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Construction and Stability Risks of Fluid Supported Deep Excavations and Their Effects On Design Parameters

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CONSTRUCTION AND STABILITY RISKS OF FLUID SUPPORTED DEEP EXCAVATIONS AND THEIR EFFECTS ON DESIGN PARAMETERS

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ABSTRACT

The construction of diaphragm walls and most large-diameter bored piles (piers) is often carried out under drilling support fluids to temporarily stabilise the excavation prior to concrete placement. In most cases such fluids are either mineral-based slurries (bentonite) or polymer support fluids. The working mechanisms of these two fluid types are fundamentally different. Designers need to consider possible fluid-related impacts on the permanent design performance of the project-specific deep foundations as well as for the temporary excavation stage during construction. Robust design methods for bentonite slurry-supported excavations have been developed in the last few decades and the working principles and associated risks of such mineral-based slurries are understood reasonably well. However, such methods have not been developed in detail for polymer-based drilling fluids.

This document provides a brief overview of the main characteristics of bentonite- and polymer-based drilling fluids as a guide for construction practitioners and design engineers alike. The paper also highlights some common construction risks related to casing installation and the selection of suitable fluid systems for different ground conditions. Typical defects caused by the incorrect application of drilling support fluids, and their pro-active mitigation, are discussed, too. In addition, the basic concepts of stability calculations for bentonite fluid-supported deep excavations are briefly introduced and their applicability for other fluid types such as polymer-based support fluids or water are reviewed.

Keywords: bored piles, diaphragm walls, bentonite fluid, polymer fluid, concrete defects, pile design, trench stability, surface filtration, deep filtration

INTRODUCTION

Piling and other deep foundation methods require the excavation of shafts and trenches to construct large-diameter bored piles up to 3,000 mm (9.8 ft) in diameter (or larger) with depths up to 100 m (330 ft) and more, as well as diaphragm walls of up to 1,500-mm (4.92 ft) thickness and design depths of more than 50 m or 165 ft (Jefferis and Lam 2013). Sometimes, excavations for deep foundations need to be carried out in challenging and potentially unstable ground conditions like loose to dense sands above and below the groundwater table, in soft marine clays, cobbles, gravels, silt, water-sensitive shales and clays or agglomerates. In such challenging environments the deep excavation needs to be supported by temporary or permanent steel casings, in most cases in combination with drilling support fluids, or by internal support without steel casings and fluids by the use of continuous flight auger (CFA) piles.

Over recent decades, piling equipment, excavation techniques and associated technologies like concrete or drilling fluid systems have developed rapidly. Modern drilling fluids need to perform in the most challenging ground and climate conditions all around the globe. They must be able to maintain their specific properties when being circulated through a hydro-cutter, excavating a diaphragm wall, as well as in systems such as the traditional bored piling applications with drilling buckets or augers. If selected and applied, drilling fluids must stabilise any soil conditions or formations encountered during excavation, regardless of the type of equipment being used or the shape and size of the excavation. The pH values, viscosity, density and sand content of the fluid must be assessed and monitored stringently to ensure the specified characteristics are met and the excavations are always kept in a stable condition.

When assessing the temporary stability of a fluid supported trench or pile excavation, groundwater pressure must be added to the destabilising earth pressure to obtain the total destabilising pressure. Groundwater fluctuations (e.g. tidal influences) must be considered for stability assessment of deep excavations where applicable.

METHODS TO SUPPORT OPEN EXCAVATIONS FOR DEEP FOUNDATIONS

Various methods can be used to form a stable borehole or trench. The use of drilling support fluids is just one of several options, and fluid support is particularly effective for deep and/or large diameter bored piles. However, temporary steel liners (or casings) are typically used to support the top section of a piled excavation. Bored piles should not be constructed without top steel liners as such liners provide a safety barricade at the surface, reducing the risk of people or objects falling into the open excavation. Temporary steel liners (which are removed after concrete placement) are typically used in combination with drilling support fluids like water, bentonite or polymer fluids. Permanent steel liners are normally used for excavations over water, where required by various authorities, in unstable dry excavations or in combination with water for rock socket drilling and subsequent cleaning.

Guide walls made of reinforced concrete provide the required near surface stability and support for the excavation of trenches or piled walls (e.g. secant or contiguous piled walls) installed under drilling support fluids. Fluid-supported excavations for piles or diaphragm walls should never be used without liners (piles) or guide walls (diaphragm walls and piled walls).

Conventional rotary piling methods using telescopic Kelly bars form an open excavation that needs to be supported by steel casings and/or support fluids. Fluid-supported deep excavation for piles of more than 100 m (330 ft) depth and pile diameters of 3.0 m (9.8 ft) have been achieved (Beckhaus et al. 2020).

