot tests first.

2.2.3.1 Ultrasonic Vibration

Within the mining and quarrying industries ultrasonic dewatering and compaction has been used. It is a method that involves gradually filling a container or skip and applying ultrasonic vibration through the base (Figure 2.15). When all of the solids have settled the clean water that has formed on top of the material can be pumped out and another layer of slurry can be pumped in. This layering continues till the container is full and adequately dewatered (Poole (b), 2009).

The final product is extremely dry and compacted to a state very similar to virgin soil. This could be applied to pipe jacking and attached to the muck collection skip. To fit in with the process on site the skip would not be able to be filled in stages. Instead the ultrasonic system could be run continuously and the excess water removed at intervals or prior to the removal of arisings from site.

Depending on the price to mobilise the plant this could be extremely beneficial and should reduce the water content of the arising whilst reducing the chance of water being released during transportation. This would reduce the cost of transporting excess water and increase the likelihood of acceptance by the landfill operators.

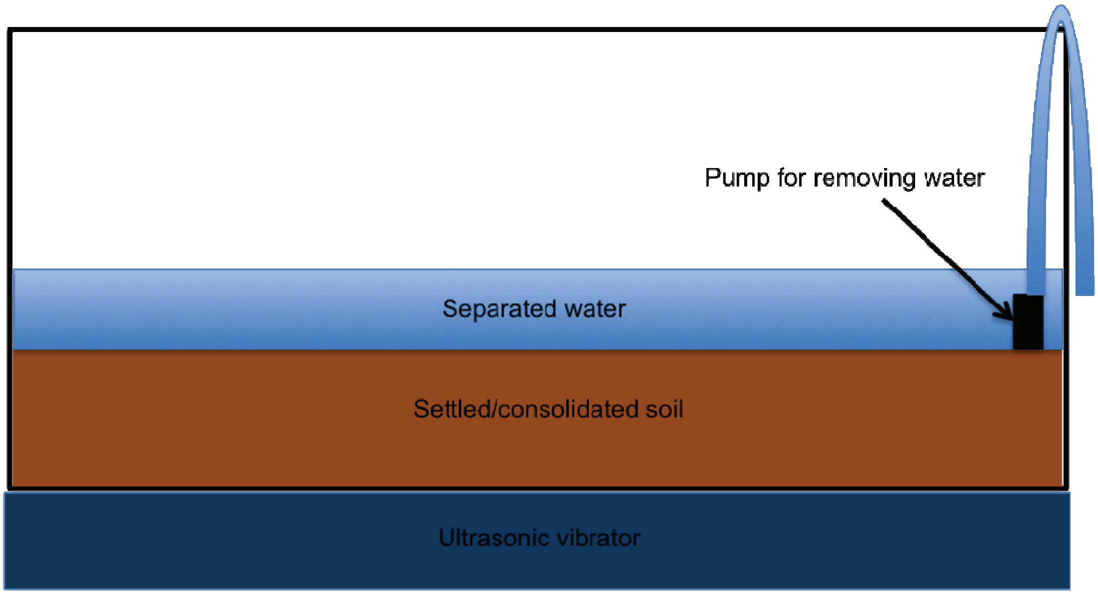

Figure 2.15 Cut through diagram of an ultrasonic vibrator container

2.2.3.2 Air Swept Tubular Drier

These units vary in size depending on the output required. They work by passing the material through a central augured section and forcing air at a temperature up to 600° over the material (Figure 2.16). It can be used with slurry and claims to be able to reduce the water content of thickened slurry from 95% to 1% in one pass. They are able to cope with slurries with a water content up to 98%. (Bulk Process Equipment.com, 2008)

Air swept driers are used in many industries from food waste to mineral processing. The units are usually fuelled by a gas or an oil product. The fuel consumption can be presumed to be high and is a major draw back to the system, especially in the long term, due to the price of these commodities rising. (Atritor, 2010) Capacities of processing with the size of the plant should be looked into and the price per unit weight for processing should also be calculated. It might be possible to use a condensation plant with this machine to recycle the water.

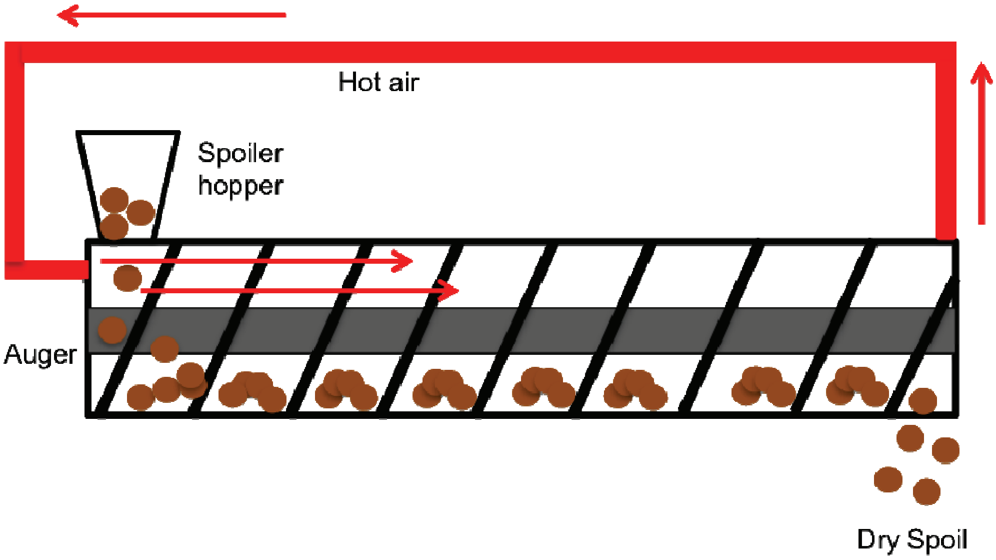

Figure 2.16 Cut through diagram of air swept drier

2.2.3.3 Electro-osmosis

The principle of electro-osmosis is the movement of liquid through a solid medium. (Electrokinetics, 2010) This could be utilised within the muck disposal skip to reducing the trapped moisture. This has been carried out within slope stabilisation projects for railway embankments but there is a time involved which may prove to be impractical. The rate at which a material is dewatered in this way is a function of both the electrical current used and the distance between the anode and cathode. This time of dewatering could be reduced if the anodes and cathodes could be placed closer together without effecting site operations. (Figure 2.17)

This technique could be beneficial in the future but requires a lot more work to make it commercially viable. The main issue is the spacing of the anode and cathode, whilst keeping a safe working current and uninterrupted site working. The spacing and current will affect the speed at which particles water particles will move towards the cathode. On site the distance between the anodes and cathodes should be kept far enough apart for ease of maintenance.

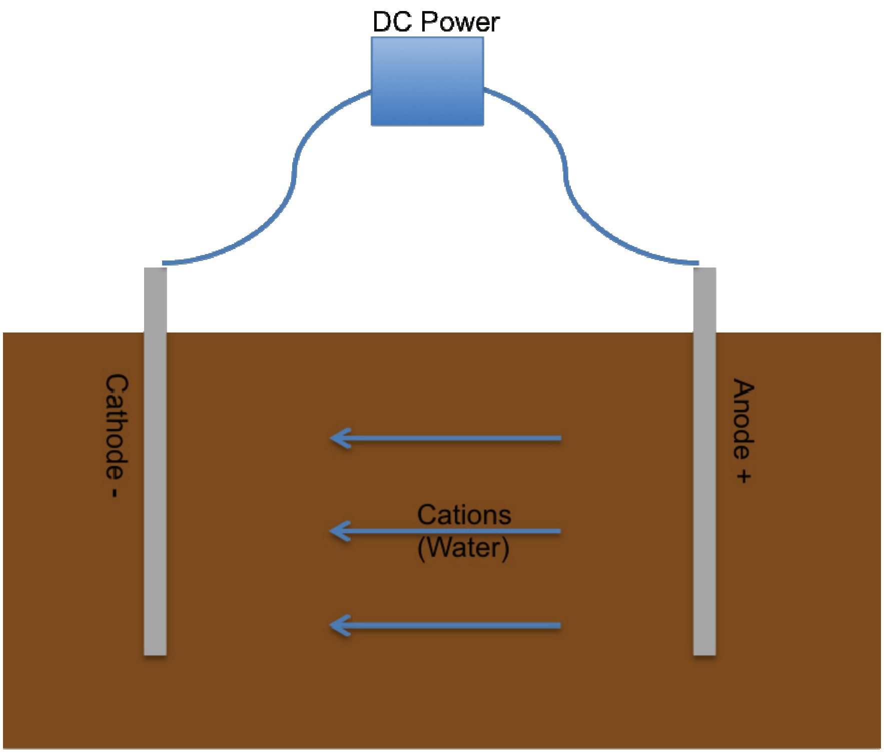

Figure 2.17 Simple diagram of electro-osmosis

2.2.3.4 Summary of Methods of Further Dewatering

Method	Advantage	Disadvantage
Ultrasonic Vibration	-Reduced water content of spoil -Easy to incorporate into the current system (skip)	-Cost of the ultrasonic vibrators -The release of water from flocculated material in from this method has not been looked at.
Airswept drier	-Extremely low water content of arisings -Easy to run and quick	-High energy consumption, cost and environmental impact
Electrophoresis	-Could be low cost -Could be incorporated into the current system (skip)	-Relatively new technology in commercial dewatering -Could be limited on anode and cathode spacing

Table 2.3 Advantages and disadvantages of further dewatering techniques

Thus there are various methods of further reducing the water content of the tunnel arisings in addition to the methods already in use. Both ultrasonic vibration and electrophoresis would require a significant amount of research and testing to check their suitability for pipe jacking. From the above information ultrasonic vibration would be the most desirable but its ability to dewater flocculated material is unknown.

2.3 Disposal

Currently the majority of tunnel arisings are sent to landfill which is both expensive and not environmentally friendly. One of the ideas suggested by the pipe jacking industry was to identify potential alternatives for this. This can be extremely difficult due to waste handling legislation within the UK and because of the quantities involved from one site. There are three methods to consider:

- Use of a centralised collecting facility. In areas where major pipe jacking projects or many projects take place it would be possible to set up a central collecting facility to allow slurry/solids to be processed
- In areas of abandoned underground and surface workings it would be possible to dispose of the slurry
- Some slurry can be modified to produce a construction product.

2.3.1 Storage Sites

A potential solution for the cost and environmental impact of disposing of the tunnel arisings by landfill would be for the Pipe Jacking Association to set up storage sites in locations around London initially due concentration of work. This would provide contractors an area where they could deposit arisings to allow them to dry out if needed and either be sent to land fill or if it was suitable to be re-used. One possibility would be to talk to the National Farmers Union about setting up a system where farmers can use it as a soil conditioner. Chalks are good to neutralise acidic soil, so this would be a benefit to the farmers. Clays are beneficial as well when the top soil is sandy in nature.

This would reduce landfill costs, although the purchasing of the land and transportation may prove too costly to make it viable. A key point is that the material can only be stored for two years otherwise it is classified as a land fill site and would significantly reduce the likelihood of gaining planning permission. With the tightening of disposal laws it may also be deemed an unacceptable method without very detailed documenting of the arisings.

2.3.2 Salt Caverns and Disused Mines

In the US salt caverns are used to store drilling fluids/ slurries from the oil drilling industry. Salt caverns are manmade sub surface caverns that are formed by drilling through the overlaying rock into the salt formations below. Water is then added to dissolve the salt and brine is pumped out. (National Energy Technology Laboratory, 2011) There are salt caverns in the UK but they are few and far between.

The cost of creating the caverns and the transport cost to get the slurry from site to the caverns is far too high. This means that realistically it is not economically viable unless one can be found close to a proposed large tunnel.

Disused mines around the UK could also be used in the same way. The properties of untreated slurry are suitable for disposal in this way as they are inert. This is because it is self levelling and will flow into the mine tunnels. Problems occur with the transport to the mines, the capital set up cost and limitations due to permitting in current legislations. Again this is an unreasonable solution.

2.3.3 Trenchmod

Trenchmod is a patented way of recycling excavated material developed by Keanes in partnership with Three Valleys Water. It uses the excavated soil, sub base and Tarmac to produce a suitable material to back fill with, an equivalent to type 1. From initial reading it processes the material with an added chemical through a robust trailer based mixing plant. The plant can process up to 700 tonnes per day and in 2007 were expected to process at least 57,000 tonnes in the South East.

From the literature tests have been carried out on the suitability for backfill (Keanes Environmental, 2008). This has a huge benefit to the environment by reducing the amount of quarried stone needed, transportation of the stone and it has the potential to maximise the use of the lorries transporting the material to site. This is because it allows the lorry to take fill material to site then pick up excavated material to take back for processing.

This could be an option to specify Trenchmod as a method of treating the dewatered slurry. There are several potential limitations with this, which are the high water content of the excavated material and the flocculants used may react with the additive used in the processing technique (www.keanesenvironmental.co.uk, 2008). A third problem could be the type of excavated material. A type 1 material is specified to have less that 9% fines (clay, silt) (Department of Transport, 2002) so unless the TBM is in rock it may be unsuitable.

2.3.4 Accelerated Carbon Transfer

This is a relatively new technology that uses waste and a carbonatable binder to absorb carbon dioxide producing calcium carbonate. The end project can be used as an aggregate for building with. For every 7 tonnes of waste there is the potential to capture 1 tonne of carbon dioxide. When used with quarry fines the carbonatable binder is principally cement or fly ash. In some soils the carbonatable binder is not necessary because the soil may already have high calcium content. (Carbon8, 2009)

This would give the pipeline green credits and would make the arisings useful. There would also be the possibility of using the CO_2 produced by the generators on site. If tunnelling through contaminated ground then the production of calcium carbonates locks in the contaminants and leaves the arisings pH neutral. This means that the arisings are then deemed to be safe and no longer contaminated.

2.3.5 Alternative Uses

The arisings from certain sites may have beneficial uses in other industries. This would stop the need for large quantities of waste being sent for landfill. The benefits from this approach may reduce the cost of disposal, add to contract earnings and reduce the carbon footprint. This might be used in conjunction with Accelerated Carbon Transfer, Trenchmod or just reusing the arisings as they are at present.

Excavated chalk could be used in several ways, the first of which is to produce cement. This would offset some of the carbon produced in manufacturing the cement for things like the pipes and shafts. This would not require paying landfill lax and may recuperate some of the transport costs. It could also be used in agriculture, being spread on fields to neutralise acidic soils. Recent tunnelling work in Sussex recycled 98% of site waste (Costain, 2011). To achieve this both the above methods of re-use was used for chalk. Along with this some was used as hard-standings for roads and landscaping. This would commonly not be available for smaller projects that are commonly undertaken by pipe jacking contractors. They also require active thinking on behalf of the client and the contractor in minimising spoil sent to landfill.

Clays could be used in the manufacture of bricks or in agriculture where the land is very sandy and lacks cohesion. Sands and gravels could also be used as aggregates, slightly offsetting the carbon used to quarry the aggregates for the manufacture of the pipes and shaft.

Arisings could also be used for land reclamation, landfill capping or landscaping. This would save small amounts of money but the offset carbon would be dependent on the use of the land. This could be hindered by the paper work needed to comply with current legislation and may be too time consuming for a contractor to look at an alternative use.

The government have started to address the topic by creating the National Industrial Symbiosis Programme (NISP). This is an opportunity for businesses to be linked to other industries where their arisings maybe useful. (National Industrial Symbiosis

Programme, 2011) The programme has already been used on several construction based contracts.

For the re-use of tunnel arisings, both the contractor and client require planning to take place. Doing so could reduce disposal costs with the exemption of landfill tax (£2.50/tonne); it would also help to increase the environmental credentials of the contract. Over time the task will also become easier, once disposal routes have been identified and relationships formed. With the cooperation of clients who will be undertaking work in common geographical areas the reduction of arisings could be possible.

2.4 Additives and Flocculants

2.4.1 Slurry Additives

In certain circumstances additives are required to be added to the basic water slurry system in order to improve several functions of the slurry;

- Face support
- Fluid/slurry loss to the ground
- Solids carrying capacity
    - Both during pumping and during stoppages
- Swelling inhibition

The following section will cover the two basic slurry additives and a potential new polymer.

2.4.1.1 Bentonite

Traditionally bentonite is used to help with the suspension of solids and to provide face support. This is often used in pipe jacking contracts. However this use of bentonite has been reducing over the last decade due to its detrimental effects on the separation side of operation. Bentonite is a form of clay, which is generally comprised of the mineral montmorillonite. Each particle is a long flat plate, the top and bottom surfaces being negatively charge and the ends positively. The plate has a stronger negative charge. There are two dominant forms of bentonite; calcium and sodium bentonite. Sodium bentonite is the most suitable as a drilling additive due to its swelling capabilities.

Bentonite exhibits thixotropic properties and when mixed using a shear mixer the plates line up in parallel, increasing its viscosity. When undisturbed the positive ends are able to rotate so and are attracted to the negative side plates. This increases the gel strength and aids in the suspension of solids. This can be reversed to decrease the viscosity. If bentonite slurry is used, then the added bentonite is only about 3% by weight. This should produce a marsh funnel cone reading of between 30 and 40 seconds and a density of around 1.3g/cm^3 (Milligan, 2000). These figures are only a guide and many modern bentonite producers sell a blended bentonite with various polymers such as PHPA's (partially hydrolysed polyacrylamide) and xantham gum. These can have a significant effect on the viscosity, gel strength and yield point of the "bentonite". This can be detrimental to tunnelling operations if the contractor is not aware of the ingredients. This was witnessed on a site in Jeddah recently where the bentonite contained xanthan gum but was quickly attacked by the parasites contained within the ground (Mutluay, 2010).

Main contractors for several reasons avoid bentonite where possible. The first is the environmental impact if bentonite enters a watercourse it can remove essential oxygen from the water, which can kill plants, fish and insects living in the water. It can also block the gills of fish suffocating them (Construction Confederations, 2007). The other reason for not using bentonite is the removing of it from the slurry once it is not needed. Due to the fine nature of the particles these need to be removed using a centrifuge and flocculants. Alternative polymers have superseded bentonite on many sites.

Traditional bentonite will not swell if mixed with saline water preventing any of its beneficial properties and it will degrade and could flocculate if used in very saline conditions. There is however one form of clay closely linked to bentonite as it contains smectite but it also contains polygorskite which is suitable for drilling in salt water. This is Attapulgite, which unlike traditional bentonite which is flat platelets, it is simply described as needle shaped. This changes depending on the level of hydration. Due to the more prominently positively charged sites in comparison to more common clays gelling occurs more easily by attraction.

2.4.1.2 Xanthan Gum

Xanthan gum is another suspension/ face support additive and can be added to bentonite or used as an alternative. Xanthan gum would generally be used when tunnelling in sands, gravels and weak strata, where carrying capacity and water control is needed. (Mudtech, 2008) It is the same additive that is used in many common foods such as, salad dressing, chewing gum and toothpaste and has the ingredient name of E415.

When tunnelling in loose, non-cohesive grounds where there is the need for extra carrying capability or to provide face support/reduce water ingress xantham gum maybe required. Due to the way that a tunnel boring machine works, especially with a pipe jack sized tunnel, a “filter cake” does not form during active tunnelling because there is not enough time for the slurry to gel. When the machine is stopped for any period of time a filter cake will develop and help create a stable face. Whilst tunnelling in granular soils some slurry will penetrate the ground in front of the machine, this will help to stabilise the ground and prevent water ingress but not in a traditional filter cake manner. Due to xanthan’s extremely low shear rates it will penetrate further in to the tunnel face than bentonite slurry.

Unlike bentonite, xanthan gum is not greatly affected by saline conditions so can be mixed with saline water if necessary, although this should be avoided if possible. It can also be used to tunnel through saline ground conditions.

Xanthan gum slurry is a rheological fluid, which means whilst it is in motion it becomes viscous, but when not in motion it gels (King, 2002). This helps to keep sands and fine particles in suspension for longer. Rheological fluids cannot really be defined by a single viscosity because their fluidity varies with shear strength. In a non-Newtonian fluid the shear stress and strain rate are non-linear and also time dependant in many examples. Although a non-Newtonian fluid cannot be defined by one viscosity on site, a simplistic, repeatable method is needed for the separation operative (mud man). A more accurate way to understand the fluid would be with a rheometer. This could be hand powered with a clutch system shown in Figure 2.18. This will give the plastic viscosity, yield point and gel strength of the fluid, allowing the mud man to understand the carrying capacity of the slurry, pumping requirements and also potential time to build a filter cake if a stoppage occurs.

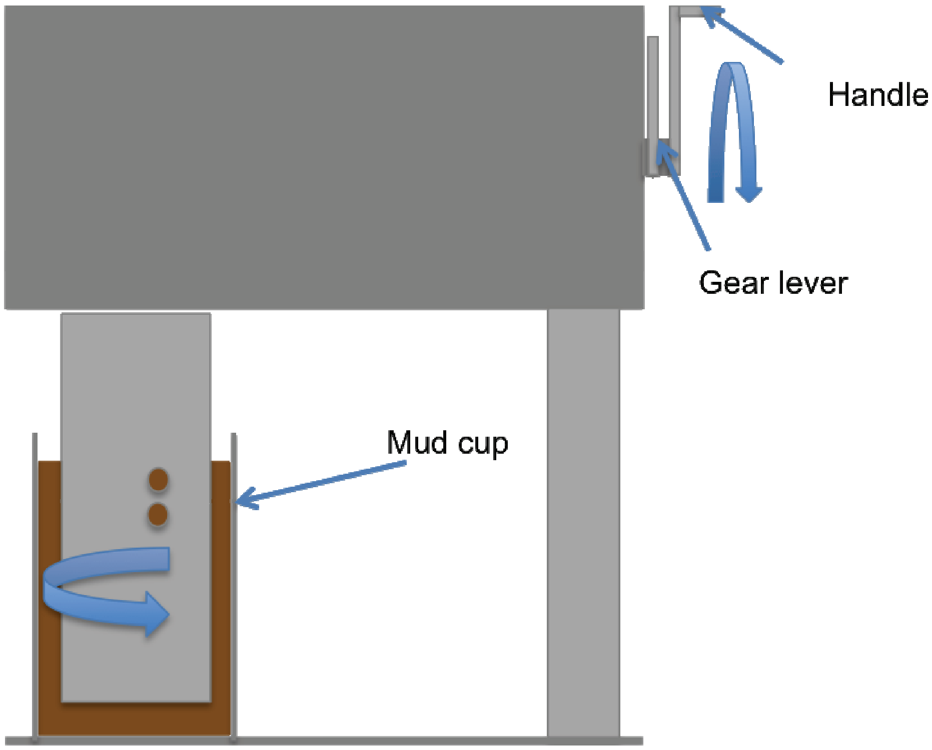

Figure 2.18 Hand powered rheometer (Fann, 2011)

Commonly on site, slurry using xanthan gum would be mixed to a marsh funnel viscosity of 55-60 seconds and due to the low quantities added have a low specific gravity of just over 1.0. Trade names for this are MX (Mudtech) and Visco (from Tunnelling Accessories). Xanthan gum is easily and quickly removed from the slurry using a cationic flocculant, but could be removed at a slower pace using an anionic flocculant. Due to the ease of removal and low mixed specific gravity tunnelling can continue even if clay is encountered. From sales information one 25kg bag of xanthan gum equals a one tonne pallet of bentonite for dosing. This obviously reduces the amount of mixing that is required to produce the required slurry.

Environmentally xanthan gum is a favourable alternative to bentonite. It is 93% biodegradable within 14 days and its eco-toxicity is also low. If a pond was dramatically contaminated then obviously problems would occur, but compared to bentonite, xanthan is a more environmentally friendly additive. Due to the shorter mixing times there are also health and safety benefits, lower exposure times, less manual handling and larger particles resulting in limited air born particles. One problem with xanthan gum is its tendency to breakdown due to bacterial infection. Xanthan gum is an extremely good source of food for bacteria, which will remove all of the gum's beneficial properties and make the slurry smell. This is more rapid if tunnelling through a contaminated area or in high temperatures. To help avoid this, a biocide is required when carrying out long drives or in the conditions mentioned above. This is to reduce the chance of degradation but may not stop it in extreme circumstances. Biocides are also detrimental to the environment so should be used carefully and avoided if possible.

It should also be noted that some bentonite products have xanthan pre-mixed to help increase gel strength and carrying capacity. This is not always made clear in the literature so care should be taken when choosing a bentonite blend.

2.4.1.3 High Molecular Weight Polyacrylamide with Varying Chains

A polymer is being developed at Oxford (Jeffries, 2009) to be used as a slurry additive and is currently being used in diaphragm walling and piling in the United States. The polymer stops the excavated soil breaking down and absorbing water, this is achieved by encapsulating the cuttings preventing contact with and free water.

There are still issues with separation of the solids from the slurry and potential blockage of screens. The polymer consists of large chains that hold the material in suspension and surrounds the arisings. The gelling ability can be demonstrated by sucking a sample of polymer through tube from a beaker. If the end of the tube is submerged when you start sucking, then it will continue to empty the beaker, even though the end of the tube rises out of the solution. (Jeffries, 2009)

If issues with separation could be overcome, the result of this fluid could prevent the need for fine particle separation (decanting centrifuge) because all cuttings should stay intact. Prevent fine particles entering in to solution.

2.4.2 Solid removal Additives

2.4.2.1 Flocculants

Flocculants are used in many industries to improve the settling rates of fine neutrally buoyant particles within slurry. Fine particles generally carry an electrical charge, this may vary due to the chemical composition of the particle. These particles may absorb polar water molecules forming a 'bound' layer around the particle, this results in a repulsive force between the particles, thus preventing the particles flocculating naturally. (Milligan, 2000) When fine particles have the same charge they repel each other; this is Van Der Waals force. The flocculants attach themselves to several particles pulling them together forming flocs. They do this by a mixture of attraction to opposite charges on the particles and chemical bonding. (Poole (b), 2009) There are three types of flocculants used. The first is cationic, which are positively charged molecules that are attracted to the negatively charged particles within the slurry. There is also anionic flocculants, which are negatively charged and attracted to positively charged particles but also bound via the hydrogen arms of the chain with the oxygen atoms on the surface of clay particles. The third type is non-ionic which from research does not appear to be non-ionic but just a weakly charged. These are generally used to flocculate weakly charged particles, producing a balance in the solution.

Flocculants are already added to the slurry prior to it being sent through the centrifuge. They work very efficiently when dosed and monitored correctly. Flocculants are very difficult to understand as there are so many different strengths/weights and amount of active particles within a carrier fluid. Typically an anionic polyacrylamide (PHPA) flocculent will be mixed at 0.5% and left to age for at least 20minutes. This is mixed gently using a slow moving paddle mixer. If it is mixed too fast then the polymer chains will break due to shearing. This is added to the slurry at a low dose rate. Non-ionic flocculants are not used in the pipe jacking industry because the low charge makes them poor at flocculating the fines. From various data sheets at this concentration it is environmentally safe when handled correctly (Morrison Mud, 2007)(SNF, 2006). There are many health and safety issues with it that should be addressed prior to use.

For separation purposes using a decanting centrifuge a high molecular weight polymer is shown to be most effective with an activity of about 30%, Figure 2.19 shows a basic anionic chain. (SNF, 2011) This is the number of actively charge bonding sites along the chain. The other bonding sites are those of hydrogen. The chain charge has a secondary function, which is to keep the chain as straight as possible to maximise the chance of hitting particles suspended within the slurry. This is achieved by the charged sites repelling each other, straightening the chain (Poole (b), 2009).

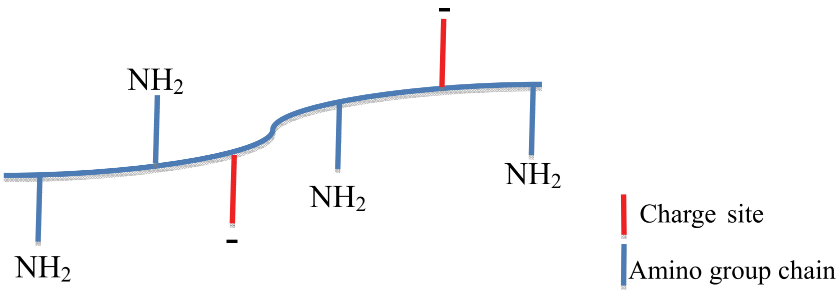

Figure 2.19 Basic polyacrylamide chain (Moody, 1992)

2.4.2.2 Coagulant

A coagulant can be used in conjunction with a flocculent to improve the settling of the fine particles. A coagulant works by reducing the electrical charge of the particles, which reduces the repulsion force. These are positively charged salts that fit between the negatively charged oxygen atoms on the surface of the clay. In doing so they reduce the negative charge of the particle and allow flocs to form. Examples of coagulants would be potassium sulphate, aluminium sulphate or ferric chloride. For optimum results the pH should be monitored and the correct salt used. This requires solubility curves. The coagulant should be mixed into the slurry under high turbulent flow to disperse the particles evenly and induce collisions between the clays. This is unlike mixing of a flocculent which is mixed under minimum force.

Generally on a pipe jacking site only a flocculent will be used. This is because it is generally found to produce adequate separation rates. If this was not the case then a coagulant could be also be dosed to the slurry prior to adding the flocculant. Due to the ever-changing slurry conditions contractors have made the decision to limit the number of variables for the mud man.

2.4.3 Post Treatment Additives

2.4.3.1 Muck Stiffening Agent

There are several products DryAdd (Morison Mud, 2012), Polyswell (Schlumberger, 2012) on the market that absorb the excess water content of slurry thus thickening it, so it can be transported as a solid. The chemistry is not made public for any of these products, so the data provided by the manufacturers cannot be checked. They do specify that the additives are environmentally friendly, totally inert and that it does not affect the pH levels of the soil. From the literature this makes the treated waste suitable for landfill.

The principle behind the additive is that it absorbs the water from the slurry, this is achieved by the constant mixing of the slurry. This type of additive comes in two forms either as a powder or as a liquid. Developments are being made for specific inline mixing equipment, instead of the method used at present of stirring it into a lagoon or skip with an excavator. This pumps the slurry whilst dosing and with the liquid form, once left for a few minutes produces a stackable material.

Work could be carried out on the benefits of using it in conjunction with lime or cement to see what the structural benefits are and if the arisings could be used in embankments, back fill or other no landfill uses. (Mudtech, 2009)

2.4.3.2 Shredded Paper

A technique that has been used in Japan to treat diaphragm wall slurry and create a reusable material is to add shredded newspaper and paper to the slurry to absorb the water. This is carried out by filling a sealed skip approximately three quarters full with slurry and adding bails of shredded paper. This is then mixed in with a rotary mixing bucket attached to an excavator, similar to an “Allu” bucket. (www.allu.net, 2010)

This is continuously mixed and paper added until the material is firm and stackable. A polyacrilamide flocculant and a small quantity of lime or cement are also added to help bind the mixture. The mixed slurry from the case study seen was being used to construct embankments. The site had two skips so that one could be filled whilst the other was being mixed. (Ishii, 2009) On a pipe jacking site this would need to be carried out once the slurry had reached a density of 1.2-1.3g/cm^3 for it to be economical. This method would require a stoppage to remove and replace the slurry. It would also cost the contractor a significant amount of money for transporting water trapped within the mixture.

There are several points that would need to be researched to make this a viable solution. These would be:

- A cost analysis,
- Waste legislation and the classification of the spoil,
- Long term stability of the material and
- Ease of procurement.

Once these areas have been researched then a more accurate conclusion can be made on the potential benefits of this technique.

2.5 Legislation

As mentioned previously current UK waste legislation (from 2007) prohibits the disposal of liquid waste direct to landfill. This results in large off site carriage and treatment charges if removed from site in slurry form. Current legislation states and is most relevant to pipe jacking arisings; the limit between a sludge and liquid is "*any waste that near instantaneously flows into a hollow in the surface of the waste*" (DEFRA, 2009)

The use of polymers and additives should be assessed prior to tunnel arisings being removed from site. A calculation should be carried out to assess the total concentration of each additive (flocculant, absorbent treatment agent and any suspension agent added to the slurry) to the quantity of soil arisings. As it is the contractor's legal duty of care to check that the arisings are disposed of in the correct way. In most cases the material sent to land fill can be classified as inert, although special care needs to be taken if the spoil contains more that 0.1% by volume of a hydrocarbon because this is then deemed as 'special waste'. As a result care must be taken with the operation and handling of plant that contain hydrocarbon fluids that spillages or leaks do not enter the spoil. (Potter and Jeffries, 2005)

A quick assessment was carried out on a 50% suspended flocculant. A liquid flocculant is often suspended in a mineral oil which has a disposal limit in inert waste of 500mg/kg. Taking this limit in to account and a specific gravity of mineral oil of the order of 0.92 a maximum flocculant dose rate can be calculated. This was seen to be 1.086ml/kg (dry solids).