CFA augers are directly attached to the drill head of the piling rig and they are not telescopic. Their maximal drilling depth is currently limited to about 40-50 m (130-165 ft), depending on rig and auger sizes (Larisch 2018). CFA auger diameters are currently limited to 1.5 m (4.92 ft). CFA augers have a hollow stem for concrete placement. Their most important distinction in relation to conventional bored piles is that they do not create an open excavation that needs to be externally stabilised. The soil inside the auger flights acts like an internal support system for the borehole walls and keeps the excavation stable during drilling and concrete placement. During auger extraction, fluid concrete is pumped through the hollow CFA auger stem and fills the void to provide internal support to the pile shaft below the bottom of the auger. The reinforcement cage is plunged into the fresh concrete after concrete placement.

CONTINUOUS FLIGHT AUGER PILING

Continuous flight auger (CFA) piles were first used in the United States of America (USA) in the early 1940s (Gupte 1989). Fleming (1995) reports the implementation of CFA piles in Europe about 40 years later. The CFA auger consists of a hollow stem auger with regularly pitched auger flights and with a constant outer diameter. The tip of the auger is sealed with a temporary end cap to prevent soil or water ingress into the hollow stem of the auger during installation. Typical auger diameters range between 400–1,500 mm (1.31-4.92 ft) with drilling depths of up to 40-50 m (130-165 ft) (Larisch 2018).
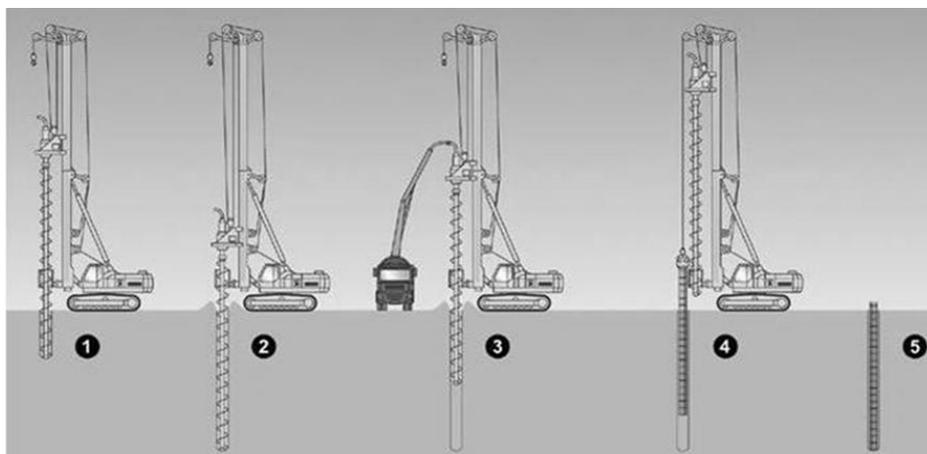

Fig. 1. Installation sequence of continuous flight auger (CFA) piles after Brueckner nd

The process of CFA piling is shown in Fig. 1 (after Brueckner nd), where the CFA (with a sealed auger tip) is rotated through the soil formation, continuing in the same direction throughout the whole auger penetration. Soil is cut at the tip and is transported upwards (inside the flights) to the surface, while the auger (filled with soil) maintains the integrity of the borehole and prevents it from collapsing. The auger penetration rate must be carefully selected to ensure that the volume of soil being transported by the rotating auger flights is minimised and corresponds to not significantly more than the volume of the central stem of the auger. This is critical, to avoid soil decompression in granular soils, which can occur when auger penetration is too slow (Thorburn et al. 1993).

Based on research on CFA piles in Italy, Viggiani (1993) developed a theoretical model to assess the minimum penetration rate at which a CFA auger must be advanced without loosening the surrounding soil and jeopardising the stability of the excavation and the soil surrounding the pile:

$$V_{a(min)} \geq nl \left(1 - (d_0^2/d^2)\right) \qquad [1]$$

Where $V_{a(min)}$ = minimum penetration rate (m/min), n = rate of rotation of the drill tool (rev/min), l = auger pitch (m), d = outer auger diameter (m) and d_0 = auger stem diameter (m).

The penetration rate strongly depends on the auger shape, geometry, the available pull-down force and rotational torque applied by the piling rig. However, in the author's professional experience, penetration rates above 50% of the pitch height per auger rotation typically do not generally cause stability problems. However, a project-specific assessment is necessary to verify this 'rule of thumb' assessment, and Eq. 1 should be used to make such an evaluation.