The disposal of flocculant containers and excess flocculant should also be monitored. Containers may need to be disposed of as 'special waste' and advice should be sought from both the supplier and the local Environment agency. Excess flocculant can only by realistically disposed of through its normal use in the separation plant. If not, advice again should be sought from the Environment Agency for appropriate disposal routes.

When dealing with pipe jacking arisings the "*Management of process arisings from tunnels and other earthworks: A guide to regulatory compliance"* (Potter and Jeffries, 2005*)* should be consulted. The continuing changes in regulations means that it is necessary to keep up to date. This brought to the attention that the excess water content of arisings above 25% by weight is discounted from landfill tax requirements, if the landfill operator is made aware of the source process. This is because the excess water is deemed to be part of the industrial process, so is not entitled to be taxed. This cost saving maybe minimal if the waste is classified as inert.

2.6 Summary

From the research on methods of separating and dewatering slurry several methods have been found that could be used on a pipe jacking site to separate and dewater the tunnelling arisings. It was also clear that the current set-up is exceptionally good at removing the solids in a compact set-up. The research has also opened up areas that require further work to identify their exact benefit to the current system.

One area where extra work is required is the effect of clarified material on the efficiency of the centrifuge. Initial review suggests that there is an increase to the solids throughput capacity of the centrifuge as the slurry density increases. It was noted that a major drawback of operation was the accurate flocculant dosing of the slurry, especially with the fluctuating slurry characteristics.

Extra work should also be carried out on the benefits of using ultrasonic vibration to dewater the tunnelling arisings. This would be hoped to reduce the water content saving money on transportation and reduce the chance of rejection from the landfill site. This could also be possible with the use of electro-osmosis. This could be achieved by designing a skip with the anodes and cathodes already built in and the inside lined with plastic to avoid the degradation of the skip.

With regards to additives and flocculants more work is required on understanding the benefits and effects of each one have on the system. There are proven examples within the industry that show the benefits of various additives. There is also still a lack of understanding about where they should be used and the exact effect.

Current waste legislation is extremely extensive and under constant review. Because of this contact should be made with the local environment agency prior to a contract starting to seek the most up-to date legislation and identify the best route for disposal. It is noted that where avoidable all arisings should be processed on site to a level acceptable for disposal or re-use and if possible no liquid waste sent from the site. Contractors and clients are also recommended to sign up to NISP with the hope and aim of another company having a use for their arisings.

As mentioned above, the current plant used by pipe jacking contractors has the ability to process slurry efficiently and within a tight footprint when specified correctly. This requires more work to find the best set-up and operation for a contractor. Many UK contractors have already spent large capital costs on separation plant so it is concluded that the best approach would be to carry out a more in depth analysis of current plant and the operation of it because they are unlikely in the short term to purchase new plant.

3.0 SITE OPERATION

3.1 Introduction

A study was carried out on a number of pipes jacking sites to gain a full understanding of how a slurry pipe jacking system operates and what affects the operation and performance of the separation plant. The sites were chosen so that the effect of the pipe jacking contractor, ground conditions, plant and operatives could be assessed highlighting the variation in working practices, problems encountered and how they were dealt with, performance rates and effectiveness of plant.

The site visits had two objectives, the first being to log the equipment and site set-up, interview operatives and witness problems. The second was to collect slurry data to see how the differences in working practices and ground conditions affected the slurry separation systems. Site events are very poorly logged and are very rarely made public. This means that literature on specific site problems is rarely found. The most effective way to assess the problems is to witness them first hand and interview the site operatives not only about current problems but problems they have witnessed in the past. As mentioned in a previous chapter the most critical problem is the increase in density of the slurry causing the pipe jacking process to be stopped. This was commonly linked to ground conditions.

This chapter covers both the quantitative and qualitative approach to information collection and the findings from the site visits. The problems witnessed are described together with assessment of the probable causes. Previous problems mentioned by site operatives were also investigated. The slurry data were collected using equipment in common use on site; a marsh funnel, mud balance and sand content kit. Samples of the slurry were taken at least at the start, middle and end of every pipe jack so that the change in composition could be monitored. The samples collected were taken from the main separation tank at roughly the mid point in depth. The location in plan varied between sites due to restrictions in positions of sampling.

Primary Factor	Secondary Factor	Tertiary Factor
Contractors	Site operatives Management and tendering systems Plant used	
Sites	Client specifications Ground conditions Space	Geology Clay content Sand content Potential for soils to break down/disperse Water content
Tunnel Boring machine	Hired or owned Type Head action	
Flocculants	Type Mixing procedure	
Separation Plant	Size/type of centrifuge Configuration Hydro cyclone and screen size Primary type- clay ball separator or shaker	
Slurry	Additive Density Contaminants Sand content Viscosity	

Table 3.1 Factors that could affect the separation process

An initial assessment of the slurry separation process at the start of the research project suggested that a number of factors could affect the success of the separation process. These are listed in Table 3.1. It is evident from this table that all aspects of the pipe jacking process had to be assessed to check whether they impact on the separation process. Preliminary studies of the process suggested that this was likely to be the case.

3.2 Aim

The aim of chapter was to gain a greater understanding of the behaviour of slurry and the factors that affect the pipe jacking process. This leads onto developing best practice based on what was witnessed on site and published information.

3.3 Site Visits

It was unclear as to the exact challenges being faced on site by contractors and the causes of these challenges. It proved difficult to gain a conclusive, un-biased understanding of the problems without witnessing them first hand. Hence, the need to arrange site visits to fit in with contractors' programmes and the site operations.

The initial task was to make contractors and key employees aware of the project by visiting a number of sites and talking to site staff. Initial contact was made with a number of contractors to identify possible sites. Once a site was identified regular contact was maintained by phone and e-mail to ensure that a site visit fitted with their programme of work.

Prior to site visits simple logging forms were devised to collect collate and log information that could be analysed off site. The forms used are shown in Appendix A and B. A key aim of the site visits was to gather experiential knowledge, to uncover operatives' experiences and opinions, and gain information on previous jobs. The opportunity was also taken to record aspects of the pipe jacking process and in particular the slurry separation process.

The slurry density, sand content, viscosity and pH (on later sites) were taken from the mid-depth of the slurry tank and at various intervals depending on the machine type and time taken to excavate a pipe length. In addition to the slurry properties, the chainage, time, jacking pressure, type of arisings and other comments were also recorded on the form. This information was recorded onto the form shown in Appendix A and displayed in Appendix G.

In the time between samples being taken and during stoppages the form shown in Appendix B was completed. This form covered the site workings. This information was used to compare different set-ups and their performance. Photographs were taken of the site set-up, plant and any incidents that occurred whilst on site to supplement the notes.

Conversations took place with site operatives about their understanding and experiences of pipe jacking. In particular these concentrated on conservations with the 'mud man' and the TBM operator. The 'mud man' refers to the site operative who managed the separation process' i.e. separation operative. They could either be a dedicated site operative or a TBM operator tasked with the responsibility of the separation process and the pipe jacking process. These discussions covered:

- problems seen in the past and their solutions;
- ways to improve the process;
- techniques to run the plant efficiently;
- 'tricks of the trade';
- the impact of ground conditions on the separation process;
- and the behaviour of different plant and machines in different ground conditions.

Operatives on site are an extremely useful source of information for several reasons. Some are very highly experienced and have been working on different plant set-ups over many years. They can also be a lot more open than managerial staff about operational aspects including problems that have occurred and how they were overcome.

3.3 Site Data Collection

3.3.1 Method of Data Collection

A number of generic and specific factors were needed to provide the characteristic features of a site and identify the difference between sites. Appendix B is the form used to record details of the site visits. Ground conditions were taken from the borehole logs.

Slurry samples were taken every 0.5 meters of pipe advancement when using a Herrenknecht TBM and at the start, middle and end of every pipe when using an Iseki TBM. The slurry density, sand content, viscosity and pH (on later sites) were determined. In addition to the slurry parameters, the chainage, time, jacking pressure, type of arisings and any other comments were also recorded on the site log form in Appendix B.

The accuracy of each test to determine the slurry characteristics varies and depends on the apparatus being used. The most common piece of apparatus used was the mud balance, which has an accuracy of $0.01 g/cm^3$. The Marsh funnel used to determine viscosity has an accuracy of ±1 second. The accuracy of the sand content kit varies with the sand content. At low sand contents the accuracy is of the order of 0.05% and can be up to 2-3% when reading close to the 25% limit reading.

3.3.2 Results

The full set of site data is shown in Appendix C-E. Appendix C shows the relationship between the tunnelling rate and slurry density for six sites. These can then be analysed against points that were witnessed on site to give an understanding of the effects that the equipment, decisions, personnel and ground conditions (see Section 3.1) can have on the slurry density.

The sand contents and viscosities are tabulated in Appendix D and E respectively. The sand contents give an indication the effectiveness of the secondary separation plant and an understanding of the variation in the ground.

In Appendix F the rates of solid removal have been calculated. These were based on the difference in slurry density at the end of a pipe drive and at the beginning of the next drive. During that period the slurry was being pumped through the centrifuge to remove the fines – no further material was being added to the slurry since tunnelling had stopped. From this an estimate of the quantity of fines being removed can be made.

3.3.3 Interpretation

The first observation made from the graphs in Appendix C is the slurry density variation on site A. These two graphs (Figure 3.1 and Figure 3.2) show how a centrifuge can run economically with the slurry density increasing as a pipe is advanced and then decreasing in the time that the next pipe is being connected. This allowed the slurry density to be controlled up to a level of 1.08g/cm^3. Over a short distance (Ch 88-93) the average density continued to increase. This could be due to several factors; e.g. a slight change in ground conditions, a break in centrifuge operation or the accuracy of the measurements.

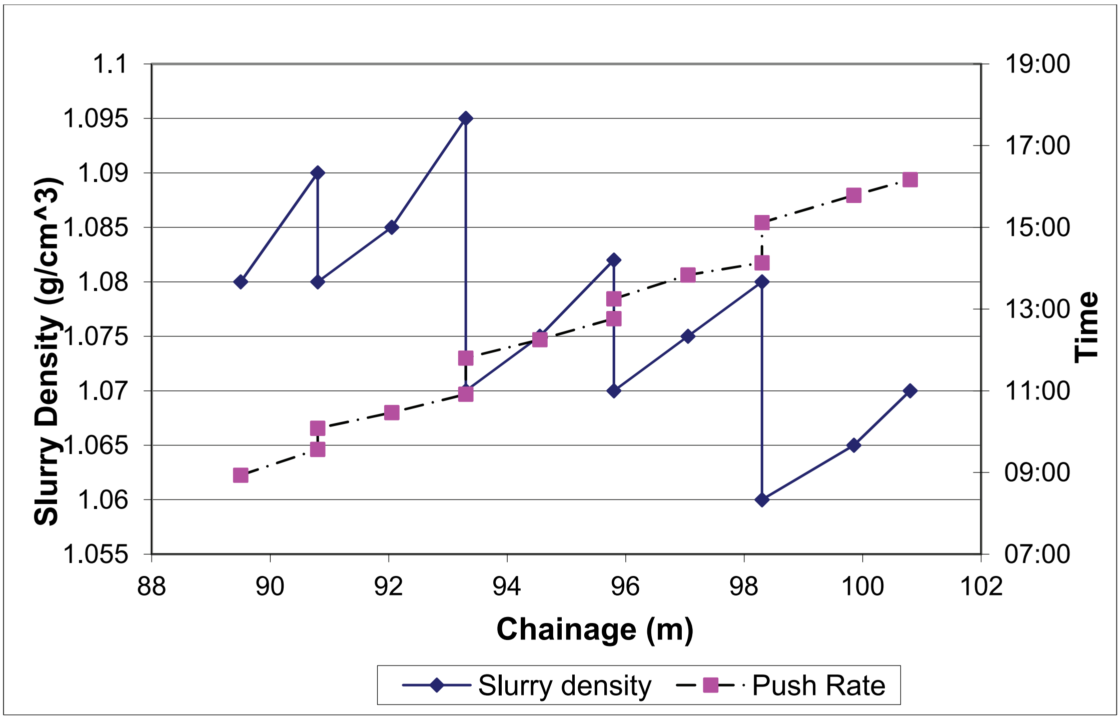

Figure 3.1 Slurry density variation against chainage for Site A visit 1

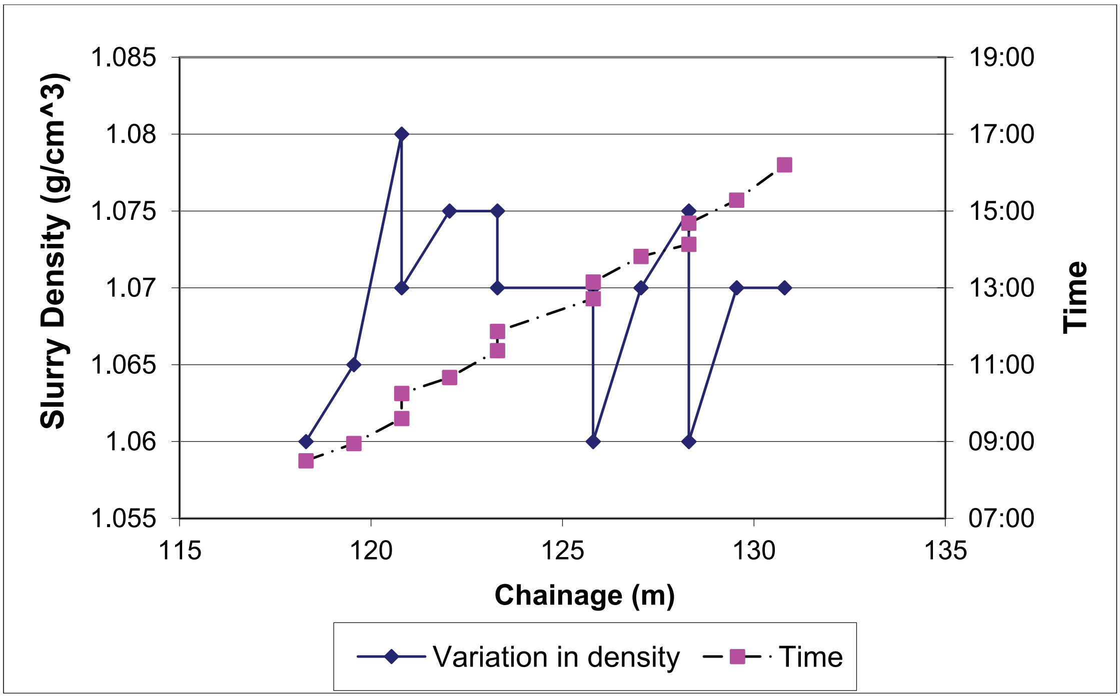

Figure 3.2 Slurry density variation against chainage for Site A visit 2

In an ideal situation when the centrifuge capacity is at its most efficient it should be able to keep up with tunnelling rates removing all the fine particles from the slurry during one pipe cycle. Figure 3.3 shows an optimum density variation graph.

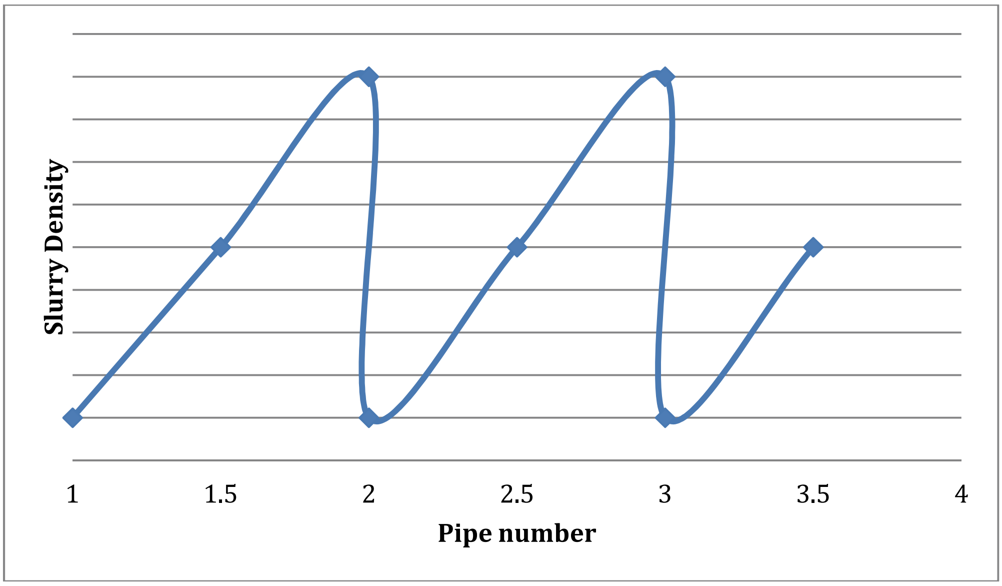

Figure 3.3 A qualitative display of the variation in density which allows a slight increase in density as the pipe advances to ensure that the centrifuges are working efficiently and reduces the density to the optimum when a new pipe is being added

If the slurry density reduced as a pipe was jacked forward or if the density at the start of each pipe jack is reduced then the centrifuge was too large to be run at its optimum efficiency for the ground conditions and tunnelling rates. This could be altered by reducing the slurry through rate. If the slurry density was not monitored, then this practice may be unacceptable because the slurry density and viscosity may not provide adequate transport or face support capabilities.

An example of insufficient centrifuge capacity was identified on site F, Figure 3.4. In this case the slurry density increased as the pipe progressed at an acceptable rate. The reduction in slurry density when the next pipe was being connected was insufficient to reduce it to an acceptable level (between 1.00-1.10g/cm^3). The consequences were:-

- Increased wear to all parts that have contact with the slurry because of the increase in solids content.
- Delays due to extending the time between each pipe to allow the slurry density to be reduced to an acceptable level.
- Increased pressure on the slurry pumps, potentially leading to failure of the system at some point.
- Increased cost in disposal because of liquid waste regulations.

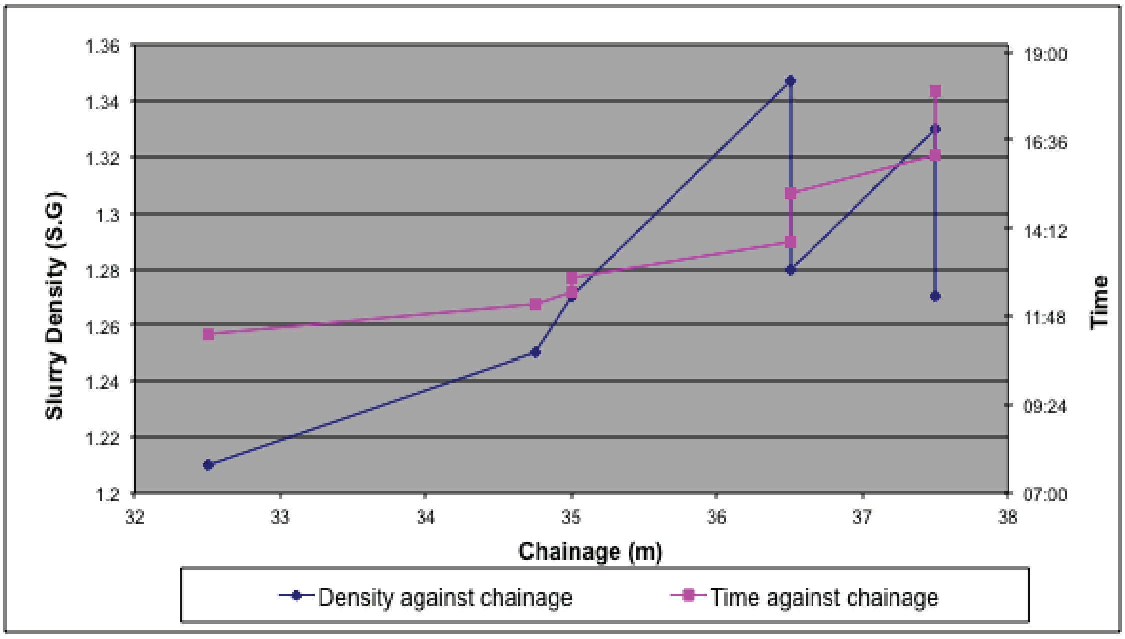

Figure 3.4 Variation in slurry density for Site F

The complete drive graphs for sites G, H and I (Appendix C) show the consequences of running the separation plant with no centrifuge. Every major decrease in slurry density is a result of the contractor replacing the slurry with fresh water. This can affect the production rate and also has a very significant cost to the contractor because of the additional cost of waste disposal. However, it should be noted that this cost may be offset against the cost of hiring centrifuges.

The failure to remove fines from the centrate also results in an increase in the viscosity of the slurry as indicated in Appendix E at site F. The pipe jack was through mudstone which broke down into silt and clay sized particles due to the tunnelling process. In this case slurry was being fed in to the centrifuge at a density between 1.2 and 1.3g/cm^3 with the returning centrate being returned at a density of 1.01-1.02g/cm^3. Although this was helping to slow the increase of the overall slurry density by removing the majority of suspended solids it was increasing the viscosity. The viscosity went from 38seconds to 54seconds over a density increase of 0.12sg. The particles remaining in the centrate are the smallest and lightest which take the highest amount of energy to remove from the slurry, they also stay in suspension resulting in thicker slurry with an increased viscosity.

An increase in viscosity results in greater pump pressures and increased centrifuge torque (with Newtonian fluids) but improved transport and face support properties can be seen depending on the gel strength. The gel strength is dependant on the constituent parts of the slurry and is not commonly monitored on pipe jacking sites in the UK. However, on balance, the viscosity was found to be unacceptable which resulted in delays because the pipe jacking process was stopped whilst the slurry was cleaned with the centrifuge or replaced.

Both sites A and D were tunnelling through very similar ground but with totally different set-ups on site. This allows for some comparisons to be made. A major and important comparison that can be made is the variation in sand content. The average sand content on site D was an average of 1.42% which was 10 times higher than that of site A 0.14%. The reason for this is believed to be due to the size of the hydro-cyclones.

The single hydro-cyclone on site D had a diameter of 18 inches and a d_{50} of 60µm. Site A in comparison was running seven 6inch hydro-cyclones that had the ability to produce a much finer cut down to approximately 25µm (quoted as optimum). The size of the cut and diameter and number of hydro-cyclones affects the amount of solids in the slurry. Because the cut size of a hydro-cyclone is quoted as 'd_{50}' (the average particle size) it does allow larger particles through in its overflow. The particle size curve of the overflow can also vary depending on the feed pressure, the cone length, particle concentration, viscosity and the state of the hydro-cyclone (CSI, 2009).

A second comparison that can be made between sites A and D is the rate of excavation. The rate of excavation on site D was half of what was being achieved on site A with very similar conditions. One factor for this slower rate could be the slurry density. All of the graphs show the slurry density increasing as the tunnel progressed. An increase in slurry density can result in a reduced tunnelling rate even if it is not the main reason for slower progress rates. The main reasons were likely to be the TBM operator running the TBM at a more conservative rate or the TBM head set-up (cutter wheel dressing and openings). Time was lost on site D due to stoppages such as replacing the slurry and replacing worn pumps.

The reduction in slurry density when a new pipe was connected can be seen in Appendix F. These rates are calculated for the times whist the TBM is not excavating. The reason for this is because whilst the TBM is operating the quantity of fines entering into suspension is unknown. Therefore the rate that the centrifuge is removing material is unknown. However, the data in Appendix F does give an indication of the efficiency of the centrifuge. The variation in rate of reduction in density can depend on:-

- Size of centrifuge
- Operator
    - How they have the centrifuge running: speed, throughput
    - The time spent operating the centrifuge
- Slurry composition

- Ground that the TBM is tunnelling through
- Flocculant

The main problem with the current results is the accuracy of the mud balance. This only measures to the closest 0.01g/cm^3 therefore the density measurements were ±0.01g/cm^3. Hence the figures shown in Figure 3.5 are ±0.001g/cm^3/hr. They are quoted to a greater accuracy because they represent the average. The time to change a pipe typically varied between 30 to 60 minutes. The readings taken at the start and the end of each pipe were taken within 2 minutes of the slurry pumps being turned off. With this level of accuracy the time difference could vary by 15%.

Site A	Site B	Site C	Site D	Site E	Site F
-0.019	-0.021	-0.003	-0.022	-0.029	-0.113
-0.028	-0.008		-0.012	-0.021	-0.083
-0.025	-0.024		-0.040	-0.025	
-0.020	-0.007		-0.030		
-0.022	-0.014		-0.023		
-0.015	-0.011				
-0.010	-0.006				
-0.023	-0.007				
-0.027					

Table 3.2 Rate (g/cm3/hr) of solids removal during stoppages (pipe installation)

3.4 Site Observations

Discussions with various contractors clearly identified the measure of success to be the number of pipes installed per shift. This was often used to cost a contract therefore it governed the profit/loss of the project. A focus of the site teams was to ensure that the slurry helped achieve success. The slurry separation process is designed to maintain the density of the slurry at an optimum for the ground conditions with a minimum increase in density as the pipe progressed. The density at the start of each pipe should be similar if the additional fines are removed during the addition of a new pipe while the excavation is stopped. Ideally the slurry density should remain constant which meant that excavated soil has to be removed continuously at the same rate as it is excavated.

The properties of any material taken off site, i.e. solids and slurry were not considered critical. This could change with the implementation of waste regulations but the focus of this project was to improve the slurry separation process and in turn the number of installed pipes per shift.

From the observations to date, comparisons are difficult to make and problems were sometimes hard to explain. This is because there is such a variation between the sites. The major variations are the ground conditions, separation plant and the TBM. This means that all conclusions are subjective.

3.4.1 Site Investigation

It was very apparent that the quality and quantity of site investigation data had a major impact on the success of the pipe jacking process. The investigation is usually commissioned by the client or the client's representative. It is noted that the outputs from site investigations are rarely sufficient to avoid issues arising during the pipe jacking process. They include unforeseen ground conditions leading to the loss of slurry, slurry contamination due to the presence of made ground and inappropriate selection of slurry separation plant because of incorrect soil descriptions. Unforeseen ground conditions are not uncommon in construction despite the efforts of the ground investigation industry to raise awareness of the impact on safety and cost.

Even if the ground conditions are foreseen the quality and quantity of factual data may be insufficient to ensure the pipe jacking equipment is correctly chosen because the routine data may not be relevant. The site operation can be adjusted to take into account the issues arising from not using the optimum selection of equipment but this can lead to a reduction in production rate.

Hence the design of a ground investigation must:

- be undertaken by a consultant/client who is familiar with the pipe jacking process and the impact ground investigation data has upon the design of the process;
- include sufficient boreholes to provide adequate information on the local geology and, importantly, the spatial variation of soil types and properties;
- include sufficient tests to characterise the ground conditions;
- and ensure that the exact location of every sample is known (i.e. borehole level, location, sample depth).

All site investigations should be set out in accordance with "An introduction to pipe jacking and micro tunnelling design" published by the Pipe Jacking Association (2007). Inappropriate site investigations will continue to be a problem unless further action is taken. However, there will be occasions where unforeseen hazards are encountered and constructions cost increases.

3.4.2 Management

On some occasions problems appeared to occur due to poor managerial decisions prior to work starting on site and during site operations. These included:

- the wrong choice of plant;
- not supplying enough operatives or operatives with appropriate experience;
- not forwarding information to the correct people within a company;
- and not enough/under specifying the separation plant.

The wrong choice of plant links in with another problem witnessed and that is using the equipment the contractor has available rather than hiring more appropriate plant. There is evidence that some contractors do not supply the site with the required level of separation plant for the tunnel being dug. There are several reasons as to why this could occur:-

- Misunderstanding/not knowing how the ground actually breaks down within the tunnelling machine. Therefore failing to understand the amount of fine particles generated and hence the number of centrifuges required.
- The inexperience of the employee designated with the task of specifying the plant.
- Apparent cost saving based on the assumption that it is cheaper to use their own machines even though they may not be the best for the project. This could actually cost the contractor more over the course of a drive because of the cost of delays.

There are three solutions to these issues:

1. Allow for delays in the pipe jacking process to create time to remove fines from the slurry;
2. Hire more centrifuges to ensure the slurry separation process is in balance with the rate of advance of the pipe
3. Replace the slurry more frequently thus removing liquid slurry from site rather than solid cake.

3.4.3 Staff Development

Currently there are no industry standards that describe the attributes of 'mud men' and hence there are no formal training courses within the UK. On some site visits it was noted that the 'mud man' could not competently operate the plant. They had not undergone an adequate level of in-house training. This problem was regularly mentioned whilst interviewing site personnel.

The lack of training can lead to a number of problems on site:-

- Over flocculation of the slurry causing contamination of the slurry in the tank and the need to replace the slurry if the problem is allowed to escalate since it affects the prime role of the slurry which is to transport solids from the face.

- Not producing a clean centrate allowing large quantities of very fine particles to build within the slurry as the centrate is fed back into the slurry tank.
- Not maximising the production from the centrifuge; not adjusting the throughput correctly. This is inefficient for both power consumption and separating the solids from the slurry.

This emphasises the need for a training course that can provide operatives with a level of knowledge and understanding so they can run the plant competently. It also requires a commitment from the contractors to train an adequate number of employees and to utilise their learning in the training. A similar level of care needs to be taken when allocating an operative to operate the separation plant as to the allocation of a TBM operator.

3.4.4 Staff Allocation

Ideally the site team should include a competent separation operative. It is possible to rectify the situation by taking the actions outlined in Section 3.3 if an operative is assigned but does not have the appropriate skills.

The alternative noted was that an untrained separation operative was directed by the TBM operator on how to run the separation plant or the TBM operator operated the separation plant in addition to his usual activities. In either case, it is likely that those issues identified in Section 3.4.3 will arise leading to delays and additional cost.

The benefits of a 'mud man' were seen on several sites. Figure 1 shows how this manifests itself in a pipe jacking performance. Prior to the first visit there was no mud man working the plant; the TBM operator and other site staff were checking the centrifuge and slurry during stoppages. The machine operator was also staying on site at the end of a shift for an hour to continue cleaning. It can be seen that the first day a specific mud man was allocated to site the density at the start of the shift was 1.08sg and rising. A small increase was seen but once the mud man gained control of the system the density was brought down to 1.06 sg. This can be seen in Figure 3.1.

3.4.5 Use of Flocculants

The problem addressed here was witnessed on a number of sites. It was mainly the use of un-aged flocculent. A flocculent takes time to age and become active, this depends on the original state of the flocculent, i.e. whether it is a powder or liquid. An un-aged flocculent means that it remains in suspension and does not actively interact with the suspended particles. Further with time it becomes active and is able to engage with the suspended particles but by this time the slurry has re-entered the main tank. This could cause settling in the tank or require an increase in torque in the centrifuge on the second pass due to the increased thickness of the slurry. A liquid flocculent requires a period in the region of 20 minutes to become fully active; a powder 45-60 minutes.

Therefore two tanks should be used; one to age the flocculent and the other to dose the slurry with aged flocculent. In the limited instances when one tank was being used it was handled in two different ways:-

1. The contractor understood the problem with only one flocculent mixing tank, so used a liquid flocculent and emptied the tank before refilling with diluted flocculent to ensure that the percentage of added polymer stayed constant. The effects of poor separation efficiency and the risk of over flocculating were limited by using a liquid polymer. The centrifuge continued to operate but produced a wetter cake when the flocculent mixing tank was being filled since no flocculent was added to the slurry.
2. A powder flocculent was being adding to the same set-up. In this case the flocculent was not being turned off during filling, causing un-aged flocculent to enter the slurry system. This was potentially causing the slurry to be contaminated with flocculent reducing the efficiency of the separation process because of the use of un-aged flocculent. With flocculent being allowed to age within the main slurry tank there is the risk that particles will flocculate in the tank and then break down as they pass through the pumps either to the TBM or back to the centrifuge.