Larger-diameter CFAs increase the risk of side loading as the external rig forces (e.g. pull-down force and rotational torque) required to maintain the minimum penetration rate, must increase to ensure constant penetration rates. The choice of a suitable piling rig with adequate pull-down force (thrust) and torque capacity is vital for the installation of CFA piles to maintain a stable internal excavation support.

CONVENTIONAL BORED PILES WITH PERMANENT STEEL LINERS (OR CASINGS)

The use of steel liners (or casings, both terms are used to define the same item) is very common to externally stabilise open boreholes for bored piles/piers. However, steel liners are unsuitable to support trenches or barrettes. Steel liners can also serve as permanent liners or temporary excavation support, with the latter being removed after concrete placement (Fig. 2).
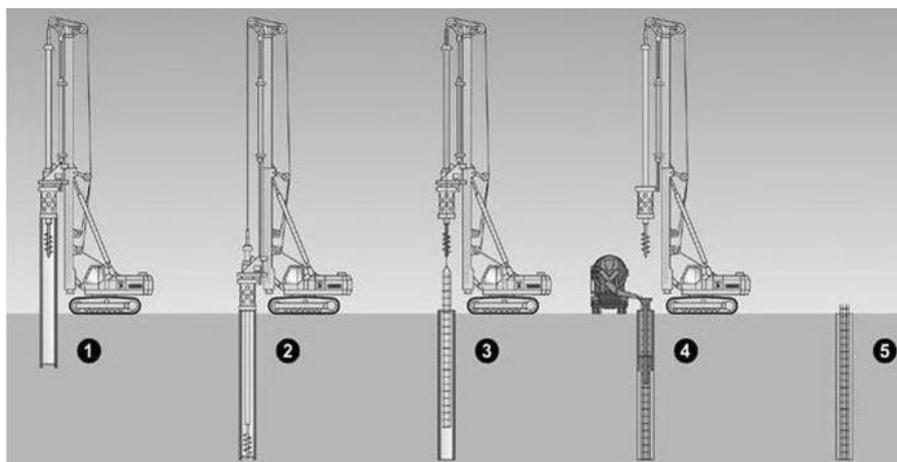

Fig. 2. Installation sequence of rotary bored piles using permanent steel liners after Brueckner

The design of steel liners for temporary excavation support requires the assessment of the buckling resistance in relation to the combined earth and water pressure acting from the outside of the liner.

The buckling resistance of the steel liner can generally be assessed using Timoshenko's method (1940):

$$q_r = 3EI / R^3 \qquad [2]$$

Where q_r = buckling resistance [kPa], E = modulus of elasticity [kN/m²], I = moment of inertia [m⁴] and R = casing radius [m].

This approach is rather unsophisticated as it does not consider potential casing deformations occurring during installation through driving, vibrating or rotating the liner into the ground. It is recommended to apply a reduction factor of at least 2.0 to allow for any impacts from casing installation, which is usually the governing load factor for the selection of the wall thickness. In addition, a pile drivability analysis using wave equation theory is strongly recommended to assess the required material strength and dimensions of the liner to ensure that overstressing of the steel will not occur during installation.

Buckling loads caused by water pressure in marine environments or when installing liners through thick layers of soft soils or after soil liquefaction in seismic regions should also be taken into consideration.

DEEP EXCAVATIONS INSTALLED UNDER DRILLING SUPPORT FLUIDS

The use of short temporary steel liners to support and stabilise the top section of the excavation is necessary for the installation of conventional rotary bored piles (Fig. 3) constructed under support fluids.
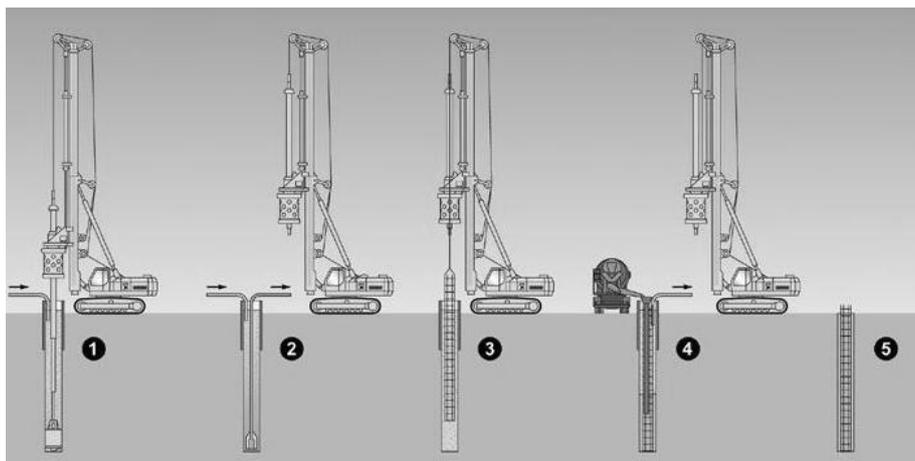

Fig. 3. Installation sequence of rotary bored piles using drilling support fluids after Brueckner

The application of drilling support fluids to stabilise temporary boreholes or trenches is generally based on the requirement to have a positive fluid pressure head inside the temporary excavation over the full depth, which must always be higher than the combined earth and water pressure outside the excavation. This is typically guaranteed if the fluid level inside the excavation is maintained at around 1–2 m above the groundwater level outside the excavation. The removal of the drilling tool from the excavation might cause a drop of up to 1 m in fluid levels inside the hole (or trench) and such fluctuations must be considered in any stability assessment. The potential lack of positive pressure head inside the excavation can result in minor to severe collapses of the borehole or trench walls, which may to result in an unstable working platform and a potential partial collapse of the pile excavation with all associated consequences.

To understand the general working mechanism of different drilling fluids and their interaction with different soil types, the next sections briefly discuss the working principles of the three most common drilling fluid systems and their performance and risk profiles in different ground conditions.

All soil particles have negative and positive charges on their surface, but most soil surfaces have a predominant negative charge (Majano and O'Neill 1993). The positive (or cationic) charge is typically

found at freshly excavated or exposed surfaces. The negative (or anionic) charge is generally found on surface areas with longer exposure to water, drilling fluids or air. The overall charge density and orientation of most soil surfaces along the walls of bored pile or diaphragm wall excavations is most likely positive right after the excavation process but turns to be negative after a short exposure to air or water.

WATER

The oldest and least sophisticated drilling fluid for the construction of conventional bored piles is water. Water has been used successfully as a drilling fluid in countless piling applications all over the world for many decades. Water works very well to clean smear and debris from the surface of rock sockets. In combination with purpose-built cleaning tools (e.g. brushes attached to cleaning buckets), water is the most suitable fluid to achieve clean side walls in rock sockets, which is critical for optimal load transfer.

In permeable and porous ground conditions fluid loss cannot be controlled when using water alone, and this can result resulting in pore water pressure redistribution. This increases the risk of partial hole collapse and significant problems for the deep excavation and safety of site crews. In such conditions, the use of bentonite drilling fluids has been found to be superior to water.

Unfortunately, water alone also has some significant shortcomings as a drilling fluid in (sensitive) clay or shale formations, fissured clays and non-cohesive soils below the water table. In cohesive soils water initiates clay hydration, which typically results in swelling and softening of the interface material, causing potential reductions of shaft capacities or even partial or complete hole collapses. Once the water molecules have entered the lattice structure of the clay particles, the internal bond between the layers of the clay matrix are weakened or disrupted as the ions that provide the bond between the layers of clay begin to dissolve and form a solution with the water. As more water molecules enter the clay matrix, they begin to electrochemically repel the lattices from one another, causing 'swelling'.

At this stage the natural cohesive and consolidated state of the soil formation is destroyed and the affected area behaves like a clay with significantly lower cohesion; it may also become mobilised or fluidised. Consequently, sensitive clay (or shale) formations that are exposed to water can exhibit significantly reduced shear strength, which will result in reduced stability and shaft capacity for deep foundation elements constructed in this type of material. It is important to avoid the contact of free water with these formations and to use drilling fluids able to minimise or eliminate clay swelling. Most of the modern polymer-based drilling fluids can provide those protective features to sensitive clays and shales.

The use of water as a drilling fluid is the cheapest option but bears some major risks, especially in granular and cohesive soil conditions. Water levels within the pile shaft need to be managed thoroughly by an experienced piling crew with in-depth knowledge of the site-specific ground conditions, the selected excavation methods and the general environment. Even if the excavation of bored piles under water might be possible, trenches cannot be supported by water. The most proven and hence safest method for the stabilisation of trenches is excavation under bentonite fluids.

BENTONITE (MINERAL-BASED) FLUIDS

The suitability of bentonite as a drilling support fluid was discovered in the early to mid-20th century by oil-drilling companies in the USA and in Europe independently (Lam et al. 2018). Bentonite is known as a swellable hydroscopic clay with unique electrochemical properties, allowing the control of fluid migration into permeable (granular) soil formations. Bentonite platelets can be best described as rectangular, microscopic particles (platelets) carrying a positive electrical charge at one end and a negative charge at the other. Hydration is required for bentonite clay platelets to be fully dispersed into a slurry, which can take up to 24 hours. When fully hydrated, the water-saturated platelets suspended in the gel-like slurry are transported to the soil interface inside the excavation.