It is recommended that two flocculent mixing tanks are used to ensure that there is adequate time to age the flocculent and maintain a constant percentage of flocculent. While one tank is used to mix and age the flocculent, the other supplies aged flocculent to the centrifuge at the correct dosage rate. In this way no un-aged flocculent enters the system and flocculent is continually being added to the slurry passing through the centrifuge.

However, there still remains an issue; it takes time for the flocculent to react with the fine particles in the slurry. Flocculent could be added upstream from the centrifuge giving time for the flocculent to mix with the slurry before entering the centrifuge; or it could be added immediately before entering the centrifuge so that mixing takes place within the centrifuge. There is no evidence to suggest which is the best.

The checking of the correct flocculant dose rate was seen to be carried out by placing a hand under the centrate discharge port. It was stated by mud operators that if you could feel a slippery feel to the centrate then excess flocculant was present. Their aim was to adjust the flow rate of the flocculant to the point where the centrate was no longer slippery feeling but if any more flocculant were added the centrate would be slippery.

This was found not to work when the centrate was looked at closer. Mark Brookes (Barhale Construction PLC) stated in a discussion that the centrate could be tested with a simple 'cup test' to see if flocculant was present. Chemical analysis is unpractical on site due to time and cost. This test involves taking a clear cup or beaker and adding roughly equal quantities of slurry and centrate. The slurry used ideally would be kaolin based at a specific gravity of 1.05-1.1g/cm^3, a sample of the slurry used within the system could alternatively be used.

The two added parts should then be mixed and visually checked for flocculation of the suspended solids. The mud man has the responsibility to adjust the flocculant dosing so that the flocculant is dosed at a maximum level that does not flocculate the test slurry.

A view from some individuals within the industry is that the exact mix concentrations, slurry and slurry density should match that of the slurry within the closed circuit. This is to see if the centrate will affect the system by flocculating the solids. From analysis the industry it would be viewed to keep the process simple and repeatable, leading to the process described above. Also it was seen that the flocculant affects the removed solids and dose levels should be kept at a minimum. These effects are spoken about in chapters 4 and 5.

3.4.6 The TBM

It was noted that the rate of advance varied between TBM's. This is thought to be due to the action of the cutter head. An eccentric cutting motion was witnessed to tunnel through clay ground at double the rate of a centred/grinding cutting head. More material was also seen to be removed from the clay ball separator (primary stage) when using an eccentric TBM. This could have been because the eccentric action feeds and extrudes the clay back through the head, rather than constantly grinding it into suspension.

The centred TBM uses clean water to jet the TBM face and aid the cutting action. This jetting action produces more suspended solids within the slurry but does not necessarily increase its density, due to a dilution effect. This increase the volume of the slurry which increases the throughput through the centrifuge and the need to dispose of liquid more frequently.

The choice of TBM may be limited to that owned by the contractor. It is uncertain as to whether it is more cost effective to hire an appropriate TBM or to use an inappropriate machine and accept delays/inefficient use of the centrifuge.

3.4.7 Separation Plant

This covers several problems with the separation plant, its set-up and use.

The slurry requires constant agitation to maintain homogeneous slurry. This prevents solids settling in the tank but also maintains a liquid with a constant density being pumped to the TBM and the centrifuge. It was noticed that a well designed paddle agitation system is more effective than air. The air has been seen to take the easiest route which is closest to the edges of the tanks, allowing sand and silt to settle in the middle of the tank. The results of air agitation can be seen in Figure 3.5.

The agitation system plays a key role in the running of the separation plant. It creates homogeneous slurry for effective tunnelling and allows the centrifuge to be run easily and effectively. It helps when disposing of the slurry at the end of a pipe jack because the tank will require minimal cleaning out. In a poorly or non-agitated tank it will require an operative to dig out the settled material.

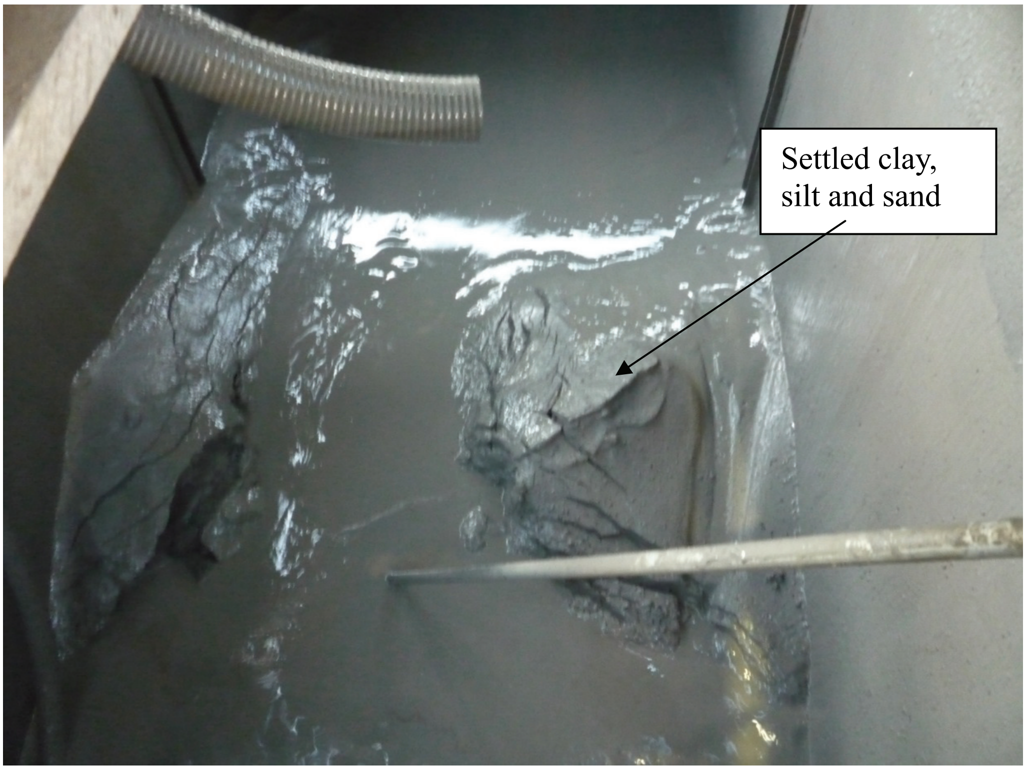

Figure 3.5 The bottom of the slurry tank using air agitation once the slurry had been removed for disposal

The separation plant must be properly maintained. It was noticed on two occasions there were extremely worn bushes supporting the screens on the shaker deck below the hydro-cyclones. This resulted in one case for the secondary separation unit to be turned off resulting in the slurry having a reasonably high sand content.

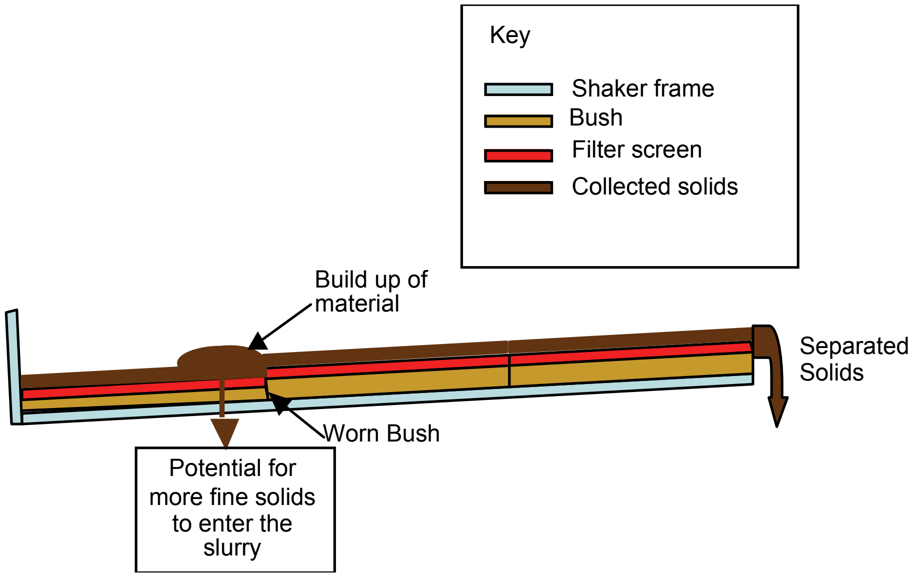

Figure 3.6 Worn bushings on shaker screen

On the second occasion the secondary separators could not be turned off because the underflow from the clayball unit was deposited at the back of the screens. This was causing a build up in sand on the screens between the screen with the worn bushes and screens further forward, this was because there was a step between the screens (see Figure 3.6). This could potentially degrade any clay on the bed and allow it though the screens into the slurry. If no action was taken to replace the bushes then a gap could appear between the two screens then large material could enter the slurry and potentially cause a blockage in a hydro-cyclone.

Worn seals on hydro-cyclones and pumps were noticed causing slurry to leak from the system. This was not a major problem for the separation process but did link to efficiency of the system leading to an untidy site and potential slip hazards.

Where plant has not been designed as a unit problems occurred because:-

- a large footprint may be required, to fit all the components of the separation plant on site;
- positioning of the centrate discharge to ensure that the effects of the flocculent dosage can be noted;
- health and safety problems; e.g. climbing ladders, leaning into the tank to get samples and test the centrifuge centrate, etc.

Whilst visiting sites it was noted that some separation plant was designed to be assembled in such a manner that it functioned as designed yet occupied a smaller footprint than equipment used by other pipe jacking contractors. This suited the urban sites leaving more space for the storage of pipes and other ancillary equipment causing less disruption to the surrounding area.

The set-up of the centrifuge and positioning of the two discharge points is very important. A good set-up is one in which it is possible to see and touch (safely) both the centrate and cake and at the same time be able to adjust the flocculent dosage. This configuration of the centrifuge was only witnessed once. On several of the sites visited the centrate could not be seen or felt without creating a safety hazard, e.g. setting-up a ladder and leaning forward. This is not a safe way to run the plant but also creates a risk of over flocculating because the impact of the flocculent could not be monitored.

The flocculent mixing plant on various set-ups also appeared to produce problems. As mentioned previously in Section 3.4.5, one set of hired centrifuges is only supplied with one mixing tank. This produces the problem that the centrifuge cannot be constantly dosed with flocculent, if it is there is a risk of un-aged flocculent entering the main slurry tank. Secondly in some instances where an automatic mixing system was being used on site problems were occurring due to the dosing system not working properly. It was also noticed that on occasion flocculent was added to the wrong tank or the tank was not filled correctly. This resulted in the system being run in the manual mode raising the risk of the flocculent concentration increasing dramatically if the problem was not dealt with.

A final issue with the plant and its set-up is health and safety. Several hazardous set-ups were seen. The key problems were the use of ladders to access and view certain parts of the plant. On more than one occasion a ladder had to be placed in an unsafe position to see and touch the centrate. This also involved leaning into the tank to touch the centrate. This situation linked to the wet and slippery conditions often found on a pipe jacking site is not safe. While in itself the hazards will not affect the operation of the slurry plant any accident or issue noted by the main contractor will lead to delays.

3.4.8 Hire Plant

Whilst speaking to senior staff from different contractors it was mentioned that there is a lack of quality separation plant to hire. The problems that were viewed with the hired plant were:

- The plant occupied an unnecessarily large footprint.
- Linkages to other parts of the pipe jacking systems were poor.
- One flocculent mixing tank.
- No agitation in the slurry tanks.
- High overflow pipe work (more energy needed for the overflow to be lifted up to the hydro-cyclones).
- Not being able to create a set-up where the centrate and cake can be seen together and the flocculent dosage altered.
- Poorly maintained plant.
- An actual shortage of plant

These factors do not help the industry particularly the small contractors who do not own their own plant. This obviously leads to the project starting with a handicap and if any other problems were to occur the control of the slurry density can soon become a losing battle.

3.4.9 Knowledge Management

Many of the issues can be linked to a failure to understand the process of slurry separation or to acknowledge the factors that affect the slurry management process. This lack of understanding can reside with those responsible for bidding for the project resulting in too small a budget to provide the most appropriate equipment. It can reside with those responsible for assigning equipment to site. As explained it can also reside with the site operatives.

Further, there are advantages for senior staff to have a full working knowledge of the site operations as they can help take decisions when problems arise.

3.4.10 Geological Knowledge

Ground is a hazard and given the uncertainties, it is the greatest risk to the project. A correct ground investigation is only helpful if it can be interpreted correctly to create a ground model that not only describes the likely ground conditions but the behaviour of the ground. This requires the contractors engineers to have a clear understanding of the geology or look for external advice.

Problems that can occur:-

- Incorrect ground conditions due to poor ground investigation data or incorrect interpretation of the ground conditions.
- Unanticipated change in ground conditions due to unforeseen circumstances or because the spatial variability of the ground was underestimated.
- Presence of boulders, claystones and other major obstructions.
- The relaxation of over consolidated clays and swelling clay minerals in the surrounding ground can cause high frictional forces on the tunnel annulus.
- Water bearing sands and gravels leading to a significant increase in water content.

The knowledge of the ground helps in estimating the cost of a project, choosing the correct equipment and operating the equipment correctly. It is also essential to understand ground behaviour both to avoid problems and deal with problems should they arise.

Contractors should make sure that their engineers and estimators have geological knowledge and spend more time prior to construction assessing the ground conditions. This could involve looking at local geological maps, potentially purchasing boreholes from the British Geological Society and attending courses; e.g. "An Introduction to London's Geology" run by GCG. They should have the ability to interpret ground investigation reports.

3.4.11 Centrifuge

A centrifuge run at its optimum should allow the maximum amount of slurry to be fed through the centrifuge achieving a suitably dry cake and clean centrate. If the slurry density continues to increase it is because there is an inadequate centrifuge capacity. If the slurry is too dense then the centrifuge will cease to work efficiently because of the low flow rates needed to avoid exceeding the torque rating of the centrifuge.

This was noted on some of sites visited and the pipe jacking process was stopped to clean the slurry or replace it thus impacting on the overall rate of pipe jacking. It was also noted that with high throughputs and some ground conditions it was impossible to produce a clear centrate when using one separation additive. With poor understanding of how to check the slurry for excess flocculant this could lead to over flocculation.

Several of the centrifuges being used had no torque measurements or readings to show the operative how the centrifuge was reacting to the load being placed on it. This could stall the centrifuge or break the drive unit if run at high throughputs with a high sand content slurry. It also does not allow the operative to know that they are running the centrifuge at its most economic.

3.5 Conclusion

From all of the data collected to date it can be seen that various changes to set-up and running of the plant can have a significant effect on the slurry composition. This in turn can affect the progress rates and the rates of wear to certain parts of the plant. This can carry a large cost implication to the contractor. Although the data do show some key points the major factors that affect the operation are described in the text above and reinforced by the data collected. What is also shown when both the data and visual evidence are read together is that there can be a number of contributing factors to problems on site. What is required is careful planning by all parties to understand the excavation of the tunnel to the best of their abilities.

Several of the graphs show that the site operation and set-up were not adequate to keep up with the ground conditions and tunnel excavation rates. The two main sites that show this are D and F. The increasing slurry density can cause long stoppages and often the need to replace the slurry, both costing the contractor time and, most importantly, money.

The main point that can be taken from the viscosity measurements is that returning a dirty centrate concentrates the finest particles and in turn increases the viscosity. This can be seen from the data collected on site F. It is important to maintain a clean centrate.

From the data collected on site D and the comparison made to site A, it can be seen that the desanding unit on site D was not set-up correctly, leading to higher sand contents. This will then cause an increase in wear through the whole system due to the coarser particles being suspended in the slurry. On this site there were several stoppages due to leaking pumps and seals. Although the cause of this cannot be proved to be as a result of the extra sand, it is likely to be a contributing factor.

The rates of excavation can be seen in some cases to slow as the slurry density increases. One reason for that is the increasing pump pressures that occur requires the pump to work harder. This can be compensated to a certain extent by increasing the pump speed. This however affects the life span of the pump. The main reasons for the difference in tunnelling rates are more likely to be due to the decisions taken by the TBM operator or the TBM cutter head dressing or machine type.

Due to the accuracy of the mud balance and the potential time delay to take a density reading further developments should be made. The weighing of the slurry density can be improved by using a set of laboratory scales. A sensible accuracy for this would be 0.1g but this would be more difficult to carry to and from site. The best improvement would be to use the times noted on the drive records (filled in by the operator) or when a Herrenknecht TBM is being used and has data logging to extract the time from this.

The data from these site observations have emphasised the need to carry out more controlled experiments monitoring how a centrifuge reacts to various changes. This should be carried out using real slurry samples with constant parameters and specially prepared slurry for repeatability. This type of testing would give a greater understanding of what affects the centrifuge operation and how it should be run most efficiently.

Observations taken during site visits and discussions with staff at all levels have highlighted:-

1. The significant variation in practice between contractors and within contracting organisations.
2. The interdependency of the various components of the pipe jacking process and the success of the output of the pipe jacking process.

Many of the issues that arise are due to inappropriate decisions which may be constrained by availability of equipment, lack of understanding of the consequence of the decisions, lack of awareness of the separation system and the impact ground conditions have upon the separation process.

A number of actions could be taken to improve the process across the industry. These include changes to site operations, training and use of guidelines. In order to achieve this improvement a number of desk studies need to be undertaken.

3.6 Recommendations

From the information given there are several recommendations to be made:-

- More care to be taken during planning to provide adequate equipment. This should include simple calculations to estimate the quantity of fine particles (sub 75µm) entering the slurry. This will need to be carried out with experience of both the ground conditions and the TBM.
- Regular and thorough maintenance checks on all plant including the internal parts of pumps and centrifuges. This could identify the worn parts before they stop a pipe jack.
- Testing soil samples from the tunnel horizon during shaft excavation for ease of flocculation should be carried out. This allows the contractor to have an idea of quantities required and whether a single flocculant is adequate.
- A thorough desk study should be carried out prior to tunnel excavation to reduce the chance of hitting unknown ground conditions or obstructions.
- The allocation of adequate numbers of operatives who are trained on their allocated job is essential. This is extremely important when referring to the separation plant. A mud man should be specified to work solely on the plant and be competent at operating the plant correctly and efficiently.

3.7 Further Work

More work is required to give an increased understanding of the separation plant and also improved ways for contractors, designers and consultants to understand the factors involved.

- Further testing with a small centrifuge to identify the characteristics of the centrifuge and how they affect the performance of the centrifuge.
- A guide to best practice to eliminate or reduce the problems occurring on site and give a reference document for people to use.
- Training courses for both mud men and contractors. This would be split into two sections, one part on operation with demonstrations and the second part looking at the specification and office based points with slurry tunnelling.

4.0 DECANTING CENTRIFUGE TESTING

4.1 Introduction

As identified in the previous sections there was a need to carry out a testing regime on a decanting centrifuge. A decanting centrifuge is used on site as the final stage of separation to separate the fine particles (sub-75μm) from the slurry. The high-speed centrifuge applies a g-force in excess of 2000g. The science and operation behind this section of separation still has some unknowns discussed below and areas that require optimising.

Current practice on site is to run a centrifuge offline cleaning the slurry constantly throughout the working period. The main adjustment made during operation is the flocculant dose rate with some variation in slurry throughput. The variation in flocculant dose rate is to maintain the centrate clarity whilst not over flocculating. This depends on the slurry flow rate, density and the mineral and chemical makeup of the slurry.

Several centrifuge tests have been carried out by manufacturers and within other industries to understand some of the limiting factors and optimise operation. There is limited research in this area and nothing was found within the pipe jacking industry. A problem that is encountered within pipe jacking is the limited understanding of how a centrifuge should be run in varying ground conditions and with varying solid concentrations. Contractors would like to be able to achieve a low water content spoil, clean centrate and maximise throughputs. It is not known if all these are achievable at the same time or if a balance will need to be made.

The centrifuge used was a Baioni 26L (Table 4.1) loaned by Manvers Engineering. This allowed the testing to take place without paying the usual hire cost and it allowed for a manageable test set-up. If a larger centrifuge had been used the quantities of kaolin and mixing time required would not have been feasible. To allow complete control of the system and for testing to be undertaken at a manageable speed it was carried out off-site in the plant yard of Specialist Plant.

Drum Diameter (m)	0.26m
Hydraulic capacity (m^3/hr)	6 m^3/hr
Max RPM	5220
Power (kw)	9.7kw

Table 4.1 Baioni 26l Technical Data

4.2 Aim

The aim of the testing was to optimise the operation of a decanting centrifuge on a pipe jacking site. In doing this a greater understanding of the exact mechanisms that control the centrifuge outputs (solid and liquid) should be gained. The main areas that required studying were:

- Flocculant concentration
- Flocculant dose point
- Effect of slurry feed rate
- Effect of flocculant dose rate
- Centrifuge speed
- Flocculant Type

With the extra knowledge gained from this, it is hoped that an optimisation approach can be systematically created to allow the site mud man to run a centrifuge at its peak. This would be to create a clean centrate, to produce the lowest cake water content possible and to maximise throughput. This may result in a compromise on certain parameters but it is the intention that a balance can be achieved.

The properties of the solid and liquid discharge from the centrifuge is dependent on a large number of factors which include the soil properties, slurry make-up water, centrifuge, flocculant to name a few. This means that the testing regime is specifically looking at trends within the data that show how the solid and liquid discharge reacts to the specified test variants.

It is the intention that a clear methodology can be given to contractors on the running of a centrifuge depending on the situation; maximising solids throughput to keep up with tunnelling, cleaning the tank out or maintaining the mud weight. In doing this the plant will be able to be run economically; minimise disposal rates and flocculant cost and maximise production rates.

It was also intended that a greater understanding of how the centrifuge operates will be gained to transfer to the industry. This will give an insight into how the centrifuge reacts to different situations and how the operator can overcome the changes in certain parameters. It should also give the industry a greater knowledge on the exact process of separation and its limitations.

4.3 Method

Prior to carrying out testing on site a detailed method document was developed (Appendix I). The testing routine followed this closely with some changes due to knowledge gained whilst testing. An added test was carried out to see the effect that the flocculant had on the cake.

Extra to the test routine was the operation of a small lamina plate settling tank in line with the centrifuge. This was part of Shih-Yun Liu's PhD project at the University of Leeds and will be documented separately (Liu, 2010).

All tests were carried out using E grade kaolin at varying solids concentrations. The data sheet for Polwhite E grade Kaolin can be seen in Appendix H. Included on the data sheet is the particle size distribution for the powdered clay. This grade was chosen because it was readily available in powder form and therefore could be easily prepared in slurry. Kaolin slurry was prepared by mixing powdered kaolin and water using a colloidal/shear mixer before adding to the main tank for further mixing by two higher turbulence agitators. The mix was then left for a minimum of 15 minutes to create homogenous slurry.

For each individual test the slurry was kept at a constant density (not recycling the centrate) and homogeneous by the two slurry agitators. This ensured a constant feed to the centrifuge and a reliable base for comparison of the results. Along with the density check on the slurry, the viscosity, pH and sand content were also checked to make sure they remained reasonably constant.

The specific centrifuge set-up can be seen in Figure 4.1 with the centrifuge pod sat above the twin agitator tank. The two $1m^3$ flocculant mixing tanks were not used during testing due to their size and large quantity of flocculant required. This would result in a large variation in flocculant age and incomparable results. It is noted that the time of aging will affect the activity of the flocculant; the performance of the mixture increases with time up to an optimum (Owen *et al*, 2002). The flocculant was instead mixed in small quantities varying from 8-30 litres depending on the test. This was mixed in a 30 litre bucket using a hand-held paddle mixer. This allowed the exact aging time of the flocculant to be controlled between 20-30 minutes for liquid flocculant (Mudtech TK50 used for the majority of tests) and 60minutes for powder flocculant. The flow rate for both the slurry feed and flocculant dose rate was monitored using separate Siemens ultrasonic flow meters. The values were logged manually.

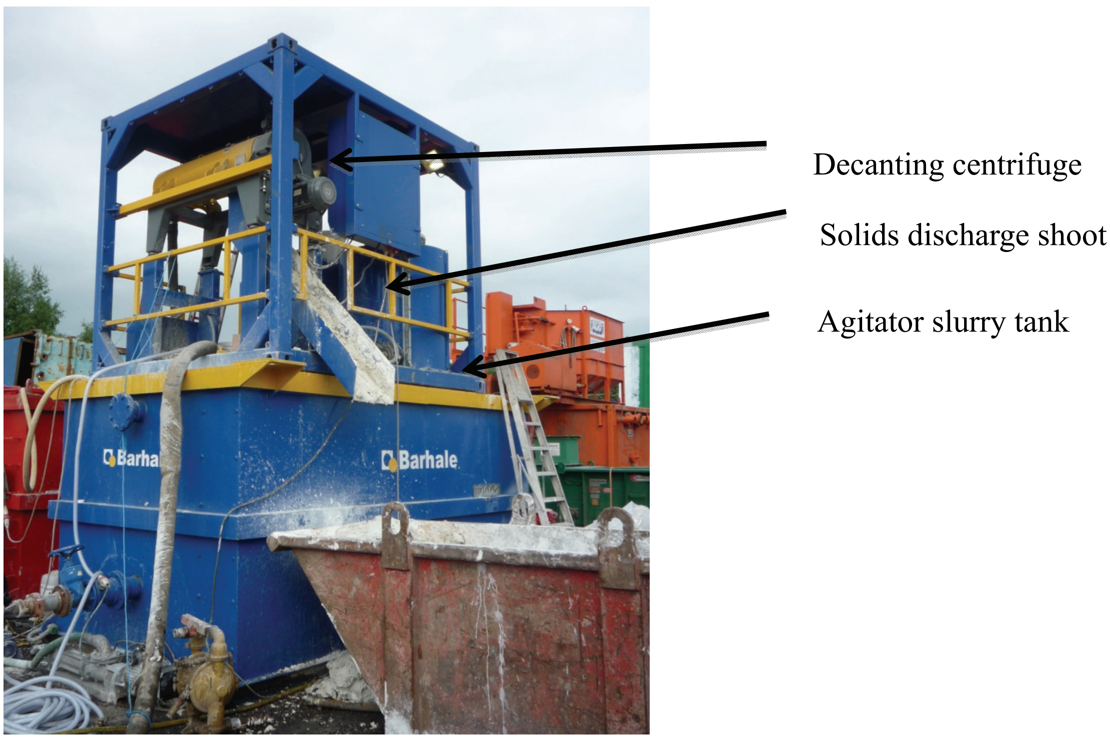

Figure 4.1 Decanting centrifuge set-up

Testing was limited to that which is reported due to time and cost restrictions. During the 3 weeks of testing 6 tonnes of kaolin was hand loaded in to the colloidal mixer. Due to the nature of the tests and the aim to see trends rather then specific values the number of tests completed is considered adequate.

Figure 4.2 shows the inside workings of the centrifuge and how the liquid is separated. It is important to understand what happens inside the centrifuge because only the discharges can be seen during operation.

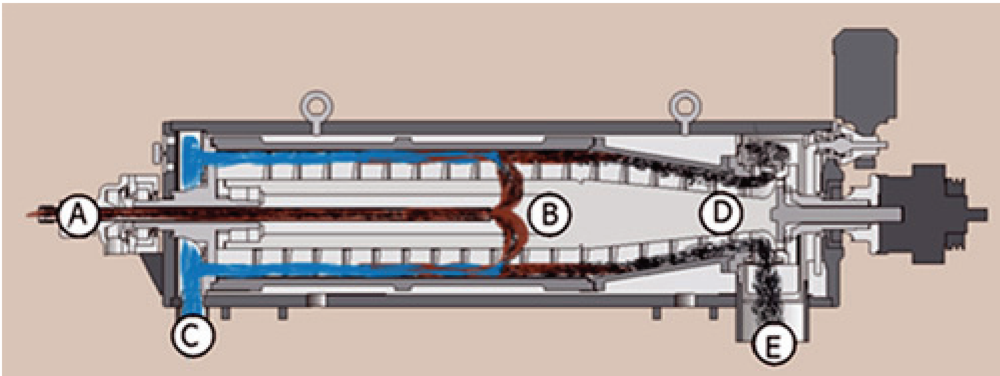

Figure 4.2 Internal workings of the centrifuge (Baioni, 2010)

A: Inlet pipe: The slurry is pumped through a pipe in the centre of the end bearing. Prior to this the slurry is dosed with a flocculant.

B: Internal discharge/ liquid-solids separation point: The flocculated slurry is released from the centre of the centrifuge. The horizontal position can sometimes be varied depending on particle sizes and solids concentration.

C: Centrate discharge: The separated liquid stage of the slurry is discharged over a weir to minimise solids being carried with the liquid.

D: Solids dewatering stage: The inner bowl reduces in diameter to allow for further solids dewatering, also know as the beach.

E: Solids discharge: Dewatered solids are discharged.

The data presented was taken with great care to provide accurate and repeatable results. The scales used had an accuracy of 0.01g and were calibrated weekly. The turbidity meter was calibrated daily and check between tests.

4.4 Results

All of the graphical results are shown in Appendices I to J and referred to in the following sections. Data were collected from the various tests carried out on site. Along with the data, some visual information was gathered by observation of the solid and liquid stage and the ease of operation.

Whilst testing the effect that the flocculant dose rate had on the separation process, it was noted that a major change happened to the appearance of the solids (cake). As the dose rate increased the cake started to appear stiffer and had the ability to roll down the disposal chute. It also had a fluffier appearance. The centrate also increased in clarity producing a clear liquid with no apparent trace of flocculant when touched (previous/out-dated test for excess flocculant check discussed in Chapter 3). For tests with a dose rate of 1.6 and 2.1 l/min excess flocculant was traceable when testing using the 'cup test' (chapter 3) of neat kaolin slurry and a sample of the centrate. Large flocs formed and rapidly settled for a dose rate of 2.1 l/min.

4.5 Interpretation

From the tests carried out on site there were several trends that appeared and methods of correct operation discovered. The interpretation of the graphs and data are based on both the numerical outcomes and the observations of the operation of the centrifuge. With some of the outcomes depending on visual observations, comments will accompany the numerical data.

4.5.1 Slurry Throughput Tests

The throughput test showed an initial increase in water content of the cake. This was the transition between no flocculant being added and flocculant dosed to the slurry. The water content then showed a general decrease with the increase of slurry and solids throughput.

The results showed the opposite results to what was expected and documented within the testing proposal. The initial assumption was that the increase in slurry flow rate would also increase the water content of the solid discharge (cake). It was assumed that this would increase exponentially. It was assumed that with the increase in slurry throughput the solids retention time may shorten and more liquid would be forced up the tapered dewatering section. When testing started it was actually found that the water content decreased as the flow rate and solids loading increased. There was an approximately linear relationship as can be seen on graphs on Figure 4.3 after 20l/min and Figure 4.4 after 125kg/hr. Solids throughput is the quantity of solid material passing through the centrifuge as a dry weight. This is a function of the slurry density and the slurry flow rate.

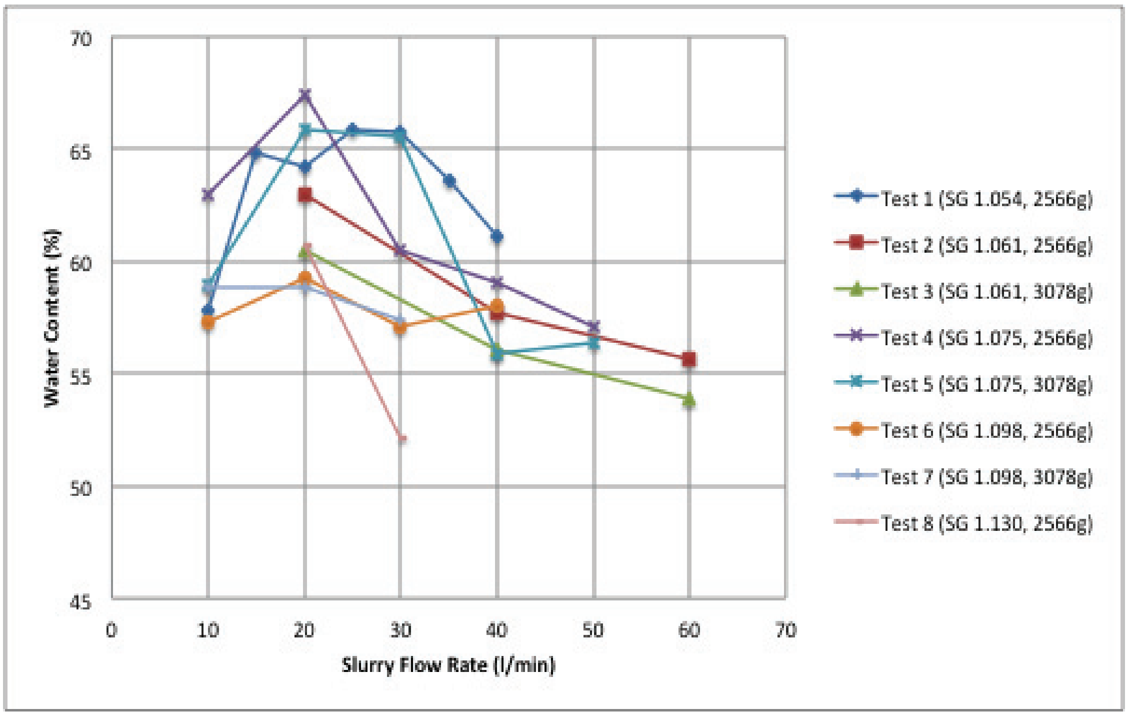

Figure 4.3 The change in water content with respect to slurry flow rate (the specific gravity and centrifugal force are shown)

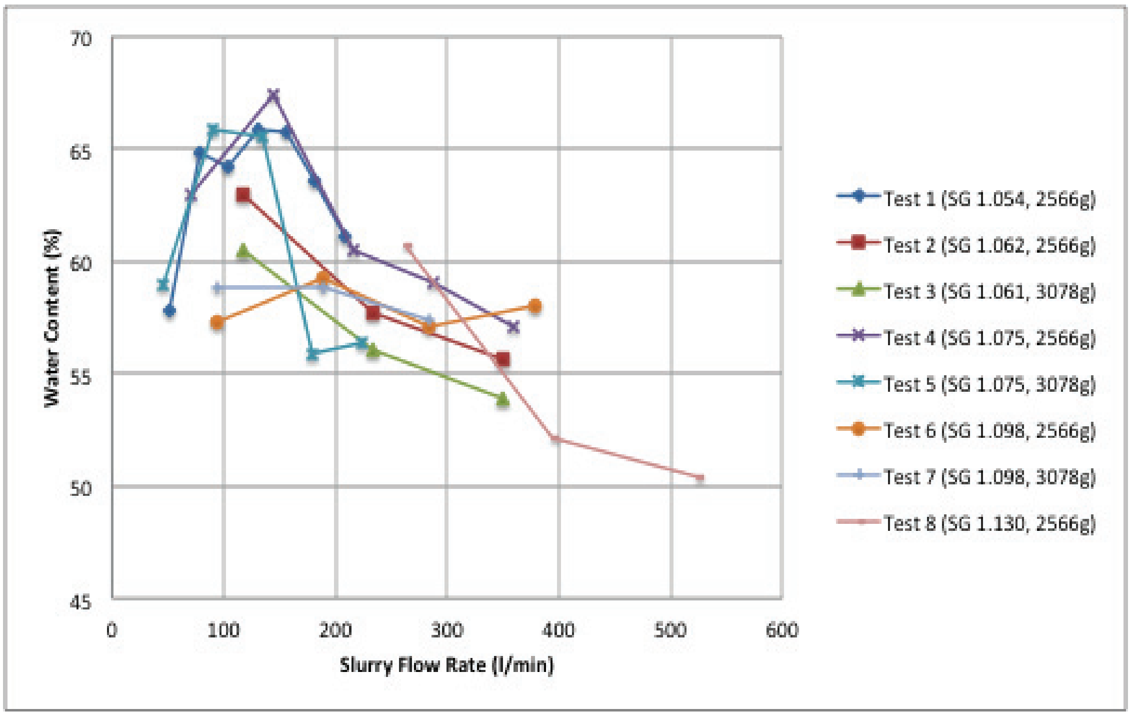

Figure 4.4 The change in water content with respect to solids removed

Figure 4.3 shows that as the flow rate is increased, the centrifuge cake decreases in water content. The reasons for the drier cake are because the bed depth is deeper (more solids in the centrifuge) increasing consolidation that happens to the cake due to the extra depth/weight of solids. The increase in solids could also push the water away from the beached/drying area at the solids discharge end allowing for a slightly longer drying time. This cannot be known due to the enclosed nature of the centrifuge.

It is noted that a small increase is seen between the initial two readings on both Figures 4.3 and 4.4. The reason for this is that the first slurry throughput at 10 l/min required no flocculant to produce a clean centrate. Flocculant has an adverse effect on the solids water content and is explained later in this chapter and in chapter 5. The flocculant dose rate was seen to have a general decreasing trend with the increase of solids throughput (Figure 4.5). There is some variation in the data due to the extremely small concentrations being monitored.

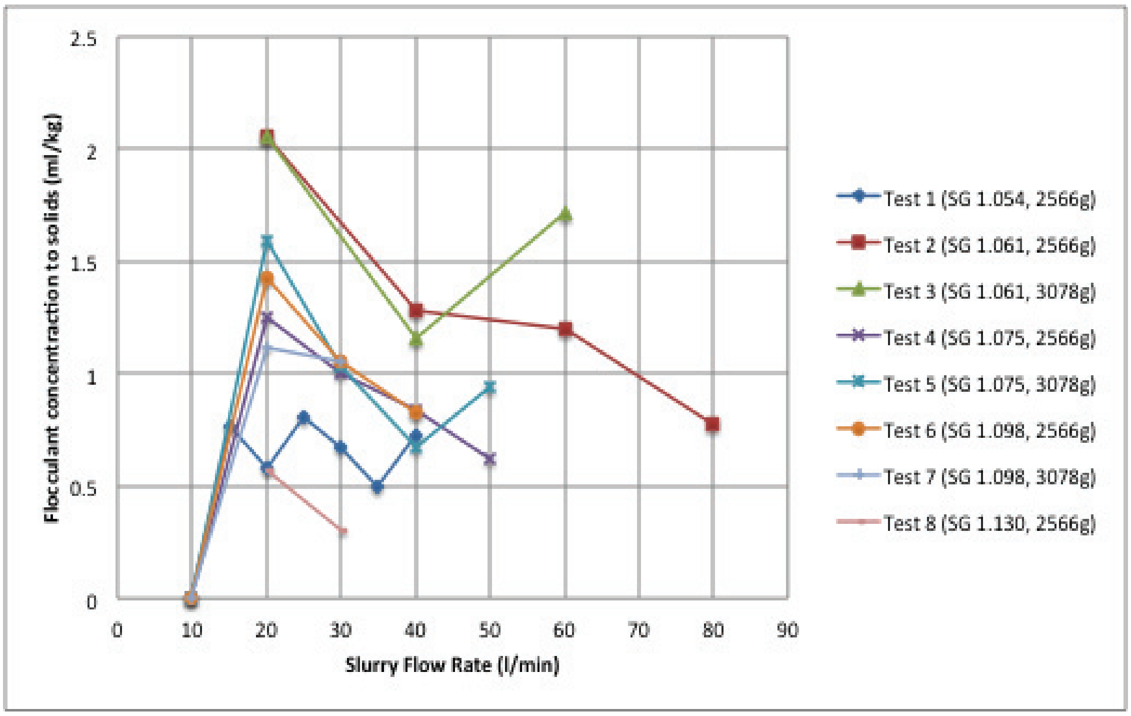

Figure 4.5 Flocculant concentrations at increasing slurry throughputs

Figure 4.6 plots the water contents of the cake, for five slurries being fed into the centrifuge at 40l/min at different densities. It shows that as the density and hence the solid loading on the centrifuge increases the water content decreases. For this sample of data there is a relationship between the water content and slurry density. The reduction in water content would be limited by the centrifugal force and the solids limit of the centrifuge. The solids limit is the quantity of solids that will be carried out of the centrifuge without overloading the drive motor.

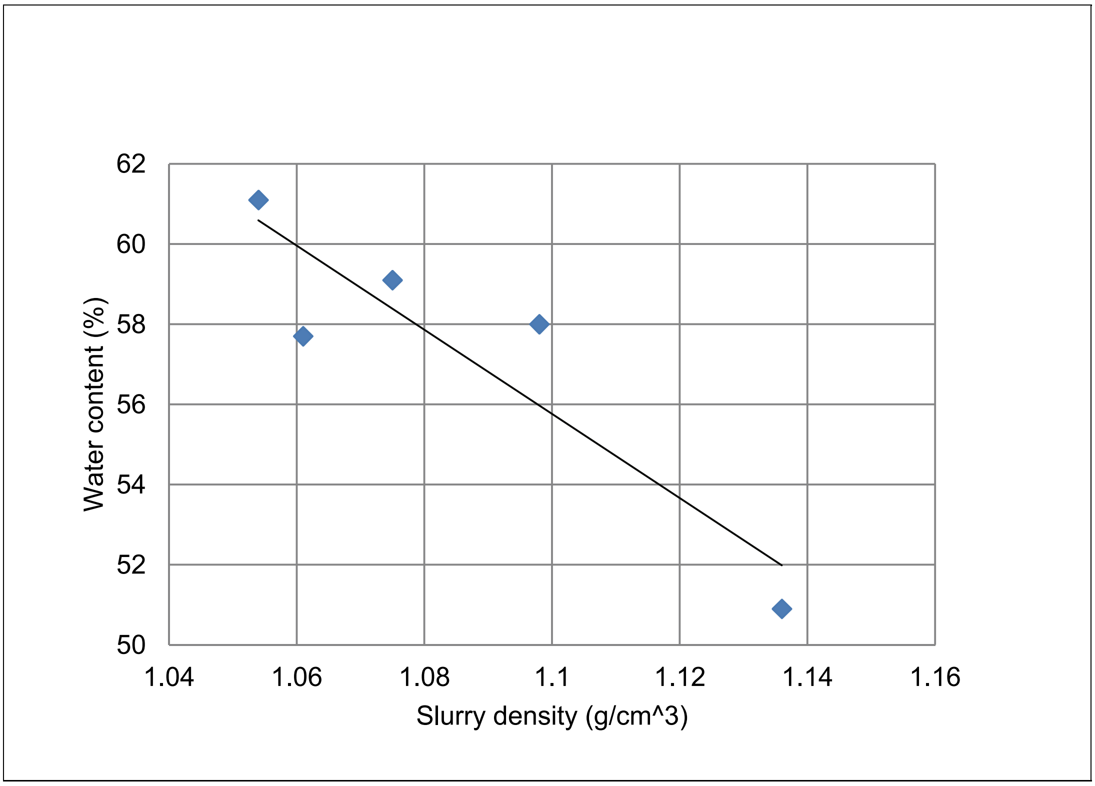

Figure 4.6 The decrease in water content due to the increase in slurry density at constant volume metric flow rate (40l/min)

The second observation made whilst running the throughput tests was the variation in turbidity as the flow rate/ solids content increased (Figure 4.6 and 4.7). What can be seen is that as the solids increase within the centrifuge so does the turbidity. This turbidity could not be lowered by the use of a single flocculant without overdosing the system. During operation the flocculant dose rate was increased up to its optimum level to gain comparable results. This was the judged by the use of the 'cup test'.

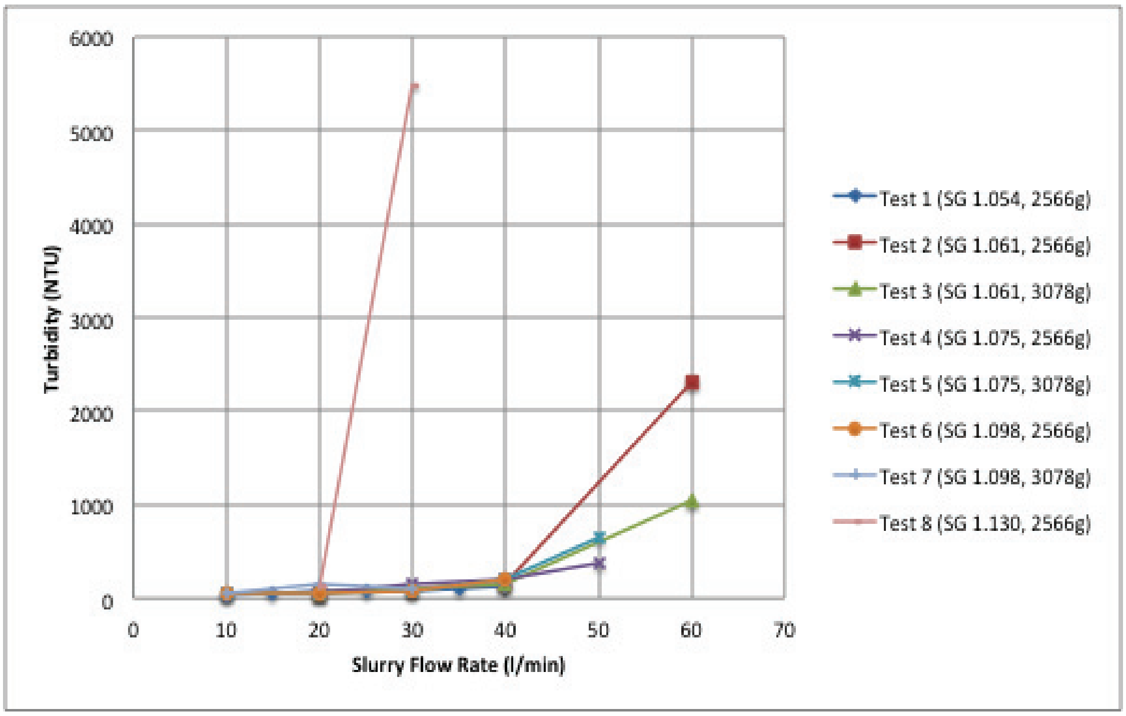

Figure 4.7 The change in turbidity when the slurry flow rate is increased

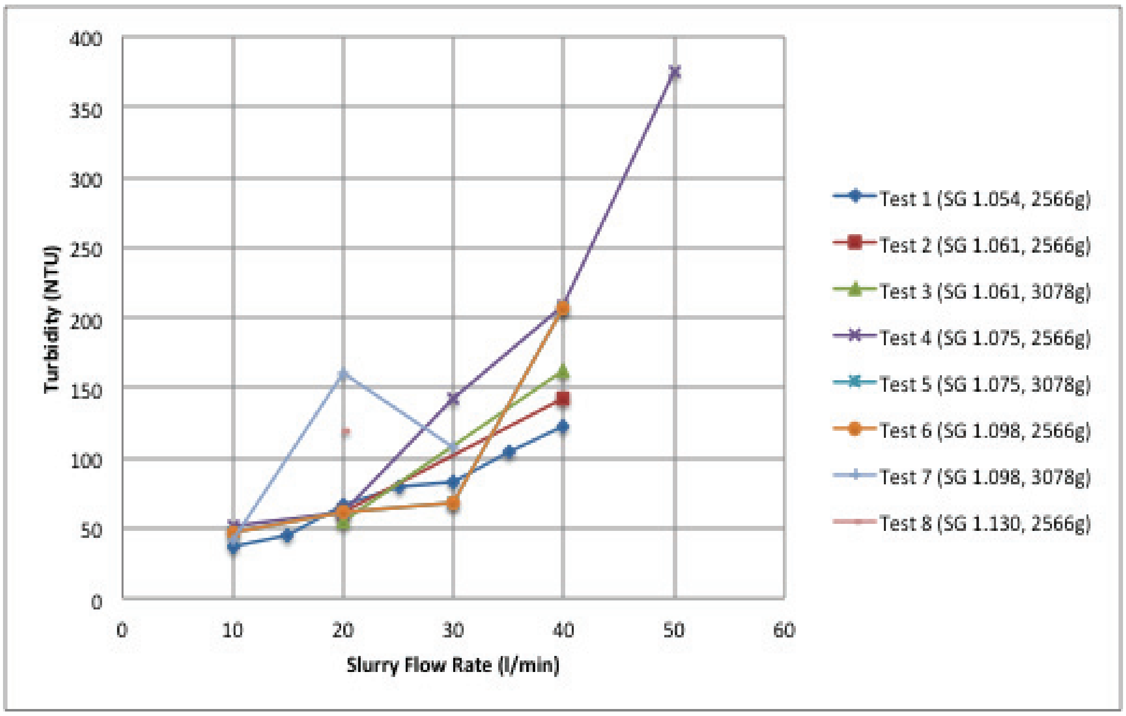

Figure 4.8 A selection of the data from Figure 4.6 showing the change in turbidity when the slurry flow rate is increased (limited to a turbidity of 400NTU)

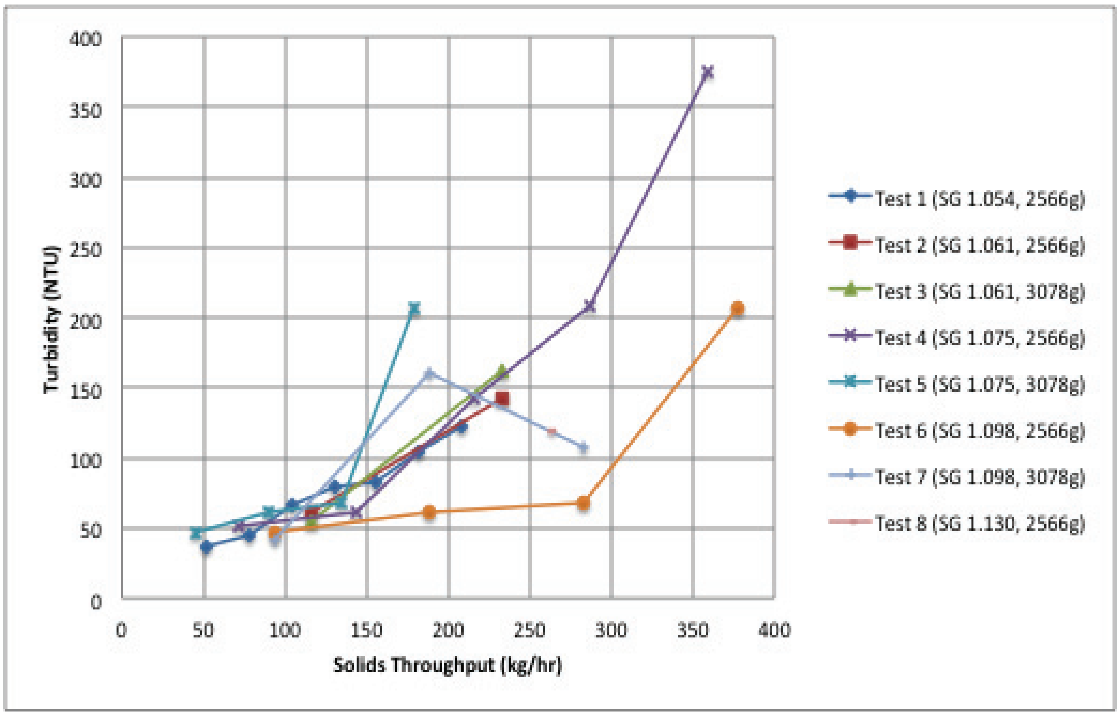

Figure 4.9 Turbidity in relation to the solids removed by the centrifuge (Data limited to a turbidity of 400NTU)

The reason for this increase in turbidity is due to reducing the time that the liquid remains within the centrifuge, shown in equation 4.1 This will reduce the time that the fine solids have to settle and when the solids loading increases significantly it will wash flocculated solids over the weir into the centrate discharge. Figure 4.8 and 4.9 show extremely well the trend that has formed with the increased turbidity. Figure 4.9 shows that the solids capacity for the test centrifuge (with the weir set in the middle of its height range) was approximately 275kg/hr. At this point the turbidity can be seen to increase significantly and at higher throughputs a large quantity of solids were found in the centrate (in excess of 1.01 kg/m^3). The particles found are those around the micron range and are the hardest to remove. If the centrifuge continued to run above this threshold then a concentration of micron sized particles would be found within the slurry giving rise to a potential increase in density.

t= time

b= Length of cylindrical section of the centrifuge

R_w= Radius to centrifuge wall

R_L=Radius to surface of liquid

Q= Flow rate

Equation 1 Time of liquid retention (Armenante, 2012)

In some tests the centrifuge current was measured (this can be directly related to the torque), to see the effect that various speeds and solids throughputs had on the current/torque capacity of the centrifuge. The Baioni 26L has a safe operating current of 13 amps; if the current exceeded this, the high torque could stop the operation of the centrifuge. Figure 4.10 shows how the current increases approximately linearly with the increase in solids throughput. It was also interesting to see that the increase in current due to the increase in centrifuge speed by 400rpm (512g) was only small, approximately 0.5amps (Figure 4.10).

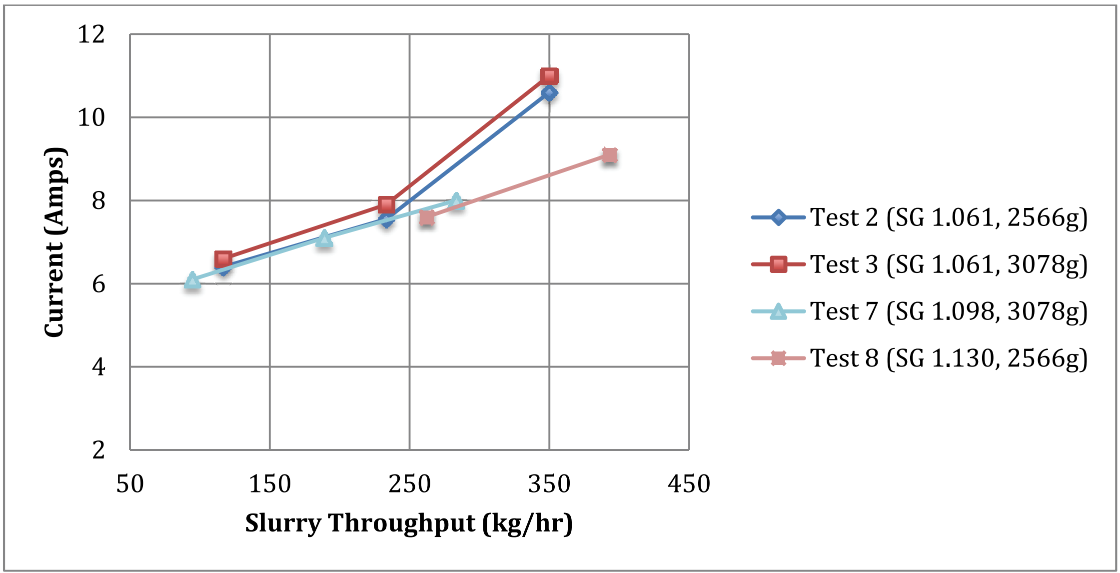

Figure 4.10 The variation in centrifuge current (torque) in relation to bowl speed and solids throughput

4.5.2 Flocculant Concentration

The second test carried out was to see the effect of varying flocculant concentration for mixing neat flocculant with water. This is then used to dose the slurry for separation in the centrifuge. Currently this is commonly set at 0.5% for a 50% liquid flocculant in a suspension agent and 0.25% per unit of water for a powder flocculant as indicated from previous work carried out on site visits and talks with flocculant suppliers. The first comment would be that the dose rate for the concentration of 0.1% on test 1 is likely to be an anomaly, this could have been due to a small blockage in the slurry feed but was not identified at the time. It can be seen from Figure 4.11 this does not match the trend of the other results that do correlate well and does not match the predicted trend, which would anticipate the dose rate increasing with the decrease in concentration. This is because the overall concentration ratio of flocculant to slurry should stay constant. All other results demonstrate this relationship.

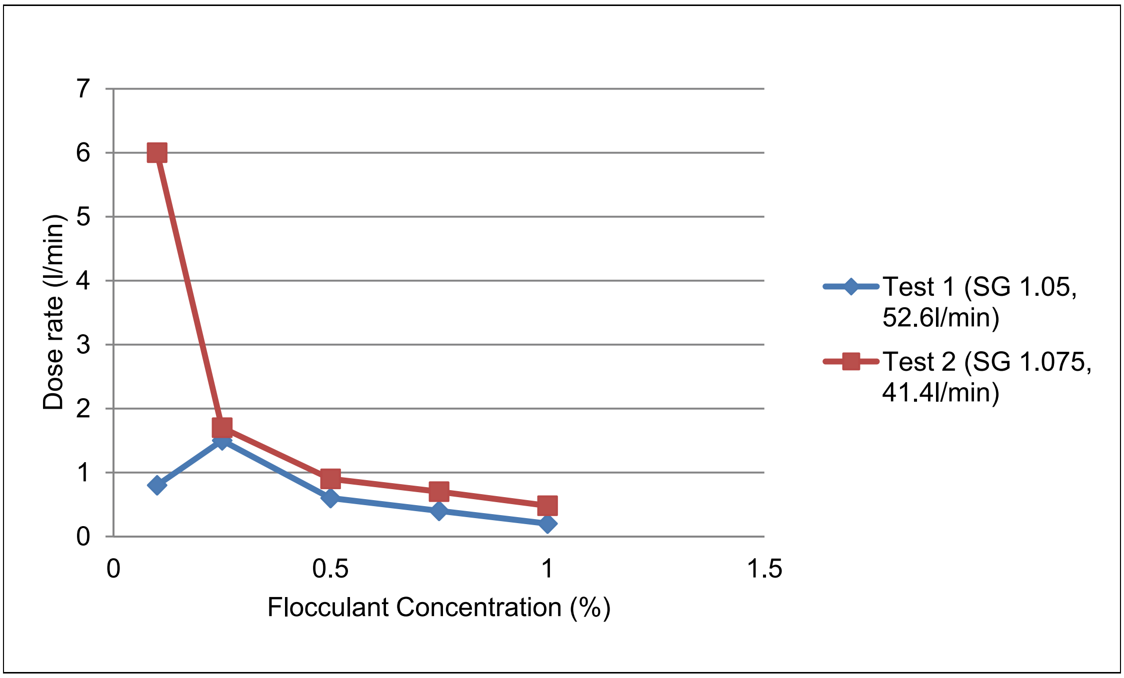

Figure 4.11 The change in dose rate due to the change in flocculant concentration (using two slurry flow rates)

From Figure 4.11 as expected the required dose rate decreases as the concentration of premixed flocculant increases. Figure 4.12 shows how the dose rate relates to actual flocculant concentration when mixed with neat slurry. This shows a much flatter relationship, with all the results above 0.25% having a final concentration within 0.02ml/l. This difference could be down to the errors produced by the flow meters (0.5%) and flocculant concentration mixing. This graph shows that above 0.1% the actual quantity of flocculant used was very nearly constant and the main benefits of not using a low concentration would be to reduce the number of mixes and the quantity of water and thus the dilution of the input slurry. The reduced number of mixes would allow the mud man more time to concentrate on the monitoring and operation of the centrifuge. The reduction in dilution did show a trend of lower water content within test 1. More work would be required to confirm this trend.

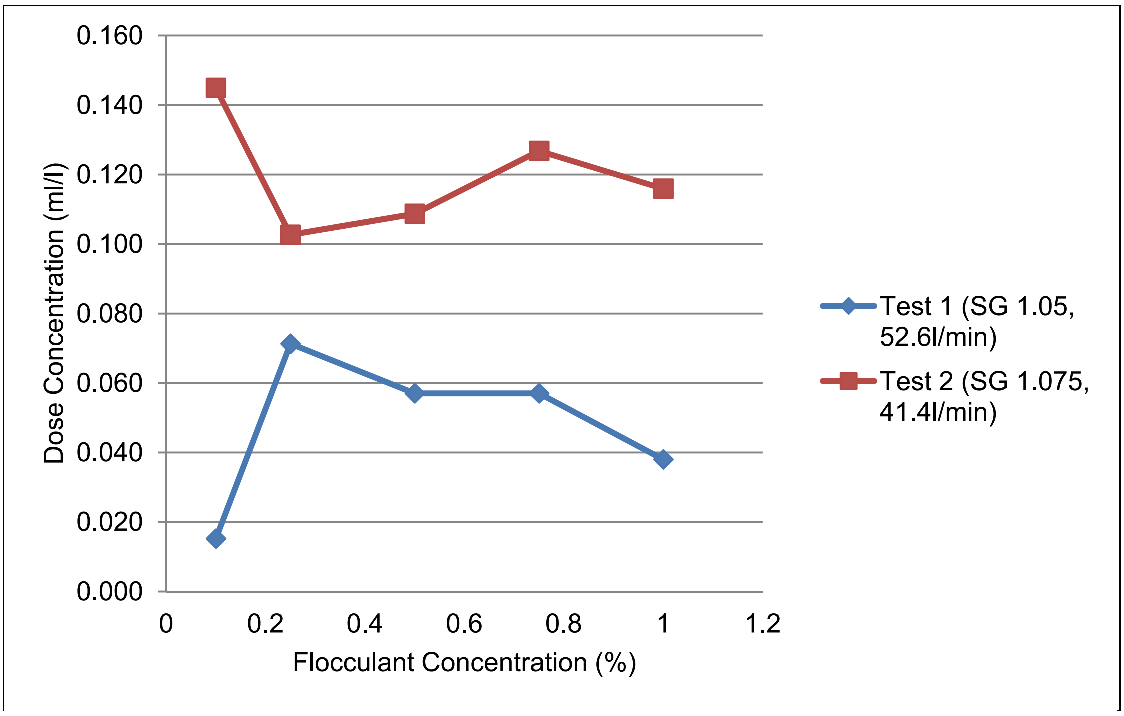

Figure 4.12 The actual quantity of flocculant per unit of slurry

The main criteria for checking the effectiveness of separation was the water content of the solids (cake) and the clarity of the centrate. For these two tests the clarity of the centrate had a correlation, again that flattened above 0.25%. This shows that for this specific parameter there is no significant benefit of increasing the concentration above 0.25%. This can be seen in Figure 4.13. A repeat of the tests would hopefully help to show this and remove any local variations. An extension of the concentration beyond 1% would help in checking if the turbidity increased beyond this point.

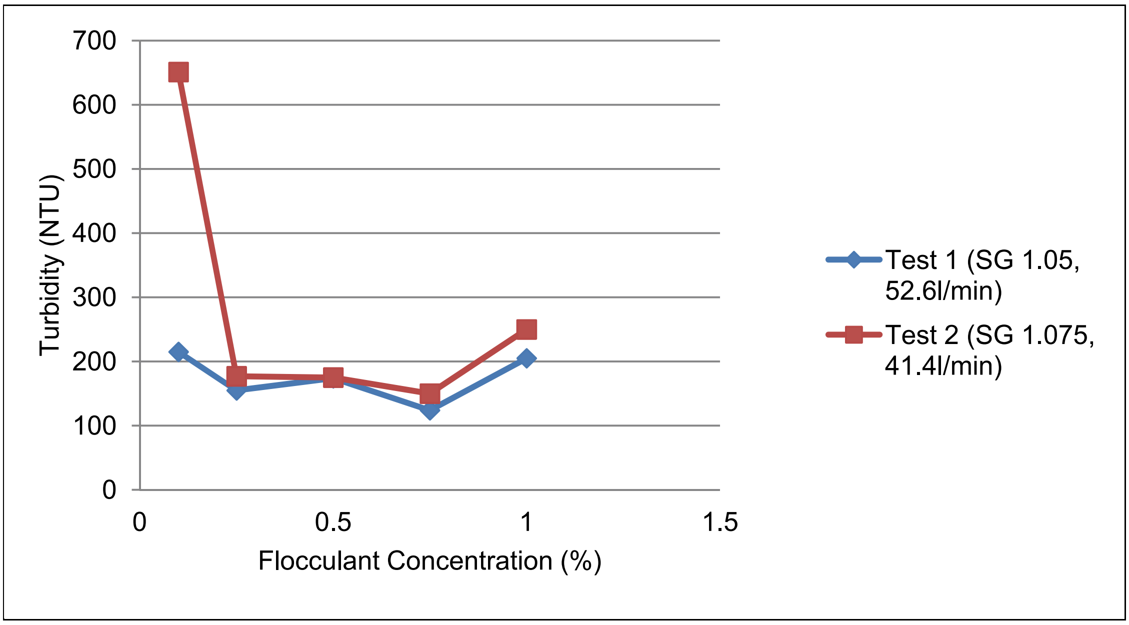

Figure 4.13 The centrate turbidity in relation to the flocculant concentration

From the tests carried out on flocculant concentration it can be seen that there is a similar performance output from the concentration range between 0.25% and 1%. From an operational point of view when trying to run a pump at low flow rates it was found to be hard to adjust. From the data and the operational experiences it could be concluded that a concentration of around the existing 0.5% would be suitable. No major benefits or problems with regards to lowering centrate clarity or water content were noted to contradict these findings. More testing could be undertaken to try and remove the anomalies and gain more evidence to back up the decisions being made.