In permeable ground conditions, the platelets suspended in the gel-like slurry will initially migrate into the soil as a result of the larger pressure head inside the pile excavation provided the bentonite fluid head is kept 1 m or more above the ground water level. Shortly after starting to penetrate the borehole

wall, the bentonite particles begin to build up at the interface between soil and excavation through filtration. Because of the electromagnetic charge of the clay particles they begin to orient in an organised way, like a chain with positive charged ends connected to negatively charged ends. Within a short time, the bentonite particles form an impermeable (clay) filter cake at the soil-drilling fluid interface, which hinders and eventually stops the flow of the bentonite drilling fluid into the permeable soil formation.

The bentonite filter cake not only stops fluid migration into the permeable soil formation but also helps to equalise the pore water pressure. As a result, the permeable soil will not be 'soaked' by the bentonite drilling fluid but will keep most of its natural characteristics, including its original shear strength. Furthermore, the filter cake allows for the bentonite slurry inside the excavation to apply increased hydrostatic pressure (because of the increased pressure head) to the sidewalls of the excavation, which results in increased stability of the excavation as long as a positive pressure head is achieved.

Even though bentonite slurries work well in permeable soil conditions, they have some disadvantages in impermeable formations like clays, shale or silt where a bentonite filter cake cannot be created because of the absence of initial fluid migration through the soil/excavation interface. Even thick and fully hydrated bentonite slurries contain significant amounts of free water molecules that will react with the interface of water-sensitive fine-grained soil formations, causing them to potentially hydrate, resulting in softening and swelling of the borehole walls (see above). This softening can drastically reduce the shaft resistance of deep foundations and/or even cause partial collapses of the temporary excavation.

The general behaviour of bentonite fluids is well understood, and international guidelines and standards have been developed and implemented globally with great success. (American Association of State Highway and Transportation Officials [AASHTO] 2010; Federation of Piling Specialists [FPS] 2006; Deutsches Institut fuer Normung [DIN] 2013; Institute of Civil Engineers [ICE] 2017; European Federation of Foundation Contractors and Deep Foundation Institute [EFFC–DFI] EFFC–DFI 2019).

The spoil removal and excavation cleaning mechanism in bentonite fluids

In bentonite slurries, the positively charged soil particles are typically suspended in the gel-like drilling fluid (Seavev 2004), either as a result of the excavation process or the loss of spoil during bucket or auger retrieval. During the excavation phase, large quantities of sand and fines can be suspended in the bentonite slurry. Free water locks onto the soil particles and they break down further into even smaller particles. This is the reason why soil particles in bentonite slurries typically stay in suspension and consequently, the bentonite fluid needs to be cleaned by de-sanders or decanters (outside the excavation), circulated and/or be replaced prior to the placement of concrete. For good concrete placement it is required to reduce the proportion of fines in the bentonite fluid to < 2–4 % prior to concrete placement (FPS 2006; AASHTO 2010, ICE 2017, EFFC-DFI 2019).

POLYMER FLUIDS

The limitations of bentonite-based support fluid systems in clay and shale formations stimulated the development of polymer-based slurries that do not cause clay swelling and hence provide a safe alternative for constructing deep excavations in cohesive ground conditions without potentially weakening and/or destabilising the borehole or trench walls. Natural polymers (xanthan, carboxyl methylcellulose or guar gums) were tested for piling applications in the 1980s and 1990s but were found to be too unstable (Jefferis and Lam 2013) with limited ranges of properties and significant weaknesses in fluid loss behaviour. Such natural polymers are generally unsuitable to support excavations for deep foundations.

Long-chain partially hydrolysed polyacrylamide (PHPA) polymers were introduced in the mid-1980s to the construction industry and the piling and deep foundation sector, following their successful use in the oil and gas industry in the USA. PHPA polymers are synthetic polymers characterised by high molecular weight and numerous long chains with negatively charged sections distributed along the entire polymer strand. Additives can be used in combination with some PHPA polymers to enhance the performance of the polymers in certain ground conditions; for example, by reducing fluid loss, blocking voids and sealing the borehole wall, accelerating suspension of solids and treating used fluids to be disposed safely.

PHPA polymers were originally designed to remove suspended fines from water systems like sewage treatment plants. It was discovered that their inclusion (in small quantities) in mineral-based fluid systems was beneficial. The polymers added into the bentonite slurry prevented clays and shales from absorbing water, which would cause swelling and softening of the clay surfaces as described above. Because the PHPA polymer chain has a negative charge, the free water molecules inside the bentonite slurry 'dock' onto the polymer chain rather than migrating into the negatively charged borehole wall.