4.5.3 Flocculant Injection Point

Shih-Yun Lui (2011) investigated the effect of mixing time on the turbidly of centrate (Appendix J). He found that it was a key factor. In this field test an in line mixer was used at different locations up to 30m from the centrifuge. The results showed that the position of the in line mixer had a small effect on the turbidity but it did effect the water content of the cake. This correlated with the trend of results of Shih-Yun Lui (2011) but showed a small benefit on turbidity. It is concluded that the in line mixer together with the centrifuge were adequate to ensure that the flocculent and slurry were thoroughly mixed for the flow rates used in these tests. The position of the in line mixer was not looked at but would be advised to be where the flocculant was injected.

4.5.4 Flocculant Type

As noted in previous sections there is a variation in flocculant type used on pipe jacking sites with no real understanding whether the type of flocculent affects the process. A similar procedure of testing was undertaken to that for the flocculant concentration and injection point for three different flocculants. Some variation was seen between the three flocculant types tested. As with all the previous tests the main drivers are water content of the cake and clarity of the centrate. The quantity used is an important factor for the economics of the job but the difference in cost would usually be ignored if a product were found to be significantly superior.

From Appendix J it can be seen that there was some variation in flocculant performance but not one that out performed in all areas. The flocculant VL2 was the best at reducing the turbidity of the centrate but gave a slightly wetter cake. VP1 produced the opposite effect with the lowest water content and the average turbidity of the two tests in the middle of the three samples. TK50 had a slightly more turbid centrate and water content in the middle of the other two samples.

Overall no real difference can be seen between the individual flocculants and to achieve more reliable results more tests should be carried out. VP1 would have a slight advantage due to cost because only half the quantity is required (the two liquids being 50% flocculant to 50% carrying agent). But as it is a powder flocculant other considerations need to be taken into account. It was extremely hard to mix, forming globules and ‘fish’ eyes within the mixture. This caused the flocculant dose line to block on more than one occasion. On a site system this would also require sophisticated dosing equipment that disperses the flocculant grains to wet them individually. The final down side is the aging time required; a powder flocculant takes up to 60minutes to become fully active which is three times longer than a liquid. Although most systems would have the capacity to cope with this time delay in some extreme situations dose rates could be high. Although the VL2 had the best turbidity it performed the worst with regards to the water content of the cake.

The main conclusion would be that from these tests all the flocculants performed similarly within the error margins that could be anticipated. Until more tests are carried out the choice of flocculant should be based on flocculant mixing set-up, cost and links with current suppliers. A key point to make from the literature review is that there are several key factors that need to be addressed when purchasing a PHPA for separation:

- Molecular weight (needs to be high around 20million)
- Range of molecular weight (should have a small standard deviation)
- Active sites on the chains (this should be in the range of 20-30%)(See Chapter 2)

4.5.5 Flocculant Dose Rate

A quick and important test was carried out to back up findings from laboratory tests carried out by Shih-Lun Lui (2011) on the water content of the cake with the varying flocculant concentrations to slurry. The laboratory results showed an increase in the water content of the cake as the quantity of flocculant used increased.

A test was run varying the dose rate of the flocculant at three different intervals. Samples were taken of both the centrate to test clarity and the cake to test for water content. Observations were made on the cake appearance and the centrate flocculant levels. Figure 4.14 shows the clarity of the centrate at the three dose rates; as expected the higher the dose rate the cleaner the centrate became. The clarity of the centrate did improve beyond that of the optimum dose rate for the through put tests for a similar solids concentration. For the optimum flocculant dose rate at a solid concentration of 215kg/hr the turbidity would be in the range 120-150NTU.

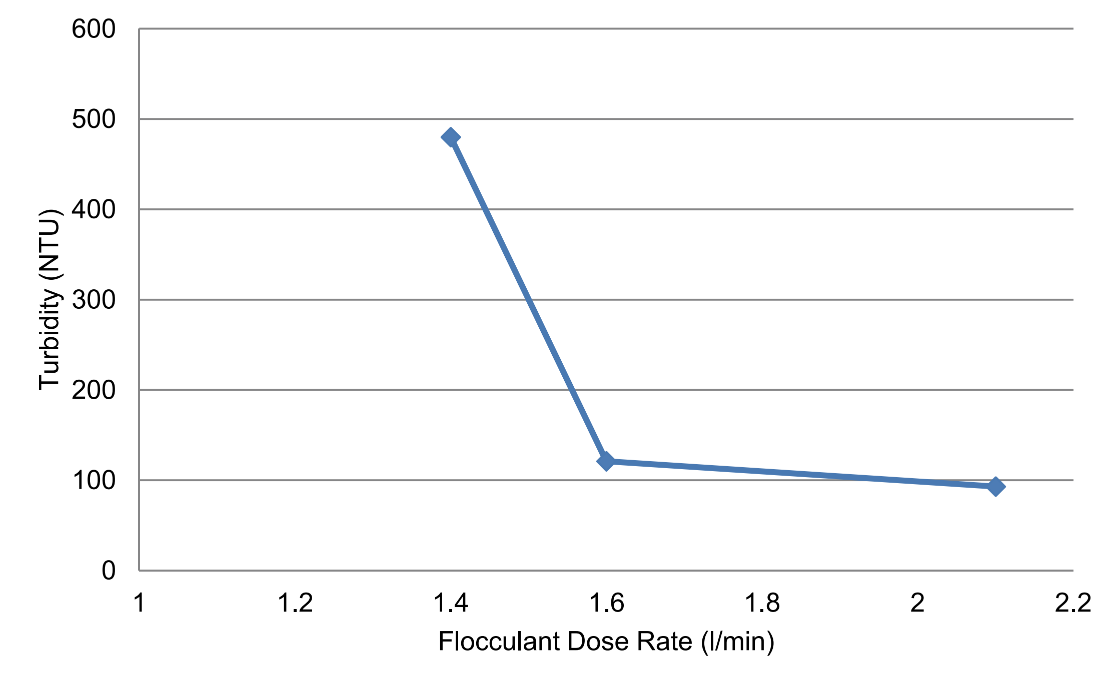

Figure 4.14 The clarity of the centrate at different flocculant dose rates

The centrate was also tested with the 'cup test' for excess flocculant by mixing neat slurry with a sample of the centrate at a ratio of 50/50 and seen if flocs formed. Both dose rates of 1.6 and 2.1 l/min had traces of excess flocculant within the centrate. The dose rate of 2.1 l/min flocculated the neat slurry instantly producing immediate settling. The traditional excess flocculant test is a feel for a slippery residue in the centrate and this showed that none of the dose rates were 'over-flocculated'. This shows that it is an inadequate test.

The water contents are shown in Figure 4.15. This graph shows very clearly how the moisture content of the cake increases dramatically with the increase in flocculant. The actual range of flocculant concentration to slurry is only 0.1ml/l, showing that very small changes can make a big difference. This shows that the flocculant traps the water inside the flocs making it hard to be released by gravitational force. An interesting observation was that as the dose rate increased the cake actually seemed to be 'drier' as it rolled down the discharge chute. It is known from the laboratory work carried out at the University of Leeds that the flocculant increases the liquid limit, which would explain the difference in appearance. What is not known is if this extra water is easily released after the separation process perhaps with time or travel.

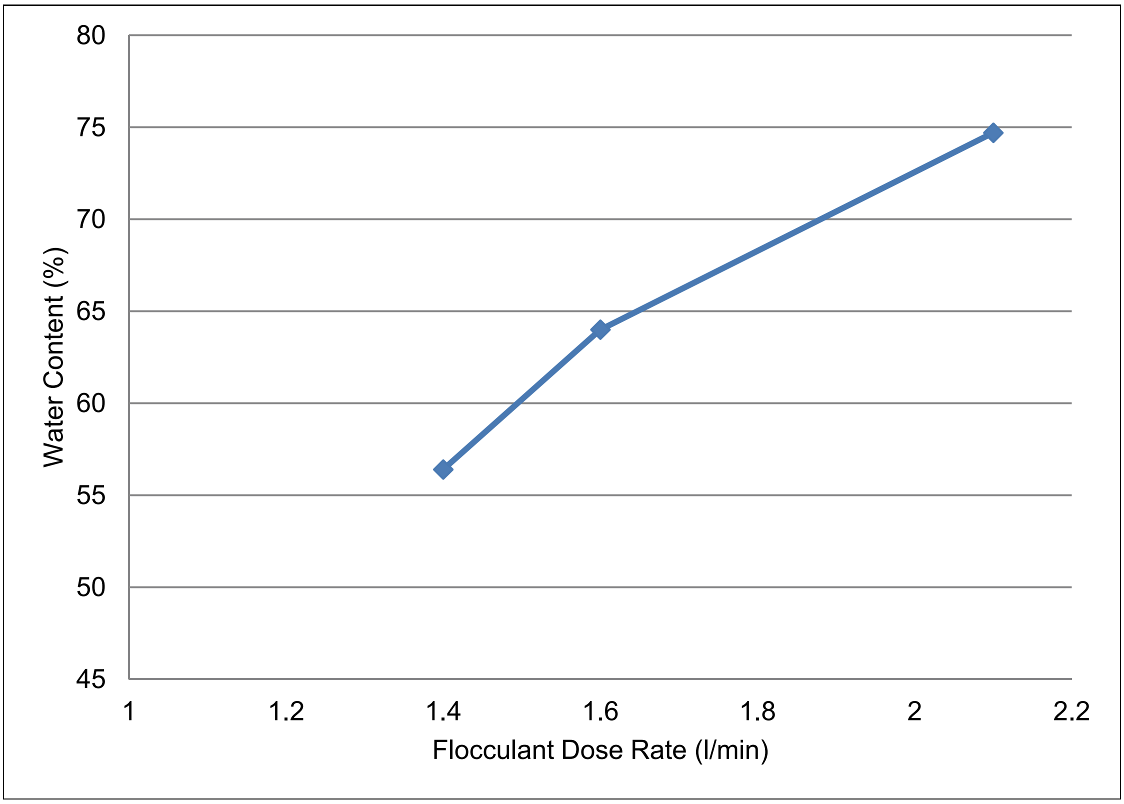

Figure 4.15 The change in water content of the cake due to the change in flocculant dose rate

The range in water contents is also very significant, 18%, causing higher disposal and flocculant costs. The higher disposal cost arises from extra transport and landfill costs. The potential extra landfill tax has the ability to be waived if the contractor informs the landfill site of the slurry tunnelling process. The highest dosage resembles what is often seen on a pipe jacking site where the centrate is tested by feel and there is a focus on achieving a “dry” cake. This test shows that in reality the operative would be over flocculating the system and producing a cake with higher water content. The spoil produced appeared visually stiffer giving a mud man the misconception that the centrifuge is producing a drier cake, whilst still thinking that he is operating the centrifuge correctly. The mud man and other influential site personnel are therefore required to understand the physical effects that flocculant has on soil properties in order to prevent incorrect operation; high water content and over flocculation.

4.6 Discussion

From the results shown within this chapter it can be seen that a successful testing routine was undertaken with results that will help to optimise the operation of a centrifuge on a pipe jacking site. It has also allowed for a greater understanding of how the centrifuge reacts to the variables and the visual signs of these changes.

The first major finding was the variation in centrate clarity with relation to the solids throughput of the centrifuge. It was seen that the centrate clarity would decrease as the solids throughput increased. This is due to the process time of the liquid stage decreases, resulting in a shorter settling period.

From this information an operative can understand how he should be running the centrifuge depending on the results he would like to achieve. For example if a very clean centrate is the most important factor then the centrifuge should be run at a low throughput to achieve this. At the other end of the scale the centrifuge could be run to gain maximum solids throughput, which could increase the density of the centrate from 1.00g/cm^3 (when correctly flocculated). The centrate would be extremely cloudy and if run for long periods of time would concentrate the extremely fine particles that remain in the centrate within the slurry.

For general operation it is recommended that the solids throughput be balanced with the clarity of the centrate, this may produce a slight turbid/semi transparent centrate but still be able to achieve relatively high solid throughputs. Further work should be carried out on the effect of using coagulants in conjunction with the flocculant to see if it will improve the clarity of the centrate whilst achieving high solids throughput.

The second major point found relating to the solids throughput of the centrifuge is the effect that it has on the water content of the cake. As stated previously it was found that the water content tended to decrease as the slurry throughput increased. (Figure 4.16) The reason for this is that when the solids level within the centrifuge is higher, the liquid is pushed over the weir faster (Equation 4.1). The second mechanism is due to the extra pressure produced by the increase in cake depth. This compresses the solids and increases the pore water pressure within the cake. In doing this the hydraulic gradient within the solids also increases allowing the excess pore water pressures to dissipate (Atkinson, 1993) (Records and Sutherland, 2001). With very low solid throughput rates it was found that the centrifuge could remove the solids without the need of flocculants. The reason for this is that the liquid retention time exceeds that of the particle settling time. This caused the peak at the start and relates to the field and laboratory work carried out of flocculant effects.

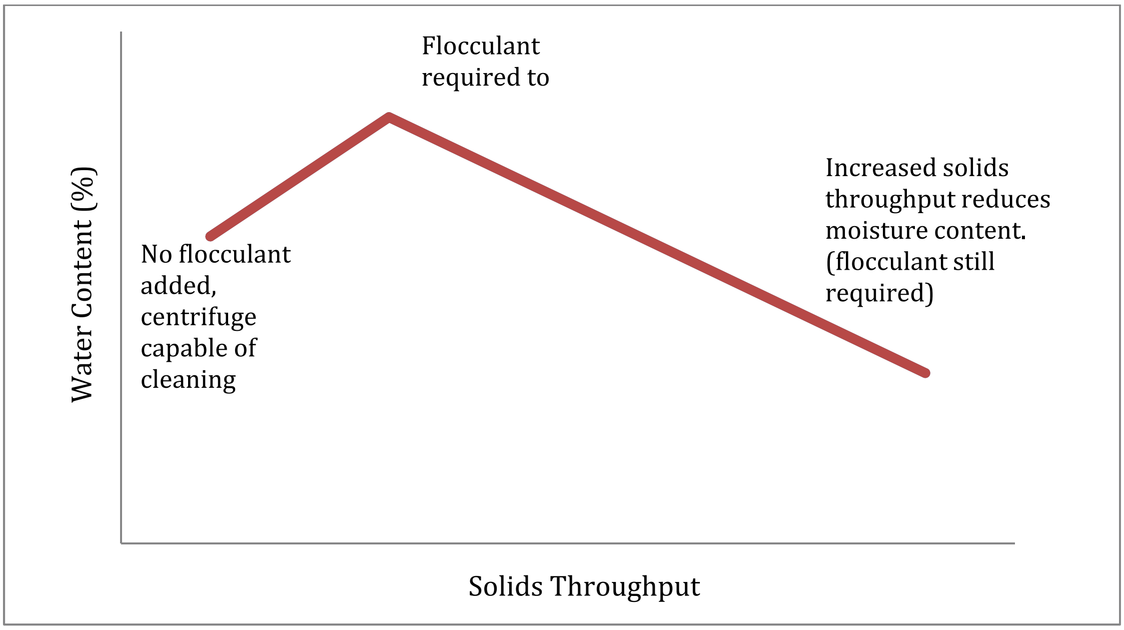

Figure 4.16 Schematic graph of the variation in solids water content due to the variation in solids throughput

From this a decision can be made on site as to how the centrifuge is operated depending on the situation. As mentioned above when relating slurry throughput to clarity, the same applies to the water content. If a clear centrate is required then the water content of the cake may need to be sacrificed but if the water content of the cake is the most important factor then a high throughput is required.

For both maximum throughput and minimum water content it was seen during operation that there is a point where the system will overload with solids leading to some solids being removed with the centrate. The centrate becomes milky as it contains flocculated material. If the operation requires peak throughput, it is best to increase the slurry feed pump at appropriate intervals and watch the change in the centrate. At the same time the flocculant feed will also need increasing.

A balance can also be made by adjusting the centrifuge speed. This may result in a slightly lower throughput rate due to the increase in torque; although the increase of 512g between tests 6 and 7 of the throughput tests only showed an increase in current (related to torque) by 0.5amps. Showing that the torque is only a factor towards the maximum solids throughput. This did lower the water content by around 1.5%. It is shown that the centrifuge may need to be run close to its maximum speed but constantly monitoring the torque to reduce both turbidity and water content. At higher speeds the internal wear may increase, along with the energy consumption.

A very important discovery was the increase in water content of the cake due to the flocculent. This is very important when understanding the composition of the cake and how the centrifuge should be dosed. It was also seen that as the flow rate increased, the ratio of flocculant to neat slurry decreased, adding to the decrease in water content. It can be seen that to produce a dry cake flocculant levels should be kept at a minimum but enough to clean the slurry. This is one reason for the operator not to overdose the flocculant. It was seen from the tests carried out that the water content due to the extra flocculant could be at least 18% higher though the visual appearance suggested it was drier. This would result in significantly increased transport cost. The cost of flocculent would also increase but compared to the total cost it is less significant.

It was interesting to see the change in the cake as the flocculant dose increased. The cake appeared drier and stiffer but there was a concern that the 'locked in' water could be released when the cake was vibrated as it was transported to the disposal site. Contractors had reported lorries arriving at landfill sites with free water on the top of the disposed arisings. This is an area of further work to discover the effects that vibration has on flocculated soil with a range of flocculant concentrations to neat slurry and the effects of storage time.

For this centrifuge and weir setting (set at middle height) it was found that the maximum solids capacity of the centrifuge with controllable centrate clarity was in the region of 275-300kg/hour. This has the potential to vary slightly depending on the specific density of the solids used (i.e. the affect of centrifugal force), ease of compaction, floc size/orientation and also the particle size distribution of the slurry. More testing would be required to precisely find the maximum solids throughput by varying the slurry (mineralogy) and using smaller intervals of slurry throughput.

Although torque is the limiting factor on total potential solids throughput, with kaolin the weir limited the solids capacity. Although more solids may have been able to be processed, this would not have been practical due to the poor centrate clarity at high throughput speeds.

It was seen from the tests carried out on three examples of flocculants that no major advantage was found on the performance of any type. One major advantage was found in the mixing of the liquid flocculants. For the powdered flocculant it was extremely difficult to achieve a smooth consistent mixture even with careful dosing and mixing. Although only half the quantity of powder was used (due to the liquids being 50% flocculant and 50% suspension agent) some of the powder would be wasted due to balling and 'fish eyes'. These balls may reduce with long periods of aging, in excess of several hours, due to untangling of the polymer chains. From this it can be concluded that a liquid flocculant would be a preferred choice for a pipe jack due to the relatively small batches mixed and the ease of mixing. This would require no specific dosing equipment and produce an aged, homogeneous polymer in 20minutes. The extra cost of using a liquid flocculant would be minimal when calculated on a per metre basis. It is also recommended that a sample of the ground is tested for its suitability to flocculate prior to tunnelling. Such a sample could be taken from a borehole but would be more appropriate from the shaft construction often undertaken by the pipe jacking contractor in order to minimise potential contamination, and avoid the need to store borehole samples for a long period of time. This can test the suitability of the flocculant and give an approximate idea of dose levels required.

It was found that an extended pipe length to prolong mixing had little to no beneficial effect on the efficiency of the centrifuge. This test was limited because each test had an inline mixer and the minimum length used was two meters. From previous literature reviews and basic principles of mixing it would be recommended that all set-ups had an inline mixer at the point of flocculant dosing to ensure that correct and thorough mixing was achieved. A short delay between mixing and reaching the centrifuge may also help to ensure that the correct mixing took place.

The main variation with the control parameters is the slight variation in slurry pH (Appendix L), due to the limited water supply and the partial recycling of water. During the test period the pH of the slurry slightly increased from 7.7 to 8.1. The pH meter was calibrated before each measurement and did correlate to the test solution, although the accuracy of the meter was ±0.1, so some of the error could due to reader error. The difference in pH is very small but could have had an effect of the performance of the flocculant. This is due to the increased negative zeta potential as the pH increases. This could be part of the reason in small variations in the clarity and dose rate in various tests.

Further work is still needed to build a fuller picture of the exact capabilities of the centrifuge and the way materials react. The first piece of work should be to see how flocculated material reacts to vibration and if the water trapped within high flocculant concentration solids is released. This will help to clarify what the optimum dose levels of flocculant are for ease of transport and clarity of centrate. This would help to understand how the solids behave when they are in transport and reduce the chance of being denied acceptance at the landfill site. It could also lead onto a further research study into the dewatering of spoil from vibration.

Secondly more work is required with a variation of centrifuge performance with soil types to gain an understanding how the optimum operation of the centrifuge changes with a variations in geology.

As previously mentioned extra work could be carried out on various types of flocculant by testing a wider range, repeating the tests and looking at the mix ability of powder flocculants. One test with a powder flocculant that could be carried out would be to see the percentage of wasted polymer due to 'fish eyes' and globules. It could also involve finding the optimum mixing procedure to reduce this. This work could also incorporate the use of coagulants in line to reduce turbidity.

4.7 Instructions and recommendations for Mud Men

4.7.1 Optimum Dose rate

It has been suggested previously and shown in this chapter that the traditional 'feel' test for over-flocculation is inadequate. To check for optimum flocculant dose rate a sample of the centrate needs to be tested with neat kaolin slurry. The cup test is performed in a clear cup or jar by mixing equal measures of centrate (taken from centrifuge discharge) to premixed kaolin slurry of density in the region of 1.05-1.1g/cm^3. Once this has been mixed the mixture can be checked for visual signs of flocculation. If flocs form then there is trace flocculant within the centrate and the flocculant dose rate should be turned down.

Alternatively if the centrate is still turbid/cloudy and there are no signs of flocculation during the cup test, then the flocculant dose rate can be slowly increased. This is a fine line that requires constant adjusting and balancing because of the variation in solids type and content. A sample of the slurry from the active system could be used an alternative to the kaolin slurry but is likely to be less sensitive to the flocculant and also has the risk of containing excess flocculant and contaminants from the tunnelled through ground.

4.7.2 The clarity of the centrate

A clean centrate is important but is not always achievable at higher solids throughputs. The clarity can be partially sacrificed by producing a slightly turbid/cloudy centrate and maintaining optimum flocculant dose rates. If clean centrate is the target then there is a risk of over flocculation or lowering of the potential solids throughput. This could lead to excess flocculant in the active system and a centrifuge cake with higher water content.

4.7.3 Appearance of centrifuge cake

The appearance of the centrifuge cake can be deceiving on occasion when judging it for its water content. This is due to the stiffening effects of the flocculant. This traps water within the flocs producing a centrifuge cake with a high water content yet appearing stiffer than a comparable cake with less flocculant. This links back to the optimum flocculant dose rate and the need to reduce the water content by increasing the solids throughput.

4.7.4 Increased solids loading

As mentioned above increasing the solids loading of the centrifuge will help to decrease the water content of the centrifuge cake if required. This will in turn have a negative effect on the centrate by decreasing its clarity. This is a balance that needs to be made on site by considering both the desired centrate and cake outputs as well as the required centrifuge throughput.

4.8 Further work

To gain the full picture of how a centrifuge should be operated at its optimum more work is required.

- Varying the mineralogy of the slurry used to understand how this effects the operation. This could be limited to flocculant type and slurry throughput tests.
- The use of a coagulant within the system would also be a helpful test case. This should be carried out with various coagulants such as ferric chloride and aluminium sulphate.
- Looking at the effect of vibration on flocculated and centrifuged spoil to see if the trapped water is released and how easily. This is critical for transportation and could be developed in to a further dewatering stage.
- With flow meters attached to the centrifuges and a constant tank of slurry (possibly at the end of a tunnel drive), a study could be conducted to check

the exact optimum solids throughput. This data could then be collected together to start and compare various centrifuges and understand what a realistic throughput is.

5.0 CHARACTERISTICS OF FLOCCULATED SLURRY

5.1 Introduction

To aid in the understanding of what effects the successful separation of fine particles with the aid of coagulants and flocculants work was required in the controlled environment of the laboratory. A variety of tests were proposed with the aim to gain a greater understanding of how a flocculant should be used and the effects it can have on the site process. The key areas of interest were:

- Clarity of supernatant/centrate
- Water content of solid arisings/cake
- Liquid limit of the arisings/cake
- The combination of coagulants and flocculants
- Post separation effect of vibration on trapped water

Although the tests carried out are limited in some aspects of their applicability to site operations they help to increase the understanding of the separation process using chemical treatment. Some of these tests were carried out by a PhD student, Shih-Yun Liu and others in conjunction with Liu.

5.2 Effect of Flocculants and Coagulants on Separation

As part of research work carried out at the University of Leeds (Liu, 2010) testing was carried out to look at the effect of combining a coagulant with a polyacrilamide flocculant. This was to ascertain how varying the doses of both would benefit the clarity of the supernatant, dry density of the flocs and the percentage of flocs produced.

Contractors were seen during all site visits to use a single flocculant with no coagulant during site operations. During water treatment it has been suggested that it is sometimes necessary to use both a coagulant and flocculant (Binnie, 2002). This led to the testing to see what effects combining both a flocculant and coagulant had on solid and liquid recovery.

These tests are briefly summarised in this section to produce a full picture of the effects on solids removal with the aid of additives. During these tests the flocculant (SNF VP1) was dosed at concentrations of 15-120mg/l and the coagulants, aluminium sulphate or ferric sulphate, at concentrations of 0-600mg/l. These tests were carried out on several different soil samples:-

- Kaolin (grade: Polwhite E)
- Bentonite
- Shelly clay from the Lambeth group
- London Clay (undefined unite)
- Mercian mudstone

The clarity of the supernatant was monitored using a portable turbidity meter (as in chapter 4) displaying the results in amount of light diffracted. The turbidity meter displays the result as a NTU value. The relationship between turbidity and density is dependent on the mineral in suspension. It provides a quick, accurate baseline for comparison of results between samples of the same material.

The percentage of flocs produced during testing is simply the fraction of settled material to the total volume of slurry.

The test regime for this was devised by Liu (2010) and reported below:

1. Beaker filled with 500ml of slurry
2. Mixed at 200rpm for 5 minutes at different pH levels (adjusted with lime)
3. Coagulant added and mixed for a further 2 minutes
4. Flocculant added and mixed until large flocs start to breakdown
5. Left to stand for 5 minutes
6. Mudline height measure
7. Supernatant sample for turbidity and flocs sampled for dry density

The results of these tests (Liu, 2010) showed both expected and surprising outcomes in relation to the use of flocculants and coagulants. The dry density reduced as the amount of flocculant increased, which was confirmed in the centrifuge testing described in chapter 4. Once a certain dose rate was achieved there was no further change in the percentage of settled flocs. The optimum dose rate would vary depending on the soil mineralogy and the speed of the decanting centrifuge (Records and Sutherland, 2001). The turbidity of the supernatant, however, did increase after this dose rate presumably caused by excess flocculant that had not settled with the solids. This was seen on all soil samples and is a reason for keeping flocculant dose rates at a minimum.

This optimum dose rate was based on the density measurements. There was no measure to check whether there was excess flocculant in the supernatant. Further these tests were at 1g and would not necessarily indicate whether the optimum dose rate was the same for slurry passing through a centrifuge.

The coagulants results were surprising showing no obvious effect on the separation process for all soils except the Mercia mudstone samples. The tests carried out on Mercia mudstone showed that the flocculent and coagulant combination reduced the turbidity and the dry density. The turbidity was reduced to below 20NTU with dose rates of either 40mg/l of flocculant and 200mg/l of aluminium sulphate or 30mg/l of flocculant and 300mg/l of aluminium sulphate.

From the above findings (Liu, 2010) it can be seen that the flocculant dose rate should be kept to a minimum to produce a clear centrate. As the flocculent dose rate increases the centrate can become more turbid and the dry density reduce. The use of coagulants surprisingly had no beneficial effects in the majority of samples tested other than that of Mercia mudstone. This can be seen when comparing Table 5.1 with Table 5.2. Further work should be carried out on the mineralogy of clays to identify a potential clay mineral that required the use of a coagulant.

	Dry Density of Flocs (g/l)	Floc Concentration (%)	Turbidity (NTU)
Kaolin	250-350	45-50	2-40
Bentonite	200-220	55-60	2-5
Mercia Mudstone	300	33	600
Lambeth Group	220	30	5
London Clay	180	26	15

Table 5.1 Comparison of varying slurry compositions dosed with a single flocculant (flocculant dose rate varies)(Liu, 2010)

	Dry Density of flocs (g/l)	Floc Concentration (%)	Turbidity (NTU)
Kaolin	250-330	45-50	Under 40
Bentonite	200-220	55-60	Under 2
Mercia Mudstone (40mg/l Flocculant + 200mg/l Aluminium sulphate)	230	55	Under 20

Table 5.2 Comparison of varying slurry compositions dosed with a flocculant and aluminium sulphate (range of dose rates sampled) (Liu, 2010)

This suggests that the use of a coagulant would only be beneficial in limited circumstances and should only be implemented when the cleaning capacity of a single flocculant is sub standard. This could be tested prior to tunnelling starting with a simple jar test using soil taken from the shaft excavation at tunnel horizon A scaled down version of the tests Liu (2010) carried out would show whether this was the case.

The test comprises of producing a representative slurry sample of what may be encountered during tunnelling. The procedure is to dry a soil sample at 105°c for 24 hours; break it down with a pestle and mortar before sieving it through a 63µm sieve. With a sample in excess of 1kg of sieved soil, a slurry in the range of 1.05-1.15g/cm^3 can be produced, it is advised (depending on equipment) that 500ml of slurry is allocated to each test with multiple tests required. Flocculant can be added to each sub sample at varying concentrations and mixed thoroughly possibly with a standard laboratory jar and paddle mixer. The flocculant dose rate should be increased in increments of 10-15mg/l until there is no further improvement is seen in clarity.

The individual tests can be compared for clarity of separated supernatant, floc dry density and percentage of flocculated material. If the flocculant dose rate required is high (+50mg/l) to achieve a clear centrate (sub 100NTU or visually slightly cloudy), then it is recommended that the test be repeated with the aid of a coagulant salt. It is suggested that only one dose rate of the flocculant or coagulant is varied at any one time.

With the test data produced from these series of tests, a decision can be made on the need of a coagulant and if the planned flocculant is adequate. In the field the dose rates will vary to that of the laboratory jar test due to the varying solids concentrations of the slurry, the chemical composition of the water and a potential change in slurry composition because of the natural variation in the ground conditions. The dose rate will also vary with the characteristics of the decanting centrifuge. (Records and Sutherland, 2001).

5.3 Variation in Liquid Limit due to Flocculant Dosing

The use of flocculants in solids separation has a significant effect on the structure and behaviour of the separated solids. Previously it was noted that the water content of the solids increased as the flocculant dose rate increases. It must also be noted (Lambe, 1953; Merritt, 2004; and Liu, 2010) that the liquid limit of the solids is also dramatically affected with the increase of flocculant dose rate.

In order to validate these reports and gain a greater understanding of how the flocculated material was effected, a testing regime was designed with Shih-Yun Liu. The testing was carried out using a cone penetrometer to determine the liquid limit of three flocculated and centrifuged samples at varying flocculant concentrations, 45, 90 and 130mg/l.

A baseline test was also carried out on pure kaolin (Polwhite E grade), giving a liquid limit of 54%. Literature denotes that this should have a liquid limit of 50-55% (Borghi, 2006). Liquid limit was chosen as the criterion since it is a measure of the point at which a particulate material can be deemed to behave as a liquid.

Each sample was mixed for five minutes with flocculant in the jar test apparatus. This had been previously proved to be the optimum mixing time (Liu, 2010). Once mixed the flocculated solids were placed in desktop centrifuge at 2000g for 10 minutes. Individual samples were then tested using the cone penetrometer according to BS 1377:7 1990.

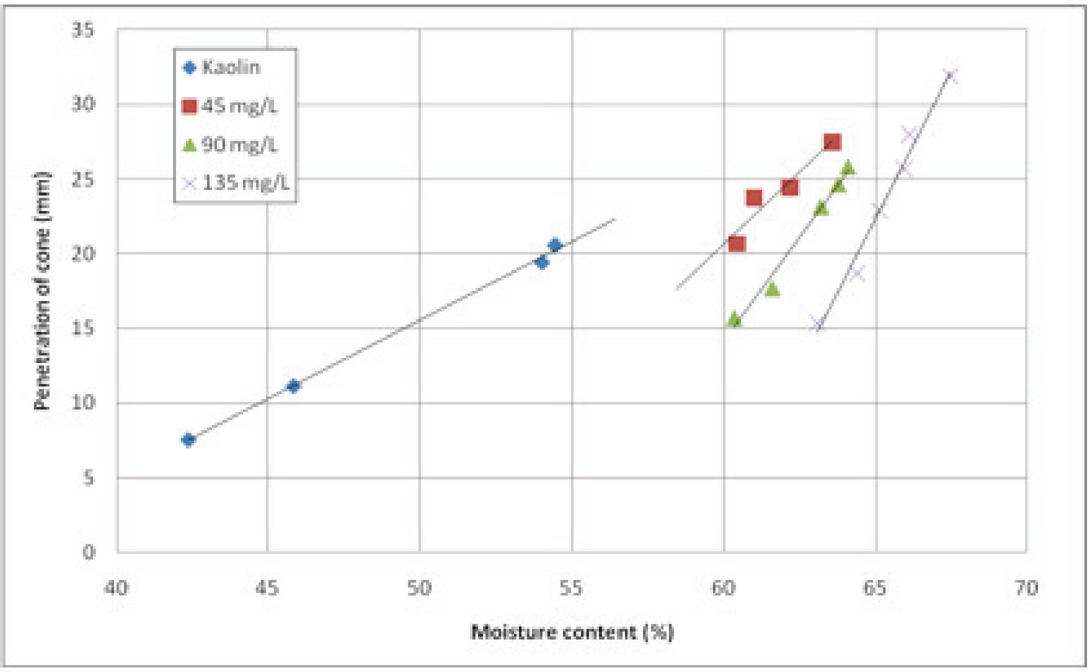

Figure 5.1 Change in the liquid limit of kaolin due to flocculant (the liquid limit is defined as the water content when the penetration is 20mm)

It can be seen in Figure 5.1 that the addition of a polyacrylamide flocculant (SNF VP1) increases the liquid limit. This was similar to the field observations where the centrifuge cake appeared visually stiffer when dosed with flocculant. Thus the increase in stiffness of the cake was partly due to the reduction in water content as a result of the centrifuge and partly due to the increase in liquid limit due to the effect of the flocculent. The cake retained water. This may have a short-term benefit of a stiffer, more stackable cake but could cause significant problems when transporting the spoil off site with the potential release of trapped water. This was seen on a site in the North West of the UK where the centrifuge was being overdosed producing a stiff cake. This however was being stockpiled and 'DryAdd' added due to landfill operators complaining that it was too wet on arrival.

5.4 Effects of vibration on flocculated and centrifuge slurry

Knowing that the use of flocculant increases the liquid limit which meant that the cake appeared to be stiffer than it would normally have been if flocculent had not been added there was a concern that the trapped water could have been released by vibration when transporting the cake off site. Contractors had mentioned that on occasion they have a problem with free water gathering on the surface of material transported by lorry. It was initially thought that was due the vibration of transportation caused the release of trapped liquid.

The testing regime involved flocculating kaolin slurry at a density of 1.09g/cm^3 with four dose rates of flocculant; 10, 25, 50 and 100mg/l. These were mixed with the jar testing apparatus at 200 rpm for 1minute. The supernatant was then checked for turbidity and the solids centrifuged for 150 seconds at 1000g. For all flocculant dose rates the turbidity of the supernatant were seen to be 92-99NTU. The floc size increased (Figure 5.1) with the flocculant concentration. This could be linked to the increase in water content of the flocs.

Figure 5.2 Variation in visible floc size 1-4 (10, 25, 50, 100mg/l)

The batch centrifuge time was had been reduced to 150 seconds from a previous used 300 seconds, to try and produce a more comparable cake to that produced by a decanting centrifuge. This was still not achievable, as the cake was still very still.

To simulate the vibration that might be applied to a cake during transportation the samples were placed on a sieve analysis shaker and vibrated for 30minutes, checking the sample at 5, 10 and 15minutes. The intention of this was to measure the quantity of free water produced.

Figure 5.3 Samples after 30min vibration showing very little free water and a stiffer sample then would be seen from a decanting centrifuge (100, 50, 25, 10mg/l)

None of the samples tested released free water. The water contents of the samples were between 32 and 49%, meaning that they were less than the samples commonly found on site. The visual structure of the centrifuged clay had a more compact appearance. This is likely caused by the static nature of the sample when g-force applied in the desktop centrifuge. A decanting centrifuge has a scroll to constantly remove the separated solids. This agitates the solids and could give it the 'fluffier' appearance and potentially a loser structure. A decanting centrifuge also requires a high consumption of flocculant, which is possibly due to the higher water content. (Records and Sutherland, 2001)

The samples with dose concentrations of 50 and 100mg/l of flocculant did however show some liquefaction around the base of the sample but no free water. This suggests that if a decanting centrifuge sample was used some water may be released from the solids. A centrifuge time of 150sec was as short a time as the centrifuge could be set to due to the time required for the centrifuge to get up to speed. This however is not the case with a decanting centrifuge that runs permanently at the designated speed.

5.4 Summary

From the range of laboratory tests carried out it can be seen that although the use of a flocculant is often necessary to aid in separation it can have a detrimental effect on separated solids if dosed incorrectly. The over use of flocculant was seen to reduce the dry density and percentage of flocs formed. At the same time it increased the liquid limit of the spoil. Due to this extra water the cost of disposal will increase and there is an increased potential for water to be released from the spoil during transportation, although not proven. This shows that the flocculant dose rate requires careful monitoring in order to provide satisfactory separation with a clean centrate and a stiff cake with minimum water content.

The experiments run towards the end of the research programme on the effects of vibration on flocculated material did not show the expected results. Contractors have logged the production of free water during the transport of material away from site. Because of this more work should be carried out on this using flocculated material from a decanting centrifuge. This would give more realistic results to base conclusions on.

5.5 Further Work

There are still areas of research that need to be carried out to gain a full picture of the separation process using flocculants and how they should be added for optimum performance. This work will need to be carried out in future research programmes.

- More work is required on the effects of vibration on flocculated and centrifuged material. This requires a decanting centrifuge to be set-up with flow meters to accurately vary the flocculant dose rate. Samples could then be taken back to the laboratory for testing with vibration or placed in a container and some how attached to a disposal lorry on site for quicker more realistic results.

- A development of the ‘cup test’ should also be carried out in order to try and ascertain the optimum quantity of flocculant to prevent excess flocculant being discharged with the centrate. This would help to provide a method of testing and prove to the Environment Agency or any other body that the centrate can be disposed of safely.
- It could be possible to use the principle of electrophoresis to reduce the water content of the spoil. This would require an in depth study looking at the time, current and distance between the anode and cathode required.

6.0 Conclusions

6.1 Summary

The research programme was commissioned with the aim of gaining a greater understanding of the slurry separation process. This included a method of best practice for specifying and operating the separation plant. The research programme covered various aspects of the separation process and how it may be improved. This work was supplemented by other research programmes carried out at the University of Leeds looking at EU waste legislations relating to pipe jacking and the management cycle of tunnelling contracts.

- Initial work was carried out in the literature review covering the separation plant, slurry additives and the EU/UK legislation relating to slurry treatment.
    - A comparison of current separation plant and others forms used across varying industries.
    - The use of additives to aid in separation, suspension of solids and ground stability.
    - Key points associated with the current EU/UK waste legislation.

- Current site operations and variation in slurry parameters were monitored on several sites around England and Wales.
    - Common separation problems and causes were established and investigated.
    - Current best practice for plant specification and operation were identified.
    - A study into the variation in slurry parameters caused by the ground conditions, separation plant and TBM.

- The operation and optimisation of a decanting centrifuge was identified.
    - The effect of solids throughput on the separation behaviour.
    - Study into the effect of slurry feed/mixer pipe length.
    - Behaviour effects of flocculant dose rate.
    - Variation in three common pipe jacking flocculants.

    - Effect of centrifuge speed on solids throughput and separation behaviour.

- The effects of separation additives on the separated solids.
    - The effect of combining flocculants and coagulants on the separation process.
    - Variation in liquid limit due to the addition of flocculants.
    - The effect of vibration on trapped water within flocculated solids.

6.2 Main Conclusions

The research programme has produced several key conclusions in relation to the objective of improving the process and knowledge of slurry separation in pipe jacking and tunnelling.

- The current separation system that, in principle, has been adapted by the majority of pipe jacking contractors was seen to be suitable and best suited for the needs of the contractors in most cases.
    - This consists of a three stage separation process explained in chapter 1.

- The correct specification of plant is very important to the success of the tunnel drive.
    - The correct number/size of centrifuges required to cope with all of the sub 65μm particles likely to go into suspension.
    - A mechanical agitation system is essential for ease of the centrifuge and TBM operations, as well as reducing the required tank cleaning.
    - Using clay ball belt separators as an alternative to a primary shaker in cohesive ground conditions will reduce operator time required for cleaning of the screen.

- The operation of the separation plant is key to the success of the tunnel drive and in turn requires a trained operative to run the plant during the tunnelling operation.
    - The operator should have a key understanding of how the solids throughput can affect the desired out comes.
    - Understand how to check the flocculant dose rate with the 'cup test'.
    - Being able to monitor changes in the slurry properties using a minimum of a mud balance, Marsh funnel and sand content kit.
    - Liaise with the TBM operator to try and predict the changes that maybe seen in the slurry and limit the effects of increasing slurry density where possible.

- The use and understanding of separation additives is key for contractors to manage the continuing operation of the tunnelling project and arisings disposal.
    - The increased concentration of flocculants will:
        - Reduce the dry density of the separated solids
        - Increase the liquid limit
    - With the increase in trapped water content produced by the flocculant an increase will also be seen in the disposal cost since a lorry has a weight limit for transportation and additional water will require additional trips. In some cases the extra landfill tax applied due to the increase in weight of water may be passed on to the contractor for simplicity of the haulage/landfill operator. The contractor can ask for this to be wavered due to the extra water content being from a process which is exempt from taxation.
    - Environmentally the increased water content could result in more leachate being produced at the landfill.

- Slurry flow rate to the centrifuge was seen to have a large effect on both the solids water content and the clarity of the centrate.
    - Increasing the slurry flow rate showed a decrease in water content of the centrifuge cake but in turn increased the amount of suspended solids found within the centrate.

    - The reverse of the above was seen at lower slurry flow rates.
    - A balance needs to be had between water content of the cake and clarity of the centrate. The outcomes of the centrifuge will depend on of the mud man manages the; density and viscosity variation of the slurry, required water content of the cake and the stage within the pipe pushing cycle.
    - At high solids throughputs the centrifuge centrate was found to be uncontrollable.

- Correct flocculant dose rate is key in the success of producing the optimum centrate clarity for any particular solids throughputs.
    - Flocculant dose rate was found to improve the clarity of the centrate; however, at some point excess flocculant will be found in the centrate. The boundary at which this happens is the optimum dose rate.
    - With an increased flocculant dose rate the water content of the cake was also found to increase.
    - The optimum flocculant dose rate gives a balance of cleaning performance whilst minimising the negative effects of the flocculant; increased water content and over flocculation affecting the active system.

- Slurry and flocculant interaction is key and should be achieved with an inline mixing system: static flow mixer or vortex mixer.
    - Increasing the length of pipe between the inline mixer and centrifuge showed little benefit to the system.
    - What benefits were seen would again be a trade off, as was seen with the change of flocculant dose rate.

- Flocculant concentration of the premixed flocculant showed equal performance at and above a concentration of 0.25% to 1% (for a high molecular weight liquid at 50% solution).
    - A concentration of 0.5% for liquid and 0.25% for powder would give adequate performance. This correlates with manufacturers' recommended levels.

6.3 Recommendations and Suggestions

The research programme has identified several key recommendations, which should help improve the knowledge of slurry separation in pipe jacking and tunnelling.

- Pipe jacking and tunnelling contractors
    - The employment of a mud man is extremely important when a centrifuge is being operated on site. The mud man should be trained and maintain constant supervision of the separation plant.
    - Understanding the limitations of a centrifuge and how various methods of operation will affect the desired outputs.
    - The correct plant specification being deployed to site:
        - Adequate centrifuge capacity
        - Correct use of primary and secondary screens and hydro-cyclones
        - Slurry agitation
    - Keeping flocculant dose concentrations to a minimum for improved dry densities of the solids.
    - Flocculant dose rate should be checked using the 'cup test', ideally with kaolin slurry. This will help the mud man to operate the centrifuge at near optimum flocculant concentration helping to avoid over dosing and excessive trapped water in the solids arisings.

- Clients and Designers
    - The allocation of space for adequate separation plant is essential. Consultations should be had with contractors to ascertain the required space.
    - Separation plant is a vital piece of the process and will indirectly control the speed at which a TBM is driven and the cost of disposing of the arisings. The cost of separation plant is high but is also vital to successful tunnelling. The final cost can/will be considerably higher without adequate plant.

- Contract cost may hinge on the allocated cost of separation provisions and the contract success could also hinge on this. A bid should be partially judged on the specification of plant and not just the 'initial' cost.
- Prior thought and planning into potential routes for tunnel arisings. This could be on near by projects or with local industries.

6.4 Further Work

To help improve the process of slurry separation further work is required to gain a full picture of the process and develop optimum separation.

- A study on the potential solids produced at each stage of separation would benefit selection of plant by contractors. This would allow a contractor to economically specify what plant is required for a particular ground condition. Stating how a soil will breakdown due to mechanical and liquid mechanisms.
- An in-depth study should be carried out on the effects of vibration on flocculated solids. This would look at whether water was released from the solids during transportation and if the concentration of flocculant within the solids affects this.
- The addition of an electro-osmosis stage into the separation process in order to reduce the water content of the solids. This would require work on balancing current, anode and cathode spacing and time required for adequate dewatering in order to make the potential system economically viable. Work will also be required to look at the change in pH of the water released and if further treatment is required to this water.

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ANONYMOUS (a), 2010

ANONYMOUS (b), 2010

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Appendices

Appendix A: Site Monitoring Form

Site Monitoring Form

Site:

Contractor:

Date:

Readings should be taken every 0.5meters and the following points logged

Chainage (meters)	Time	Slurry SG	Jacking Force	Viscosity (seconds)	Sand Content (%)	Approx spoil separation percentages	Comments

Appendix B: Site Data Record Form

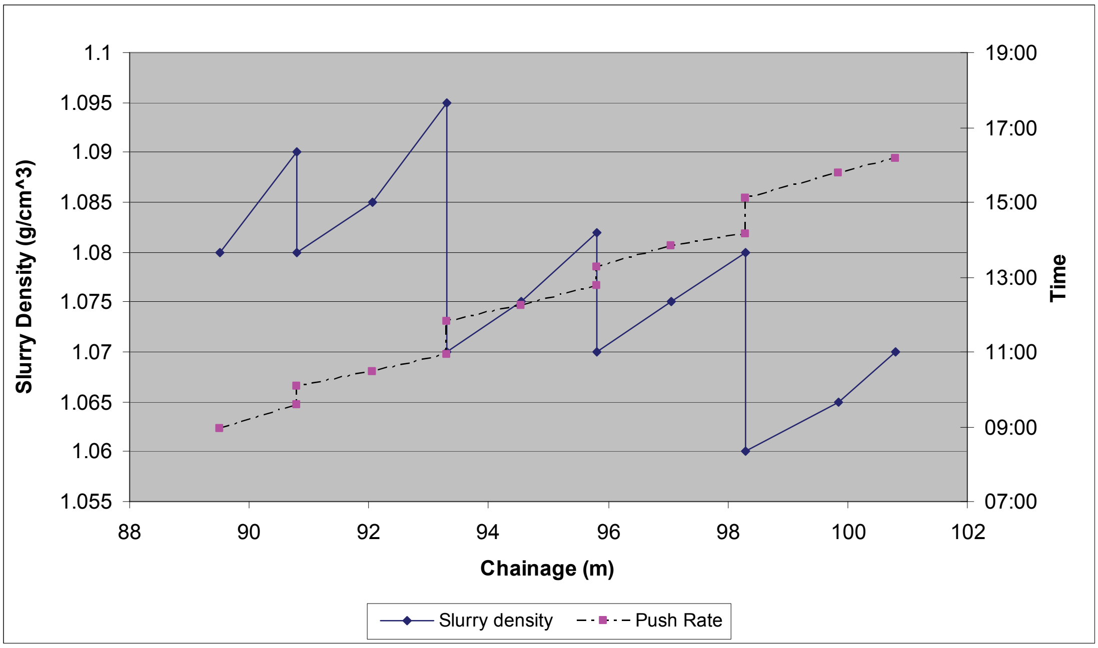
Trenchless site data record	
General data	
Record date	
Project Name	
Location	
Client	
Consultant	
Contractor	
Supplier (Sub-Contractor)	
Operators	
Started date	
Finished date	
Duration	
Contract type	
Contract value	
Project data	
Pipe	
Length of pipe	
Dia. of pipe	
Depth of pipe	
material of pipe	
Driving length (working rate)	
Shaft	
Size	
Shape	
Depth	
Number of Shaft	
Soil	
Type of soil	
Particle size	
Water content	
Water level	

Ground condition	
Ground treatment	
Machines	
Type of machine	
Monitoring system	
Type of soil separation	
Additives	
Type of Add.	
Quantity of Add.	
Adding time	
Construction difficulties	
Ground movement	
Alignment	
Levelling	
Loading	
Monitoring	
Health and safety	
Regulations	
Other site inspection records	

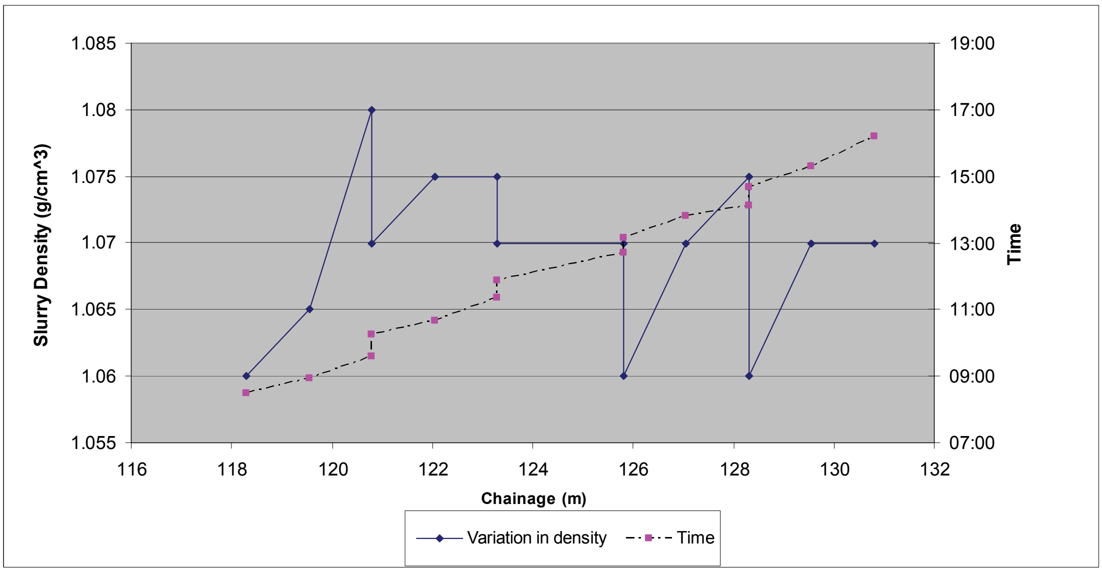
Appendix C: Variation in slurry density with progress rate

Site A

Visit 1: Variation in slurry density with progress rate

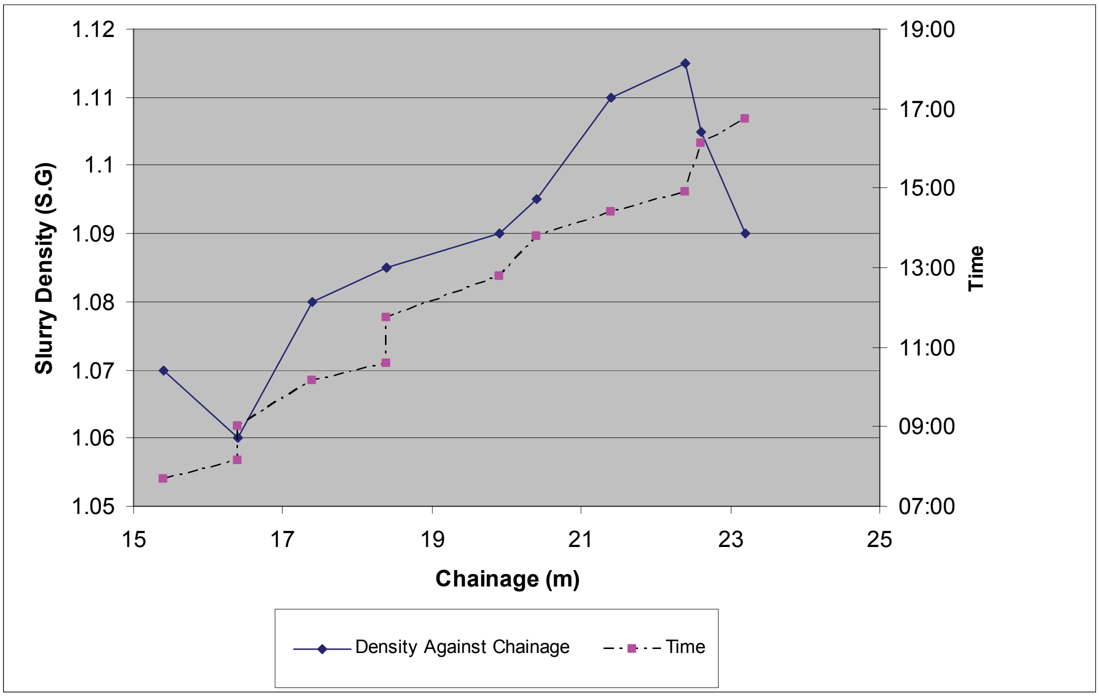


Visit 2: Variation in slurry density with progress rate

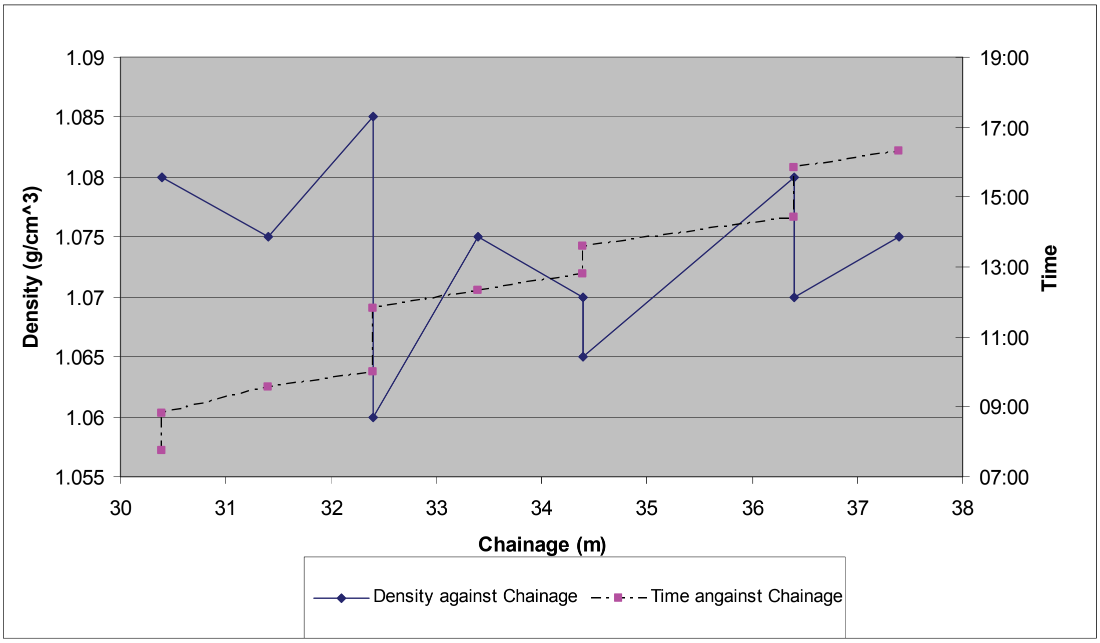


Site B

Visit 1: Variation in slurry density with progress rate

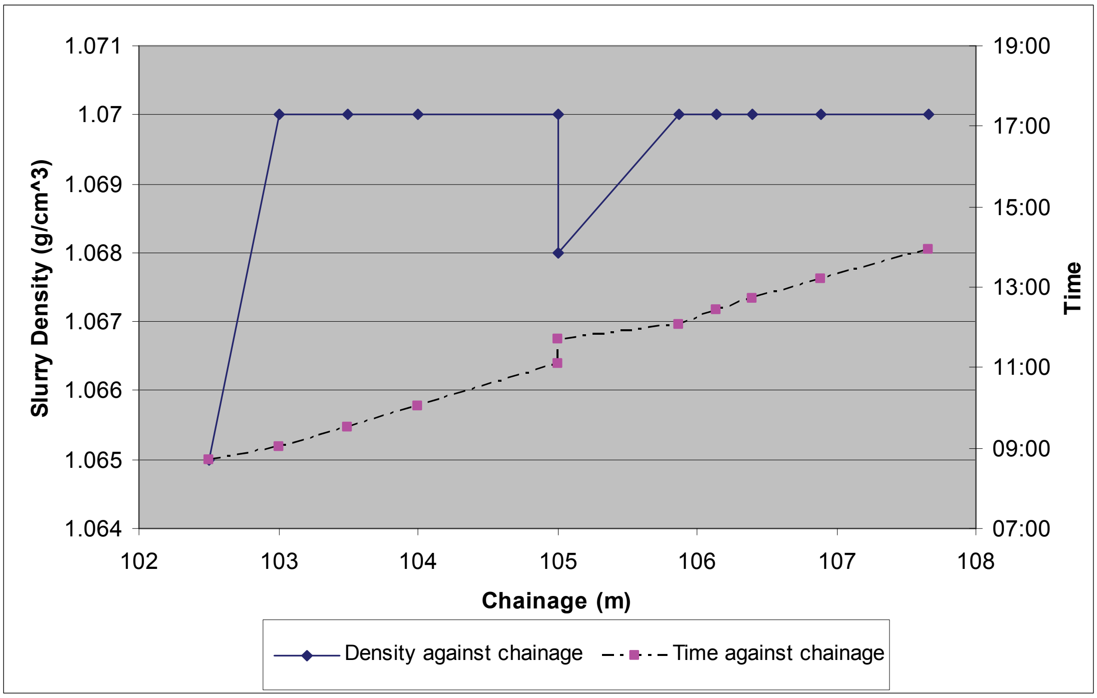


Visit 2: Variation in slurry density with progress rate



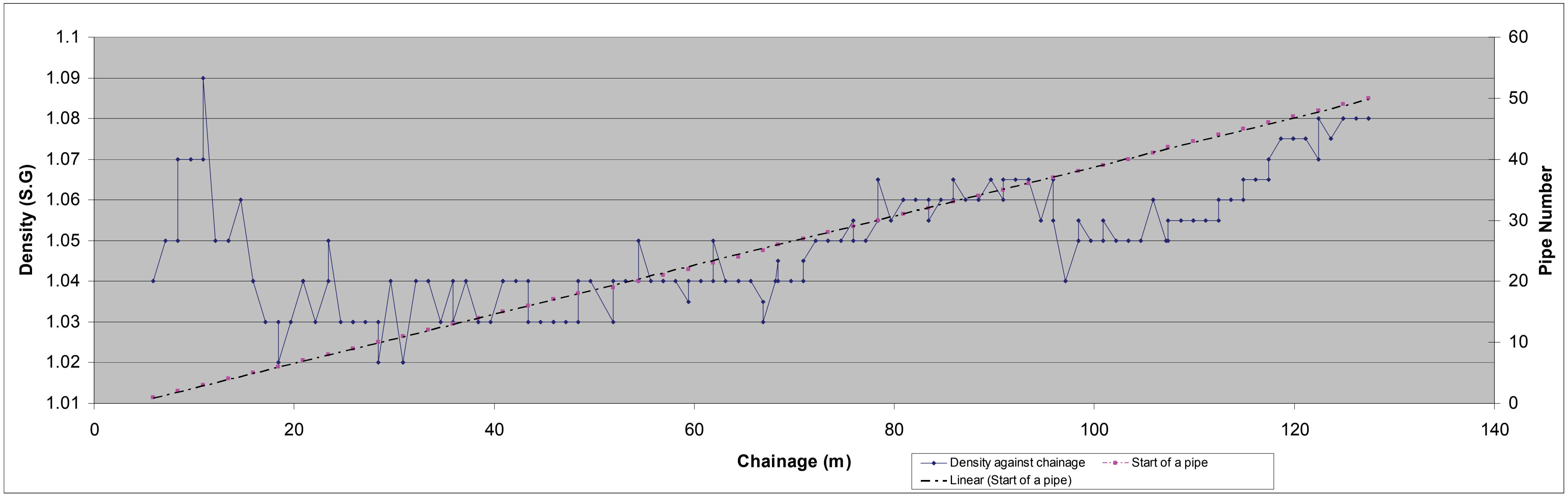
Site C

Visit 1: Variation in slurry density with progress rate



Complete Drive: Variation in slurry density

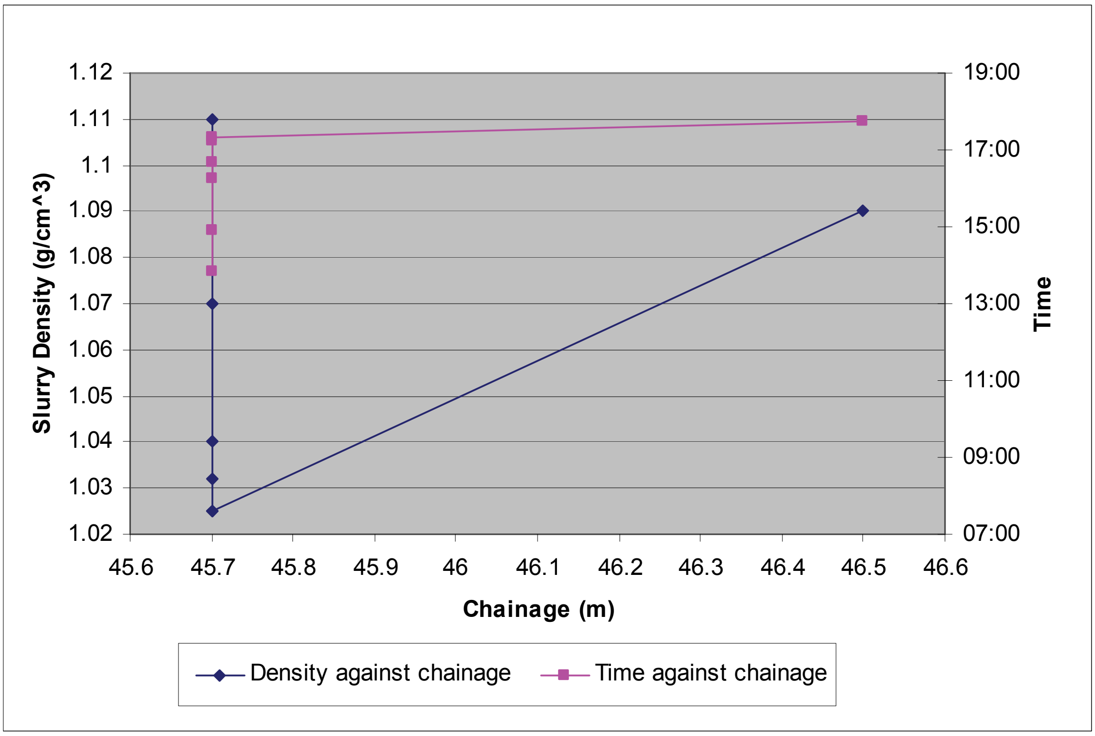
The graph below shows the variation in slurry density as the drive progressed. The secondary axis shows the start of each pipe to give a simple reference point for the density variation. For this drive slurry density measurements were taken at the start, middle and end of every pipe.