In cohesive soils, the PHPA polymer system builds a protective barrier at the borehole wall, preventing contact of water with the potentially sensitive clay, which would result in swelling and softening. However, these combined bentonite–polymer slurries require a minimum polymer concentration being maintained in the slurry to allow for the ongoing absorption of free water. Every time a negatively charged polymer molecule locks onto a positively charged soil particle (at the borehole wall or inside the fluid), a water molecule is freed from the polymer chain. Consequently, the concentration of polymer in the bentonite slurry needs to be kept stable throughout the entire excavation and cleaning process to prevent free water from penetrating the clay surface and instead being attracted to the PHPA chains in the slurry.

Once the required concentration of polymer in the combined bentonite-polymer slurry falls below the critical level, the process of soil softening and swelling is likely to accelerate. New soil particles (positively charged) will be suspended in the fluid and a negatively charged polymer strand will 'dock' onto floating particles in the slurry, releasing its water molecule. Consequently, the protective polymer barrier that has built up along the borehole wall will decrease quickly and the released free water will migrate further into the soil formation, resulting in more clay swelling and softening. This will cause more new soil particles to be suspended in the slurry, starting a chain reaction. The suspended clay or shale particles will further break up into smaller parts binding more and more PHPA polymer chains, which will thus not be available to build and maintain the protective barrier at the interface. The slurry system will be quickly converted from a balanced polymer system to an in-situ soil system without a protective barrier at the borehole wall. The risk of excessive softening and swelling of the cohesive soil interface layer will increase exponentially with a potentially negative impact on shaft friction performance of the pile and general excavation stability (Jefferis and Lam 2013). It is recommended to slightly overdose PHPA systems with polymer and to implement strict quality control to ensure the required polymer concentration can be maintained throughout the excavation and concreting process.

Pure PHPA polymer systems (without being added to bentonite slurries or without added additives) can be used to support pile excavations in cohesive or layered ground conditions. It is critical to ensure there are no coarse-grained layers (even thin layers) are present that might cause rapid fluid losses. The polymer concentration must be checked and adjusted in a similar manner as described above.

In permeable soil formations, the use of PHPA polymers without additives is not recommended because of their singular negative charge, which can promote the formation of polymer-coated channels in the permeable soil layer. Such effects can result in rapid and severe fluid losses, which typically destabilise borehole walls, causing sloughing and potential collapse of the excavation. Furthermore, the development of a real differential pressure head is difficult to achieve with pure PHPA polymer systems in permeable soil formations, mainly because of the absence of a filter cake and uncontrolled fluid loss.

However, modern polymer fluid systems (which include the pure polymer fluid plus some additives) can be successfully used in granular ground conditions and stress equilibrium inside the soil can be achieved via a mechanism called rheological blocking. The polymer fluid, loaded with fines and sand particles, penetrates the formation until the shear stresses between the load-ed fluid and the soil particles restrict further flow. The stability principles do not rely on filtration, as for bentonite slurries, but rather on shear stress between the particles and the slurry (and its sand and fines content). The penetration depths may range from a few hundred millimetres to several metres from the borehole wall as the soil becomes saturated with 'loaded polymer fluid'. The achievement of stress equilibrium will take time and the pressure head inside the excavation must be monitored closely and topped up regularly with fresh polymer support fluid until equilibrium is achieved.

The addition of additives can modify base polymer fluid properties in a way that the polymer fluid creates a membrane along the borehole wall, that works in a similar way as the filter cake in bentonite slurries. Such a membrane in combination with rheological blocking can reliably stabilise deep excavations in granular soil conditions. Case studies of Lam et al. (2018) show that 'vinyl polymer systems' and modern PHPA polymer systems have performed well in supporting bored piles and even diaphragm wall trenches in granular ground conditions. It is important to emphasise that such polymer-based fluid systems do not rely on the base polymer itself but rather on a range of additives required to enhance the base polymer. It is also important to note that a dedicated, competent and experienced polymer technician or drilling fluid specialist should always be on site to ensure the performance and quality assurance of the selected polymer-based fluid support system is maintained throughout the entire excavation.

It is essential to thoroughly understand the performance criteria and limitations of a selected polymer product and its additives to ensure the required stability of the project-specific deep excavation will be maintained throughout the entire construction process. Suppliers of polymer systems should be involved early in the project to assist with technical advice and essential quality assurance (QA).

Typical spoil removal mechanism in polymer fluids

Unlike bentonite slurries, appropriately designed polymer fluid systems contain only minimal quantities of free water, which reduces soil hydration and further breakdown of soil particles and cuttings in contact with the fluid. Larger soil particles (from drilling and excavating) are kept intact and will quickly sink to the bottom of the polymer fluid excavation rather than being sus-pended in a bentonite fluid system. This allows, where the pile base is cleaned with purpose-built cleaning tools (examples are shown in Fig. 4) after minimum standing time. Cleaning of the polymer supported excavation is carried out inside the excavation. No de-sanding or de-cantering equipment is required and, polymer fluids can be cleaned significantly faster and with less equipment set-up on site than in bentonite-supported excavations.

REMOVAL OF SOIL PARTICLES AND DEBRIS INSIDE THE EXCAVATION

The removal of drill cuttings from the deep excavation is critical and according to good practice documents, the sand content in fluid-supported excavations should be limited to < 1 % for polymer systems and < 2–4 % for bentonite systems (EFFC–DFI 2019).

After 'cleaning' the deep excavation by fluid replacement, external (bentonite) or internal cleaning (polymer) processes, the reinforcement cage can be put in place and concrete placement can commence. However, cleanliness of the base of the deep excavation is of greatest importance, especially for end-bearing piles or barrettes. During the movement of the cleaning bucket, the fluid velocity in combination with localised suction can cause significant scouring and partial hole collapses as well as head losses inside the excavation (Fig. 4).
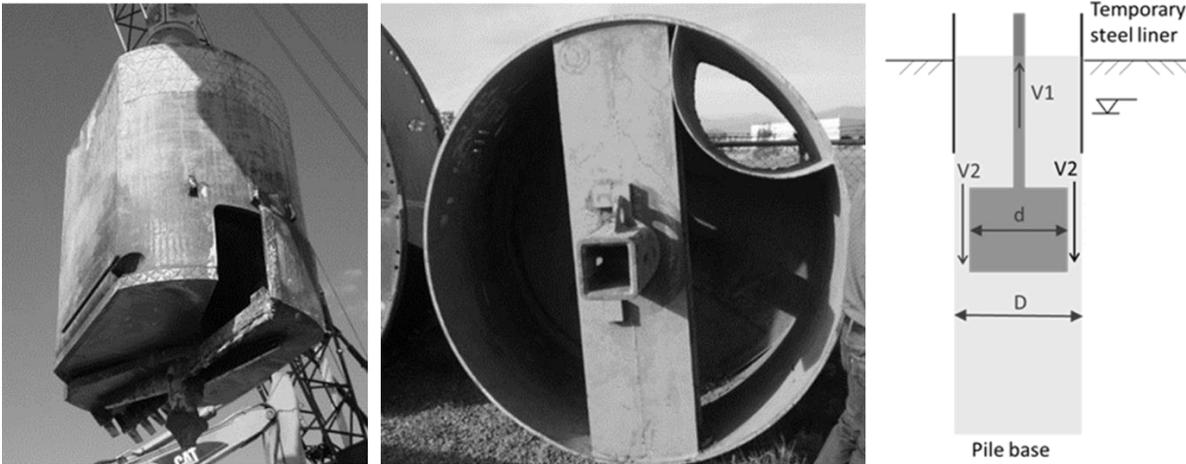

Fig. 4. Cleaning buckets with flow channels reduce fluid velocities during tool movements

Moving excavation tools like drilling buckets, augers, cleaning buckets and diaphragm wall grabs can destabilise borehole walls if those tools are extracted or lowered back into the fluid-supported excavation too quickly. High fluid velocities during the cleaning phase can cause partial collapses of the borehole wall and sediments can settle to the pile base, providing an unwanted layer of debris that needs to be cleaned prior to concrete placement. Base cleanliness of the bored piles is critical to ensure that the required design load transfer and load-settlement behaviour of the piles can be achieved.

It is important to avoid turbulent flow when moving the drilling tool during the excavation phase or pile base cleaning. Turbulent flow might locally reduce the support pressure of the borehole wall and lead to minor or moderate collapses of the borehole wall, loading the drilling support fluid with additional sandy or silty soil particles. Collapses and scour in sandy soils will lead to the ongoing settlement of sediments from the borehole wall to the base. In bentonite slurries, the overall sand content suspended in the support fluid might increase, causing potential concrete contamination. Therefore, it is important to identify the optimal speed of lift of drilling tools. The design and shape of buckets is as important as the viscosity of the drilling fluid, to minimise additional sedimentation. Internal fluid bypass channels and other suitable features must be applied (Fig. 4). It is also advisable to perform basic hydraulic calculations to estimate the optimal speed of lifting and lowering the tools, which requires a detailed knowledge of the size and shape of the fluid channels, the viscosity of the fluid and the actual tool and hole diameter.