(Anonymous (a), 2009)

Site D

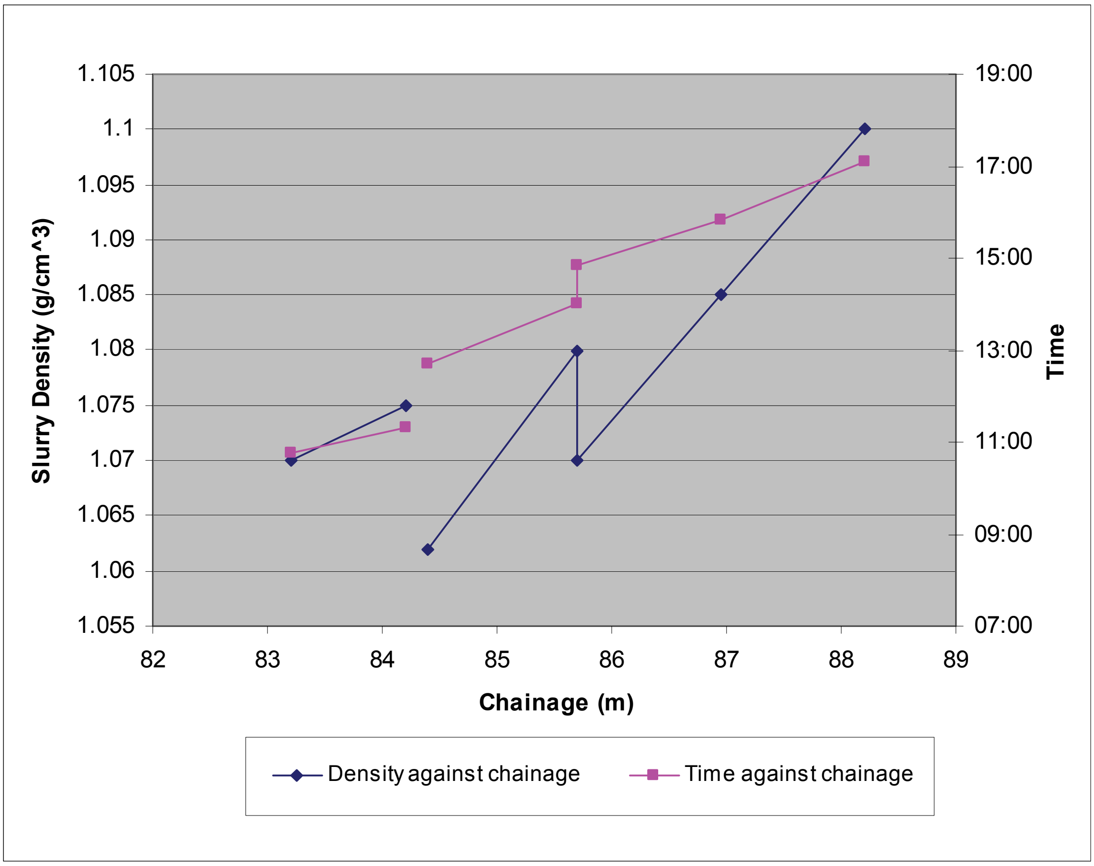
Visit 1: Variation in slurry density with progress rate



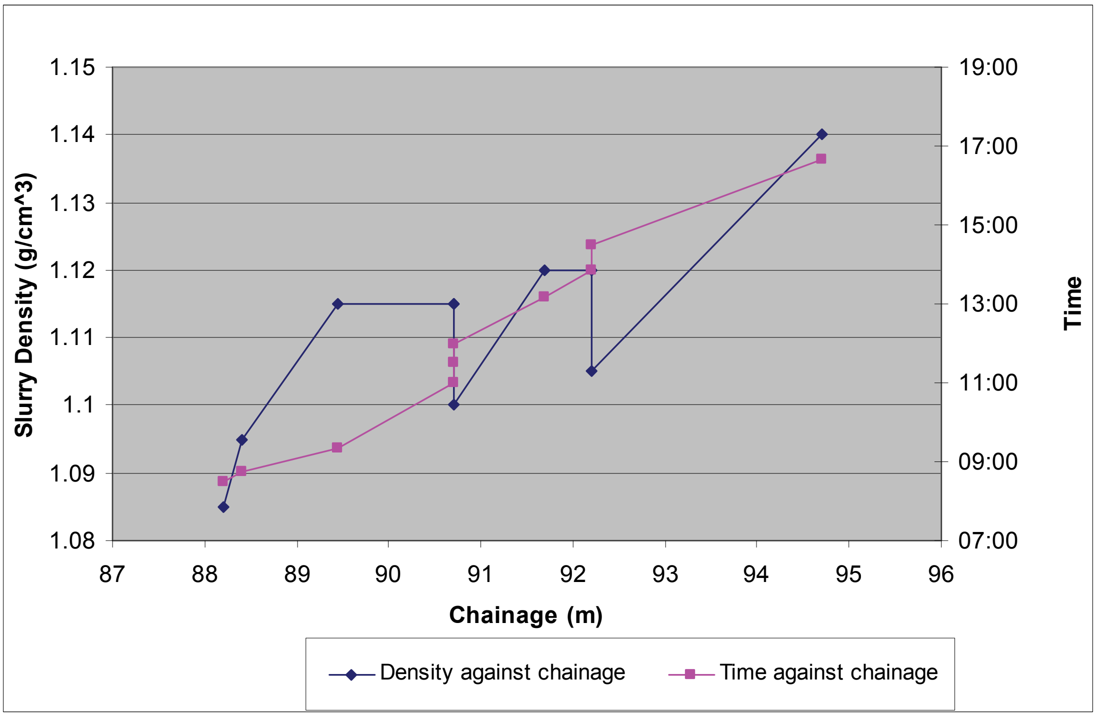
The continuous drop in slurry density at 45.7m is due to an extended delay while the slurry was being constantly cleaned with the centrifuge. This stoppage was due to the pushing ring for the inter-jack not fitting the pipe.

The sudden rise again in density from 45.7m to 46.5m is due to the centrifuge being turned of at 17:30 for cleaning before the site closed at 18:00. This site was in a residential area and site operations had to stop at 18:00 but the centrifuge required cleaning at the end of each shift which took approximately 30minutes.

Visit 2: Variation in slurry density with progress rate

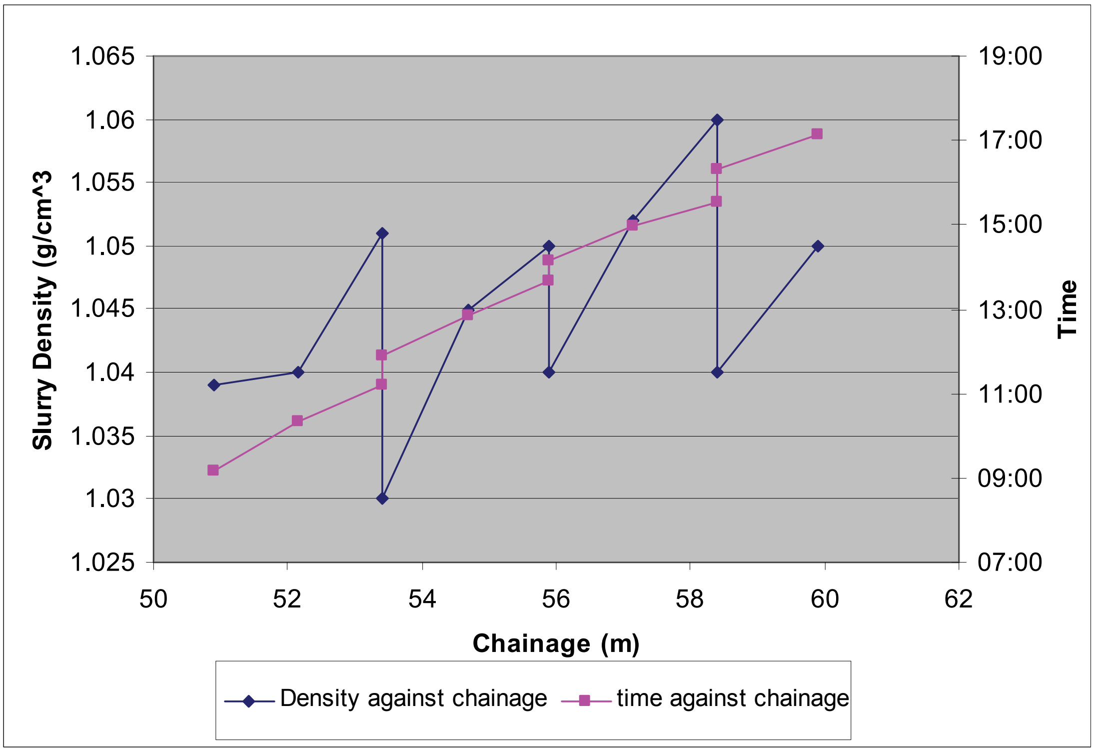


Visit 3: Variation in slurry density with progress rate



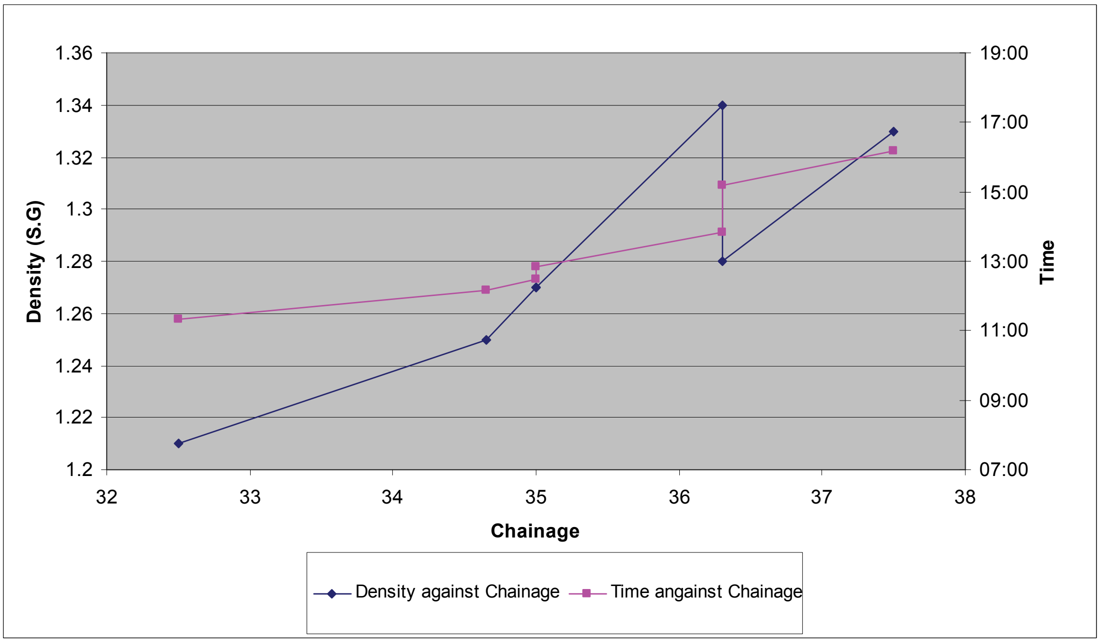
Site E

Visit 1: Variation in slurry density with progress rate



Site F

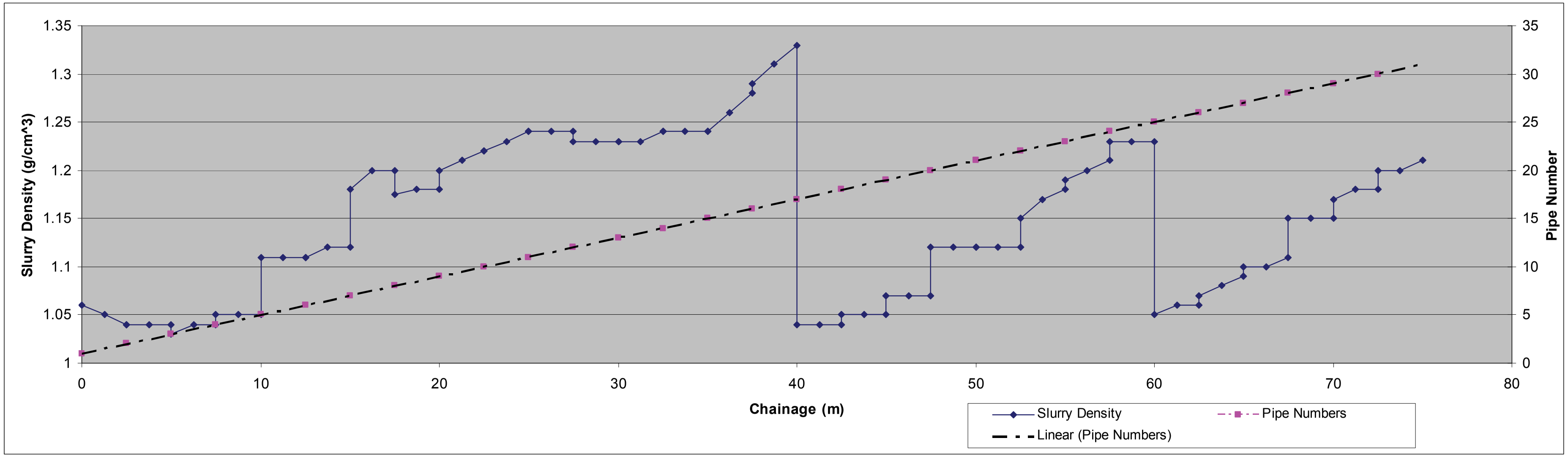
Visit 1: Variation in slurry density with progress rate



Site G

Full Drive Date: Variation in slurry density

The graph below shows the variation in slurry density as the drive progressed. The secondary axis shows the start of each pipe to give a simple reference point for the density variation. For this drive slurry density measurements were taken at the start, middle and end of every pipe.

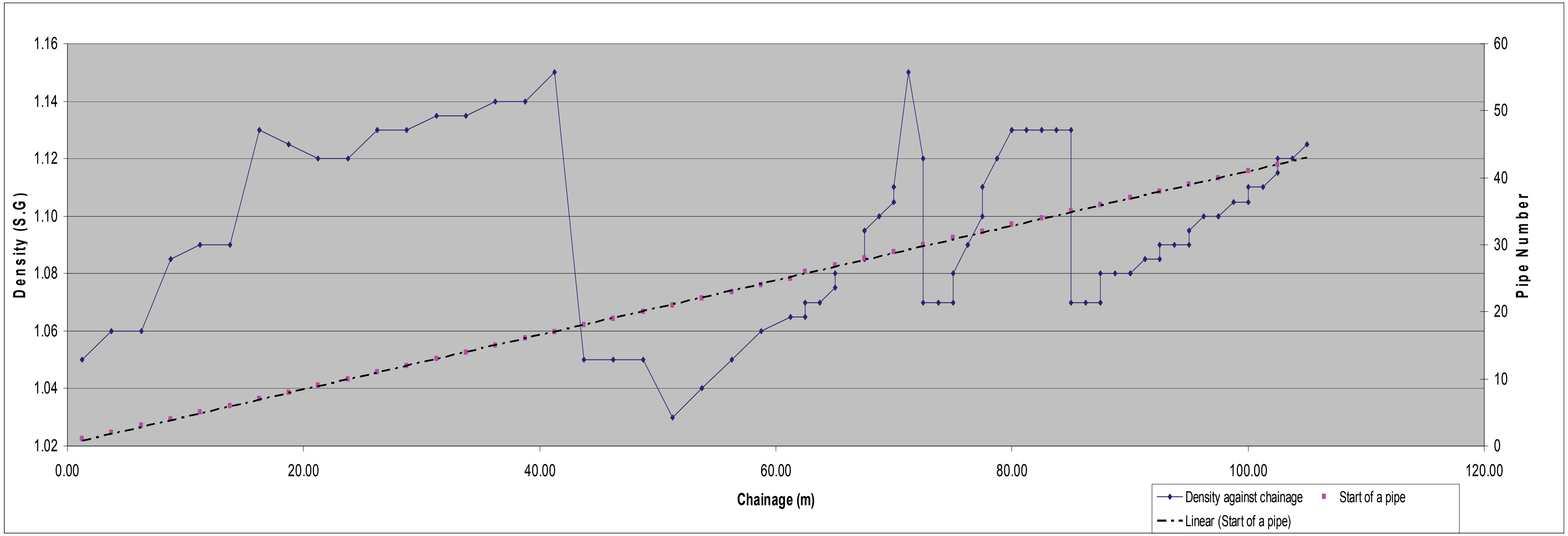


(Anonymous (b), 2009)

Site H

Full Drive Date: Variation in slurry density

The graph below shows the variation in slurry density as the drive progressed. The secondary axis shows the start of each pipe to give a simple reference point for the density variation. For this drive slurry density measurements were taken at the start, middle and end from pipe 26 or 62.5m, Previous to this, measurements were only taken at the middle of the pipe.

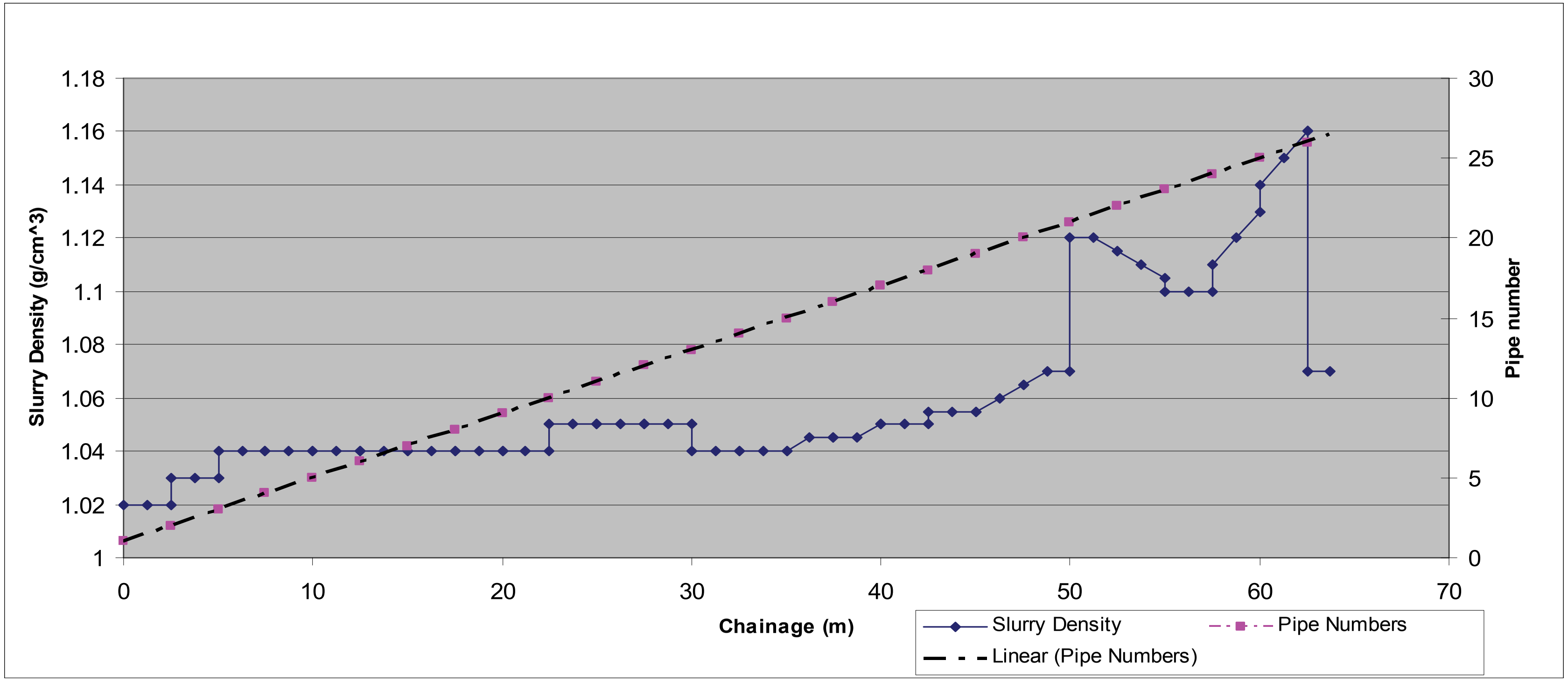


(Anonymous (a), 2010)

Site I

Full Drive Date: Variation in slurry density

The graph below shows the variation in slurry density as the drive progressed. The secondary axis shows the start of each pipe to give a simple reference point for the density variation. For this drive slurry density measurements were taken at the start, middle and end of every pipe.



(Anonymous (b), 2010)

Appendix D: Sand Contents

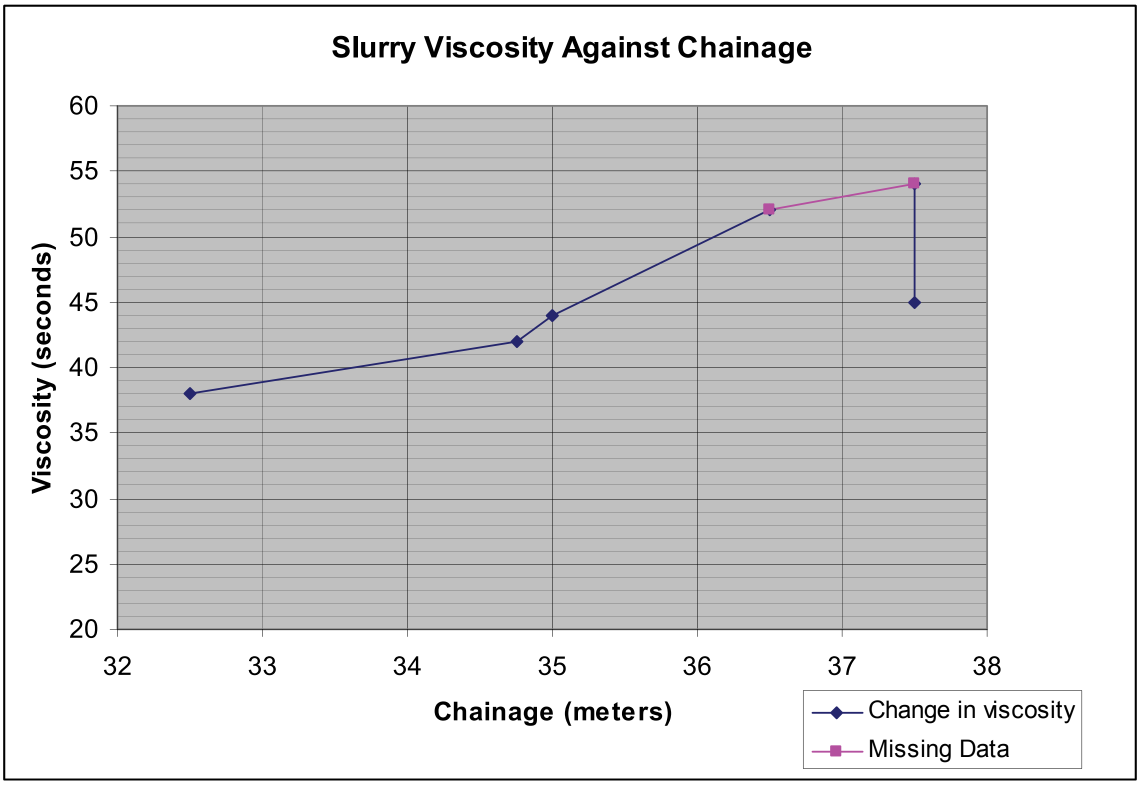
All sand contents are given in percentages and taken using a standard site sand content kit. The particle cut point using this apparatus is 74µm.

Site	Min Sand Content (%)	Max Sand Content (%)	Number of readings	Average Sand Content (%)
A	0.05	0.25	6	0.14
B	1.5	4	22	2.28
C	0.25	0.75	6	0.41
D	0.6	3	8	1.42
E	No data	No data	0	No data
F	0.3	0.65	4	0.44
G	No data	No data	0	No data
H	No data	No data	0	No data
I	No data	No data	0	No data

Appendix E: Viscosity

Site	Min (seconds)	Max (seconds)	Average (seconds)	Number of readings	Additives
A	27	27	27	3	
B	33	38	35.5	22	bentonite
C	No Data	No Data	No Data	0	
D	27	28	27	4	
E	29	29	29	2	
F	38	54	46.6	7	bentonite
G	No Data	No Data	No Data	0	
H	No Data	No Data	No Data	0	
I	No Data	No Data	No Data	0	

Site F Viscosity Graph



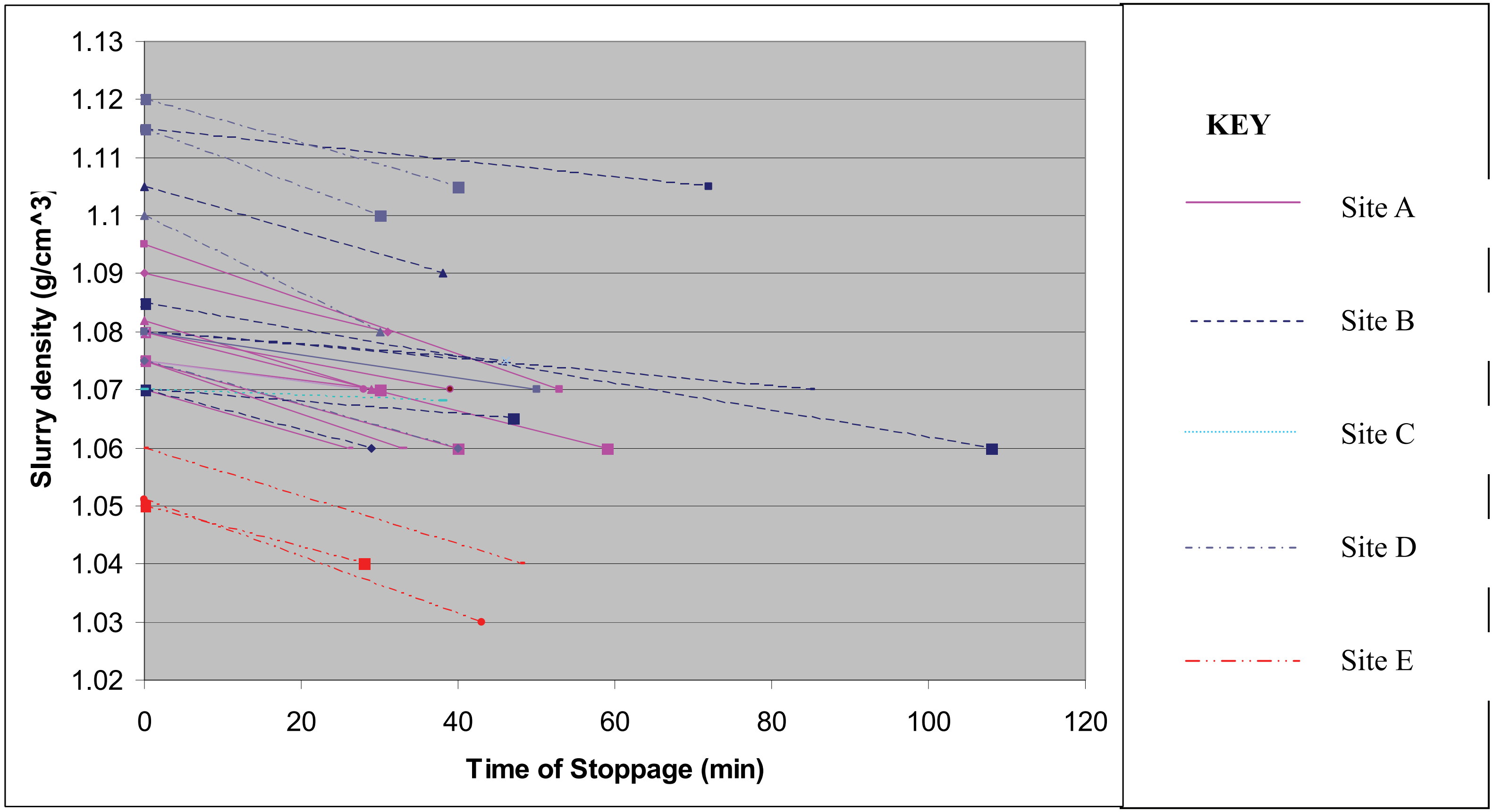
Appendix F: The reduction in density when a new pipe was connected

The data below shows the reduction in density whilst installing a new pipe. This shows the true rate of decrease because no solids are being added into the system. All data is given in g/cm^3/hour.

Site A		Site B		Site C		Site D		Site E		Site F	
Time of Stoppage	Rate of Decrease	Time of Stoppage	Rate of Decrease	Time of Stoppage	Rate of Decrease	Time of Stoppage	Rate of Decrease	Time of Stoppage	Rate of Decrease	Time of Stoppage	Rate of Decrease
00:31	-0.019	00:29	-0.021	00:38	-0.003	00:40	-0.022	00:43	-0.029	01:20	-0.113
00:53	-0.028	01:12	-0.008			00:50	-0.012	00:28	-0.021	01:45	-0.083
00:29	-0.025	00:38	-0.024			00:30	-0.040	00:48	-0.025		
00:59	-0.020	00:46	-0.007			00:30	-0.030				
00:40	-0.022	01:48	-0.014			00:40	-0.023				
00:39	-0.015	00:28	-0.011								
00:30	-0.010	00:47	-0.006								
00:26	-0.023	01:25	-0.007								
00:33	-0.027										
Average	-0.021		-0.012		-0.003		-0.025		-0.025		-0.098

Figure D1: A Comparison of slurry density reduction rates between the various pipe jacking sites

(Site F has not been plotted due to its high density rates and compressing the scale)



Appendix G: Construction Site Data

Site data for D, F and G was not collected during site visits

	Site A	Site B	Site C	Site E
Pipe				
Tunnel Length	170m	56m	128m	97m
Length of pipe	2.5m	2m	2.5m	2.5m
Dia. of pipe (ID)	1200mm	600mm	1200mm	1200mm
Depth of pipe	11m		8.86m	13m
material of pipe	concrete	vitrified clay	Concrete (Buchane pipes)	Concrete
Driving length (working rate)	15-17.5m per shift (0730-1830	≈8m/day (12hr)	10m per day with jetting, 5m without	10-15m (10hrs)
Shaft				
Size	6m ID	3.72m ID	5.2m ID	7.5m ID
Shape	circular	Circle	circular	circular
Depth	12	≈4m	8.86m	13m to base
Number of Shaft	2	2	2	2
Soil				
Type of soil	shelly beds, Lambeth group	Made Ground- sand, flint gravel, clay, silt, nails, wood, (everything)	Clay, possibly Lambeth but looked like London clay	clay with sand and silt. Occasion Gravel/cobble fragment
Particle size	silty, clay, with beds of shells	All sizes up to large cobbles/small boulders	silty, sandy clay	silty, sandy clay
Water content				
Water level	some water, but not free flowing, due to being clay. Water in the river terrace above	below pipe		below the water table
Ground condition				

Machines				
Type of machine	Iseki uncle mole	Iseki Uncle mole	Herrenknecht AVN 1200	Iseki uncle mole 1200
Monitoring system	laser and video camera	laser and camera	Laser and Target	video camera and target
Slurry type	water	Bentonite (300kg/90m^3)	water	Water
Type of soil separation	clay baller, Derrick shaker, 6x hydroclones, centrifuge	clayballer, 10x 4" hydrocyclones, 1x Brandt centrifuge	clayballer with fan, 24" cyclone + 6" cyclone and shaker screen, small centrifuge	Brandt Clay baller, Brandt vibrating screen with 6x 6" hydrocyclones and a Brandt Centrifuge
Flocculant	TK50 liquid (0.5%)	EZ Mud Gold powder (500ml/1m^3)(0.05 %)	SNF VP1 flocculant (auto dose with no %)	TK50 liquid (0.5%) (≈1m^3/pipe)
Lubrication Additives				
Type of Add.	TK50 and sloop		SNF VL1	
Quantity of Add.	5L and 4L per 1000L			
Adding time	200L per pipe			

Appendix H: Kaolin Data Sheet

Polwhite™ E

Polwhite E is a high quality medium particle size kaolin produced from deposits in the South West of England.

IMERYS PERFORMANCE & FILTRATION MINERALS
Par Moor Centre,
Par Moor Road, Par
Cornwall, PL24 2SQ - UK
Tel: +44 1726 818000
Fax: +44 1726 811200

SPECIFICATION

Brightness	(ISO R457)	78.5 ± 1.5
+ 300 mesh	(mass % max.)	0.05
+ 10 µm	(mass % max.)	35
- 2 µm	(mass % min.)	25
Moisture	(mass % max.)	1.5

TYPICAL VALUES

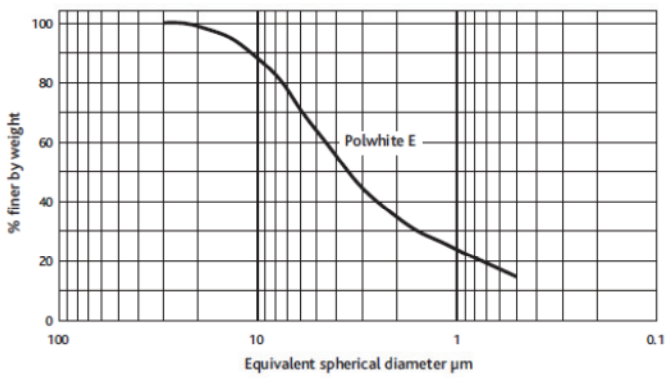
Yellowness		7
Specific gravity		2.6
pH		5.0
Surface area	(BET; m²/g)	8
Oil absorption	(g/100g)	33
Water soluble salt content	(mass %)	0.15
Aerated powder density	(kg/m³)	360
Tapped powder density	(kg/m³)	810
Chemical analysis by X-ray fluorescence		
SiO_2	(mass %)	50
Al_2O_3	(mass %)	35

CAS No. 1332-58-7

ISO 9001
FM 14752

Kaolin does not appear in **EINECS** as an individual entry but is classified as "naturally Occurring Substance" with the **EINECS No.** 310-127-6.

TYPICAL PARTICLE SIZE DISTRIBUTION



The data quoted are determined by the use of IMERYS Minerals Ltd Standard Test Methods, copies of which will be supplied on request. Every precaution is taken to ensure the products conform to our published data, but since the products are based on naturally occurring raw materials, we reserve the right to change these data should it become necessary. Sales are in accordance with our 'Conditions of Sale', copies of which will be supplied on request.

IMERYS Performance Minerals

DAT020K
March 2008 - Sixth Edition.
This data sheet supersedes the data sheet dated March 2004.

Appendix I: Centrifuge Test Procedure

1 Introduction

In the United Kingdom centrifuges are predominantly used to separate the fine particles of tunnel spoil from the slurry on pipe jacking contracts. This is the final stage of separation and is used in conjunction with a flocculant. The optimum working conditions for a centrifuge are not currently known in the pipe jacking industry and are very much an educated guess based on experience, depending on the ground conditions.

This working practice has resulted in a need for trials to be undertaken to find the optimum working conditions thus establishing the most efficient use of centrifuges and ensuring that the separation process is optimal. This will lead to the most economical way of working for both the contractor and client. Similar tests to the ones explained within this document have already been carried out in waste water, mining and quarrying industries. The available space on site and the variation in ground conditions which could be encountered over the course of a tunnel drive means that the knowledge from these other industries may not be applied to pipe jacking and tunnelling projects.

This programme of work has been possible because Manvers Engineering have made available a small 26litre Baioni decanting centrifuge. This would be used for pilot testing, to establish the parameters that most affect the performance of the centrifuge along with site centrifuges once the procedure has been perfected and with the contractor's cooperation. With out this centrifuge it would be extremely difficult to carry out the testing needed on a live pipe jacking site. It would also be a risk that if anything did go wrong the blame would be placed on the researcher.

Various options are available for the location and slurry used in the test procedure. The first would be to mix an artificial from kaolin or bentonite and the pilot tests carried out at Manvers plant yard or a non-pipe jacking location. This would allow testing to be undertaken in controlled conditions and would allow for repeatability. This would enable the characteristics of the soil separation process to be identified thus establishing the most critical parameters. There are three disadvantages to set-up. The first is the need to dispose of the slurry; the second is the cost of purchasing kaolin; the third is the failure to replicate realistic slurries which change during the pipe jacking process due to the variation in soil composition and increase in density. The other option would be to run the centrifuge offline on an active pipe jacking site to allow the use of slurry from the running slurry system. The disadvantages of this are the cost of transport, the possible problems and inconvenience to the contractor and the inability to repeat tests with the same parameters of slurry.

2 Aim

The aim of this project is to gain a greater understanding of how fine particles are separated from tunnelling slurries by using a combination of flocculants and centrifuges and the variations that can affect the efficiency. The aim is to gain some specific parameters for the contractors to work too and use the centrifuge efficiently.

The areas that testing will focus on are:

- Throughput efficiency curves
- Flocculant efficiency curves
- Best flocculant for different conditions
- Optimum position for flocculant input

The ability to run the centrifuge offline allows us to create the optimum throughput of the centrifuge. The throughput of slurry to the centrifuge is increased and the moisture content of the solid discharge (cake) is measured. This produces a set of graphs showing the characteristics of the centrifuge.

The flocculant curves are to show what the optimum concentration of flocculant dosage is. This is shown as a percentage of neat flocculant to water, currently this is running at around 0.5% for a 50% active suspended flocculant but there is a variation between contractors. This can also be developed to give guidance of the differences between powder and suspended flocculants.

At present the optimum position for flocculant injection into the slurry is not known. Currently this is injected directly before the slurry enters the centrifuge. Laboratory tests suggest, in some cases, there has to be a period of misting before the slurry enters the centrifuge. Therefore the position of injection should be varied and measurements taken of the flocculant dosage and solid discharge water content. The use of a turbulence inducer like a statimeter would also like to be tested.

The findings from the planned experiments will be directly fed into the planned "Guide to Best Practice for Slurry Pipe Jacking and Microtunnelling". The aim is that with an increased understanding by contractors on the science behind separation the industry will improve to a higher standard.

3 Method

3.1 Site Set-up, Equipment and Generic Test Procedure

The test procedure will be the same independent of the composition of slurry used. The only differences will be in the mixing/preparing of the slurry. If mixed slurry is created from kaolin then a colloidal mixer will be used to mix the slurry to a density of 1.06g/cm^3. When testing using a contractor's slurry from a runny pipe jack, the slurry will be decanted into an agitated tank prior to testing. This allows for a fixed density slurry to be used.

The on site set-up would consist of:

- 26litre centrifuge with flocculant mixing and dosing pack
- 1x agitated storage tank
- 1x tank for centrate storage
- 1x pump for slurry transfer from main tank
- 1x pump to supply centrifuge with slurry

- 1x skip for spoil
- 1x data logger

Once the quantity required has been pumped across the density, sand content, PH and viscosity of the slurry should be tested and the ground conditions that the TBM was tunnelling through logged. This is the basis of all tests that should be carried out.

Once this has been completed testing can begin. This will involve running the centrifuge to clean the allocated slurry on the tests that are described below. The solid discharge (cake) will be collected in a skip and then sent away from site with the contractors spoil. The centrate may need to be collected in a further tank for testing by the contractor. This will be discharged in an approved manner, either back into the main slurry system or down a foul water sewer. The reason for not discharging straight into the contractors system is to avoid any impact on the contractor's processes, because of potential contamination of the centrate. The centrate shouldn't be over flocculated, but precautionary measures are needed.

3.2 Throughput Curves

The first goal is to create the throughput versus moisture content curves. The through put curves will be created by keeping all variables constant except for the slurry feed. The moisture content of the arisings will be tested using BS 1377:1990 "Moisture content, Oven method." This allows for lots of samples to be tested at once. The microwave method ASTM 4643 may also be used in certain instances for its speed, this would possibly be when testing the optimum position of flocculant injection and flocculant concentration. Issues may arise if the ground contains high quantities of montmorillonite, this may stay hydrated due to its swelling nature.

The throughput speed of the centrifuge will be increased at set increments from the minimum operating speed up to the maximum. Work will need to be carried out prior to testing to identify a practical increment to increase the throughput at and what are the safe operating limits of the centrifuge, to avoid damage. For every increment increase the centrifuge should be given time to equalise before a sample is taken. This should be about one minute. A 200gram sample of the centrifuge arisings should be taken and placed into a sealed bag and labelled for testing at a later point.

Off site these samples can be tested using BS 1377:1990 as mentioned above. Three 50gram samples at each increment will be taken and placed in an oven at 110°c (±5°c) for 24hours. The samples can then be re-weighed and the moisture content calculated using the formula below. The results will be plotted onto a graph against the through put.

$$w = \frac{M_{cws} - M_{cs}}{M_{cs} - M_{c}} \times 100 = \frac{M_{w}}{M_{s}} \times 100$$

W= water content (%)
M_{cws}=mass of container and wet specimen (g)
M_{cs}= mass of container and oven dried specimen (g)
M_{c}=mass of container (g)
M_{w}=mass of water (g)
M_{s}=mass of solid particles (g)
(ASTM, 1991)

3.3 Flocculant Concentration

The second test will involve running the centrifuge with various concentrations of flocculant. This will use both powder and suspended flocculants. The test procedure will involve running the centrifuge at the optimum throughput found in the previous tests and dosed with the mixed and aged flocculant. The dosing speed will be varied to gain a clean centrate, with no excess flocculant. The flow rate of both the slurry and flocculant will be taken and a 200gram sample of the solid discharge (cake) placed in a sealed bag. The range of concentrations to be tested is between 0.2-0.8percent with a step of 0.05% (for suspended polymer). A 50% active suspended polymer has only half the activity of the same weight of powder polymer. This requires scaling to be carried out. Care needs to be taken too empty the mixing tank and it washed out prior to mixing the next batch. The flocculant must be allowed to age, 20minutes for a suspended polymer and 60min for a powder. This time should be kept too strictly because if the flocculant is not aged sufficiently then it will hinder its performance and if left longer could possibly give an advantage to that set of results.

The next step is to calculate the actual flocculant concentration per unit of slurry. This is calculated by dividing the flocculant concentration by the ratio of slurry to flocculant dosage. This can then be plotted onto a graph of mixed concentration against dosed concentration. The moisture contents will also be tested by either BS 1377:1990 or ASTM 4643 and calculated as described previously. This can also be plotted on the same graph with a secondary Y axis.

3.4 Optimum Flocculant

From the above work an analysis of powder and emulsion flocculants can be carried out. This will look at moisture contents of the cake at optimum dosages, concentrations and cost. When making a final conclusion ease of mixing, time for ageing and cost of mixing/dosing plant should also be considered. This is because a powder flocculant has to be wetted slowly during mixing and requires a longer ageing period than a suspended polymer.

3.5 Optimum Position for Flocculant Dosage

As previously mentioned the flocculant is currently dosed at the entrance to the centrifuge and on some sites a statimeter is also used. For this test the position that the flocculant is dosed will be varied. The positions that will be tested will be developed as the test progresses.

Again this will follow on from the previous findings and be a further development. The centrifuge will be run at the optimum throughput speed and the optimum concentration of flocculant. The first stage of testing will involve positioning the flocculant input at the neck of the centrifuge, mid way down the pipe and also on the centrifuge side of the slurry pump that draws the slurry from the tank. This will be carried out with and with out a statimeter mixer. The dosage will be varied at all of these points to produce a clean centrate, with no traces of flocculant. For this test the flocculant dosage should be noted down along with the data from point 2.1. A sample of the centrifuge solids should also be taken and a moisture content test carried out. For this test if a microwave is available on site, it maybe appropriate to calculate the moisture content using ASTM 4643. If calculated in this way, an extra sample should be taken and the test validated using BS 1377:1990.

As with the previous test the position with the lowest dosage rate, (as long as the moisture content is not too great) would be the optimum position for the initial tests. The position of dosing can then be refined to get the actual optimum position. The results can then be plotted onto a graph showing position against moisture content on one axis and dose rate on another.

3.6 Limitations

There are several limitations with these test procedures, which are hoped not to hinder the workings. The first limitation could be finding a site to carry out the testing. The site will need to be large enough to allow for the extra plant without disrupting the contractors activities. The site also brings other considerations and limitations in terms of an adequate water supply to allow for the contractors tank to be maintained at a working level thus replacing the slurry extracted for the pilot centrifuge tests. There also needs to be the provision for disposing of the centrate if the contractor will not allow it to be pumped back into their main tank. Another limitation would be the ground type that the pipe is being tunnelled through. There is a requirement for the slurry to be kept at around 1.05-1.07 for testing. A granular ground would not be appropriate because it is unlikely to produce enough fine particles quickly enough and there would be the possibility that the contractor would be adding bentonite or a polymer/gum to the slurry.

Another main limitation is the range of soils that the tests could be carried out on. This again could be due to the lack of multiple sites that fit the above parameters and the cost of transportation. This is also a large limitation because each plant movement will add to the cost of the testing. The hiring of equipment will also add to the cost.

The plant itself could also be a large limitation because the testing relies on Manvers Engineering's good will by hiring the centrifuge at a nominal cost. If they received a hire order for the centrifuge then it would be more commercially viable for them to hire it out to a paying client.

A major limitation is the exact scaling and applicability to other centrifuges. This is because every contractor uses a different centrifuge. A further development could be to carry out some of these tests on other centrifuges for contractors.

Time is also a constraint on the test procedure. There is currently 11 months left on the research project and all the results need to be written up within this time. Also as mentioned above the centrifuge would be on a loan for the purpose of the research and would not be earning the Manvers Engineering a direct income.

Although slurry from an existing contract would allow the testing to be carried out with real ground conditions and avoid the need for mixing, other problems do arise. There is a possibility that the main contractor has over flocculated the slurry. This may require the contractors operations be monitored closely from the start or just taken as a possibility and deemed to be acceptable because the slurry is a constant. Contamination in the ground could also have an effect of the experiments. Cost dependant, an extra test could be carried out by testing the slurry for contaminants if deemed possible. This could possibly also pick up any surplus flocculant, if test were carried out.

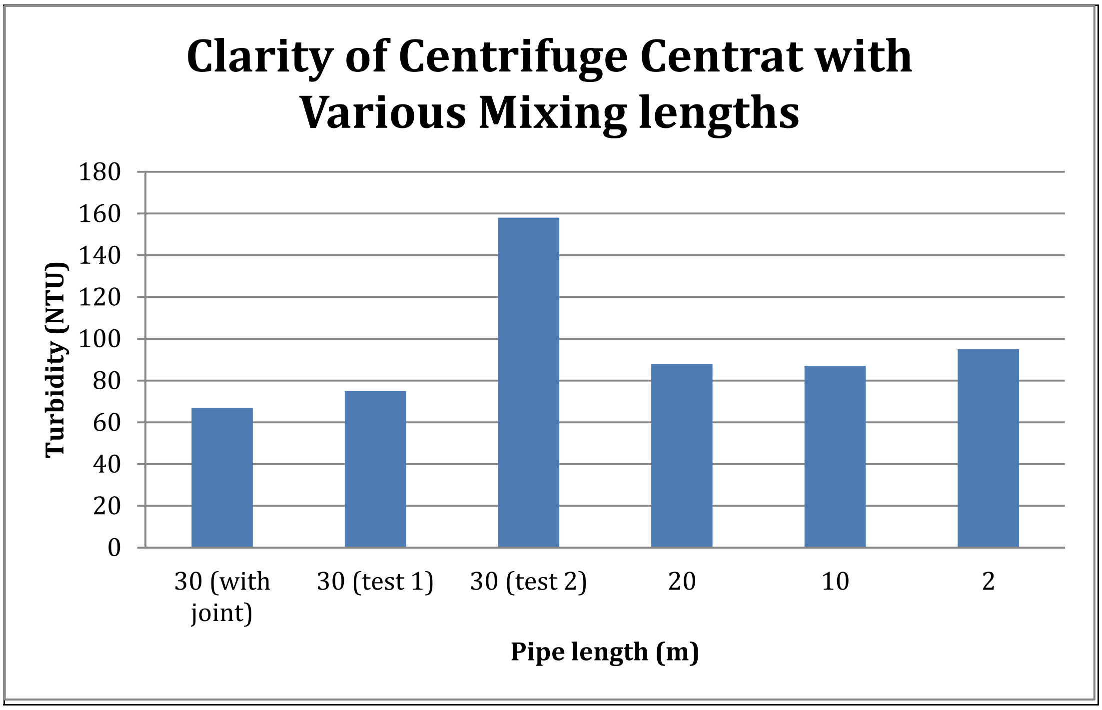
4 Summary

The above test procedure has been produced as accurately as possible. These tests have not been carried out before on a pipe jacking construction site. This will almost definitely require refining whilst on site. These amendments to the procedure will be noted down and stated in the final report.

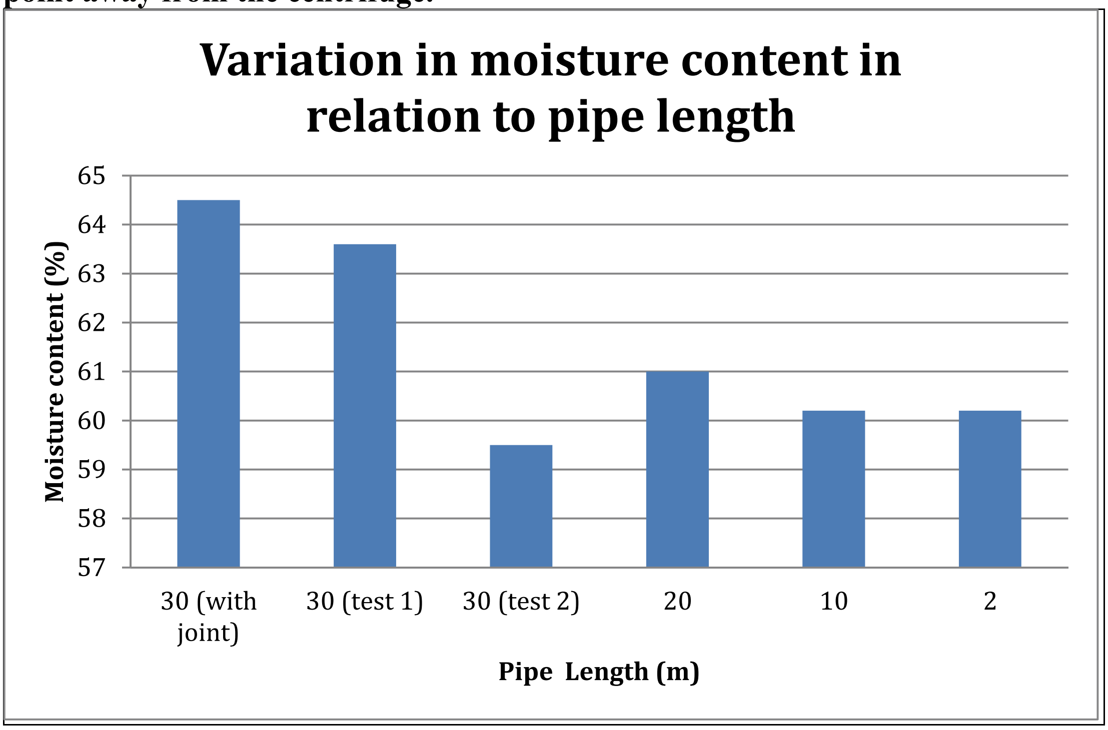
References

ASTM,1991, *Annual Book of ASTM Standards, Section 4- Soil and Rock; Dimension Stone: Geosynthetics,*

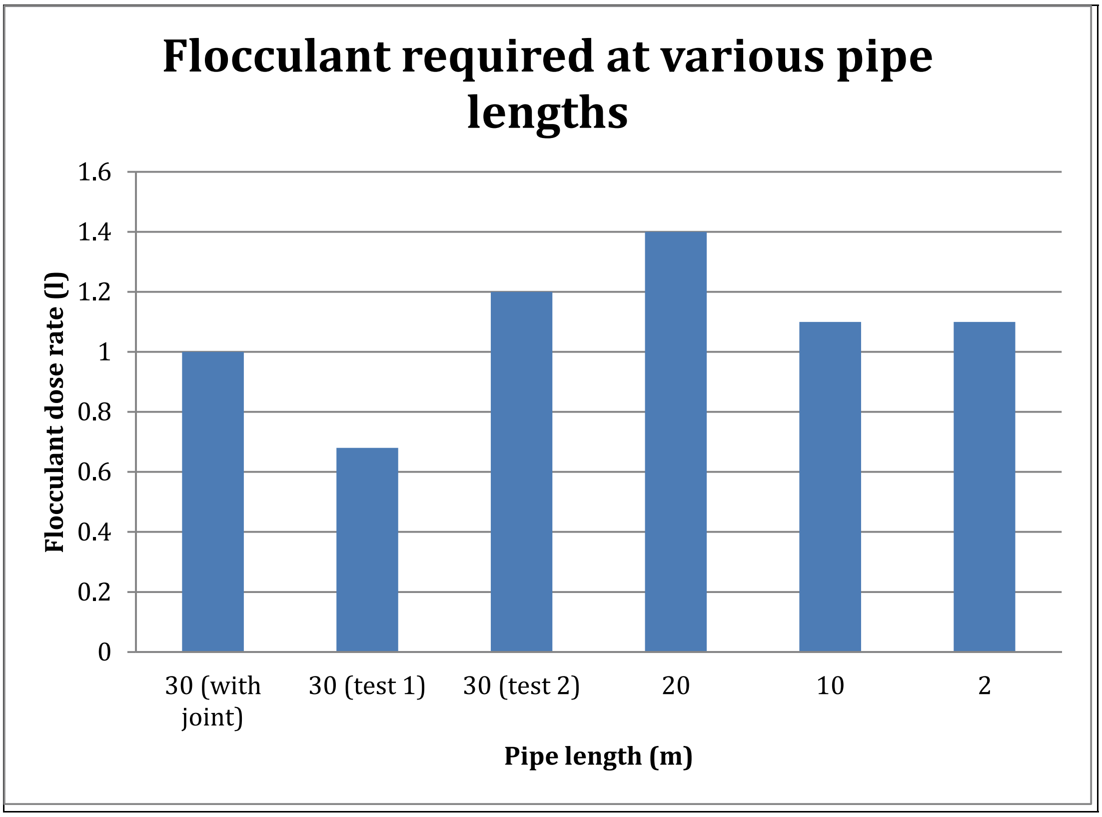
Appendix J: Position of flocculant dosing



The change in centrate clarity due to the change in distance of flocculant dose point away from the centrifuge.

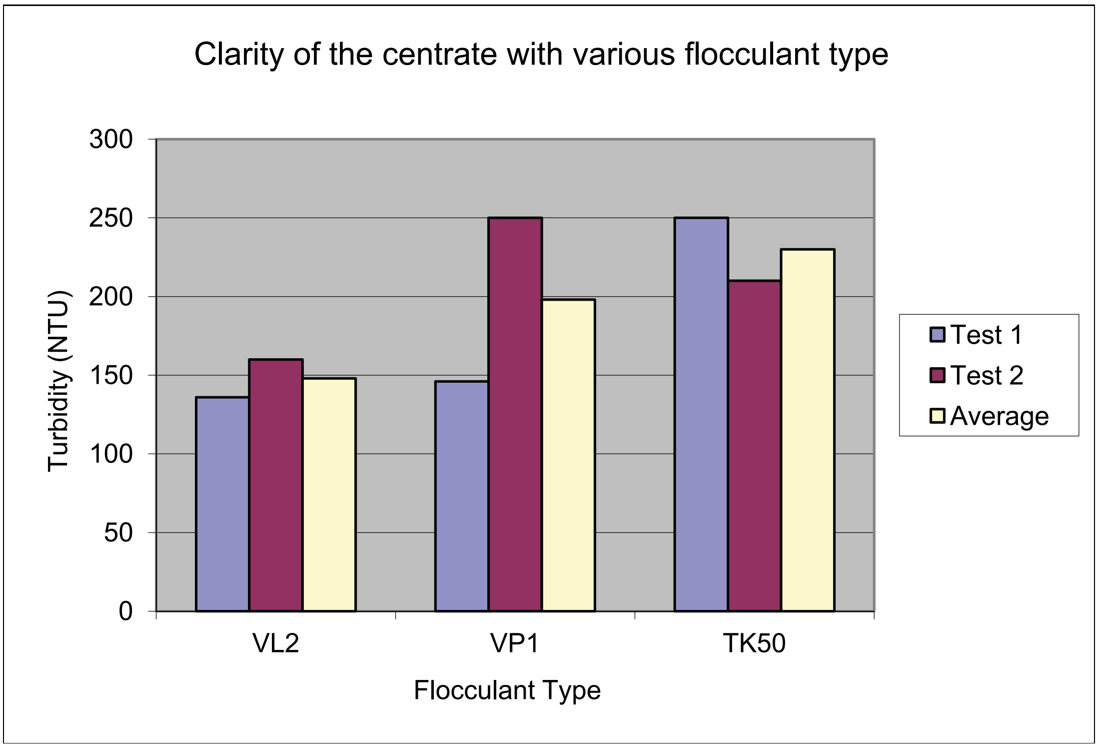


The change in the moisture content of the cake due to the change in distance of flocculant dose point away from the centrifuge.

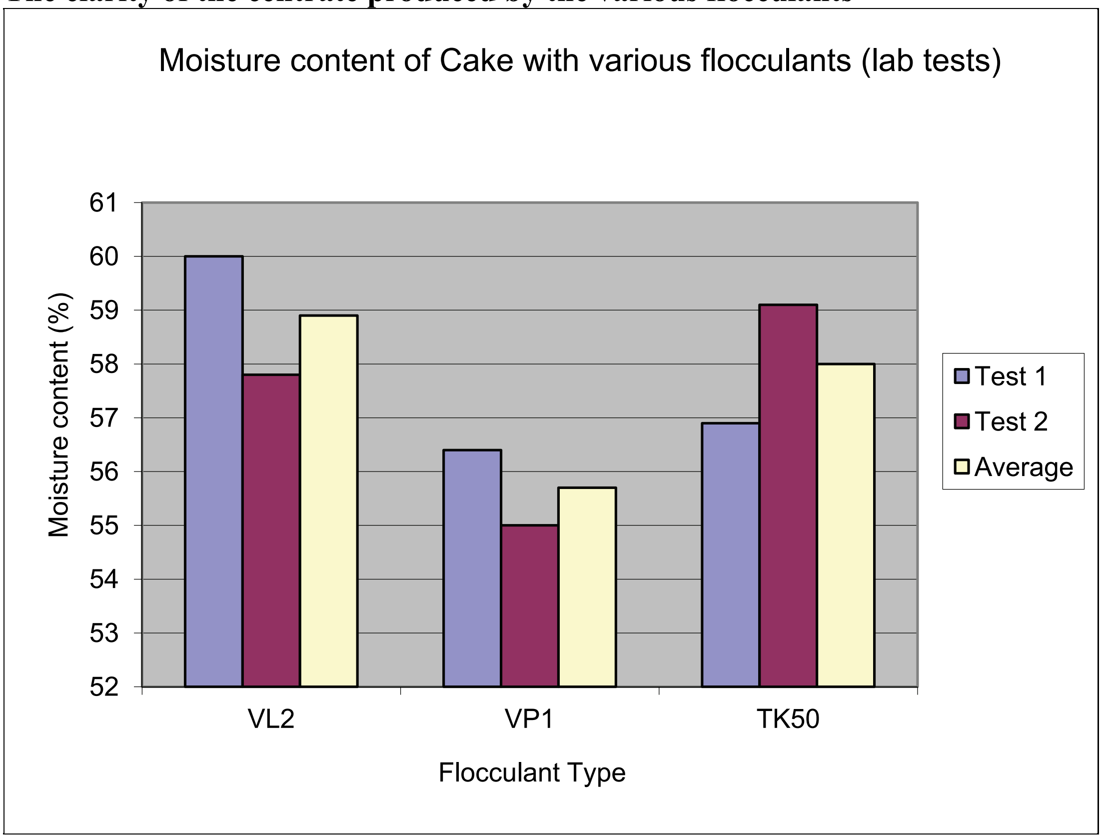


The require dose rate to clean the centrate at different pipe lengths

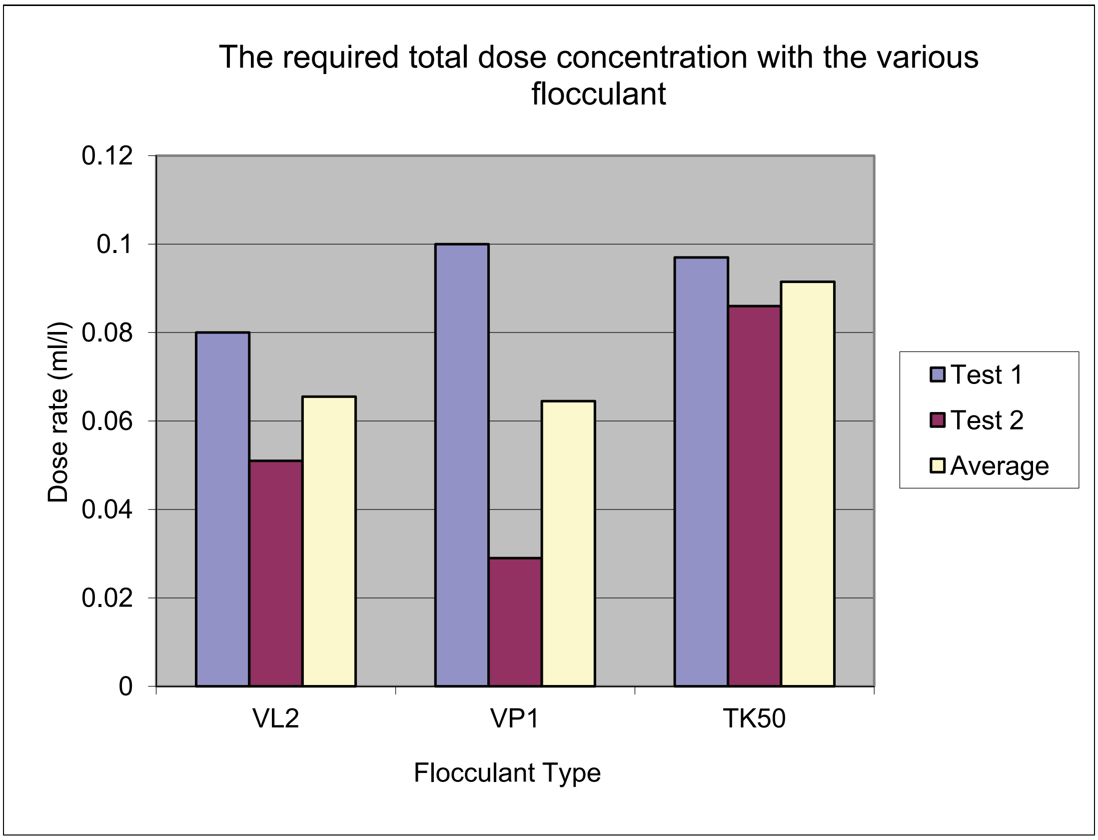
Appendix K: Flocculant Type



The clarity of the centrate produced by the various flocculants



The moisture content of the cake due to the change in flocculant type



The required flocculant concentration to slurry for a clean centrate

Appendix L: Slurry pH

Test	pH
Throughput Test 1	7.8
Throughput Test 2	8.1
Throughput Test 3	8.1
Throughput Test 4	7.7
Throughput Test 5	7.7
Throughput Test 6	No data
Throughput Test 7	No data
Throughput Test 8	No data
Flocculant concentration Test 1	7.7
Flocculant concentration Test 2	7.7
Flocculant Dose Rate	No data
Flocculant Dose point	8.1
Flocculant Type Test 1	7.7
Flocculant Type Test 2	8.1

Variation in slurry pH during testing