Basic calculations of fluid velocities passing through the annulus between the drilling tool and the borehole wall can be made by using Eq. 3 (Fleming and Slivinski 1991) and the sketch shown in Fig. 4:

$$V_1 = V_{Tool} (d^2/(D^2 - d^2)) \tag{3}$$

Where V_1 = fluid velocity through the annulus (m/s), V_{Tool} = lifting rate of the drill tool (m/s), d = drill tool diameter (m) and D = borehole diameter (m).

By increasing the area available for the passage of the fluid using cleaning buckets with flow channels, the fluid velocity and associated risk of scouring and partial hole collapses are reduced. Assuming a lifting rate of the drill tool of 40 m/min (131 ft/min), a pile hole diameter of 940 mm (3.08 ft) and a drilling/cleaning bucket diameter of 900 mm (2.95 ft), the fluid velocity through the annulus would be ~7.3 m/s (24 ft/s) assuming a full cross-section of the cleaning tool. Using an internal or external fluid bypass channel (Fig. 4), providing a bypass section of 15% of the cross-sectional area of the tool, the fluid velocity inside the annulus would be reduced to ~2.7 m/s (9 ft/s), a drop in fluid velocity of about 60%. It is obvious that tool extraction rates should be monitored carefully, especially during cleaning.

It is important to treat this type of estimation with great care as the rheology of the drilling as well as the flow through the annulus (laminar or turbulent) has a significant effect on the result. Turbulent flow should be generally avoided as the stability of the borehole wall might be more compromised by turbulent flow. Other hydraulic parameters like the Reynolds number should be considered in a site-specific assessment, as should the rheology of the fluid system.

GENERAL RHEOLOGY OF DRILLING SUPPORT FLUIDS

Rheology is the study of the deformation and flow of materials that are controlled by the yield stress (YS) and plastic viscosity (PV) of the material (Lam et al. 2018). Fig. 5 shows the general behaviour of different drilling support fluids with respect to their rheology. All three drilling fluids discussed in this document (water, bentonite and polymers) are described and defined by different rheological models.

The shear viscosity (η) of a fluid at any shear rate (γ) under the applied shear stress (τ) is defined as:

$$\eta = \tau / \gamma. \tag{4}$$

If $\eta = 1$, the fluid behaves like a Newtonian fluid. Water is a Newtonian fluid with a low viscosity and no yield point (YP).
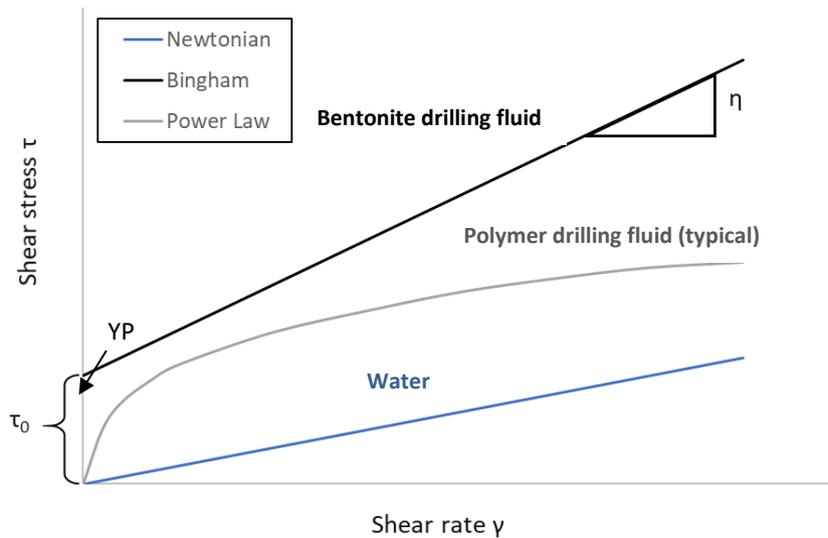
Fig. 5. General rheology of different drilling support fluids

The behaviour of bentonite slurries can be expressed by the Bingham plastic model, where the fluid appears solid up to a certain shear stress τ_0 after which shear deformation occurs. The fluid will only move if the applied shear stress τ is greater than the minimum shear stress (yield stress τ_0):

$$\tau = \tau_0 + \eta_p \qquad [5]$$

The plastic viscosity (PV) η is defined as the slope of the shear stress/shear rate diagram (Fig. 5). The parameters τ_0 and η are also defined as YP and PV, respectively (Caenn et al 2011). Both parameters can and should be directly obtained through laboratory testing.

Bentonite support fluids are generally expressed by using the Bingham model and its YP is the element which makes it so valuable as a drilling support fluid. The YP of a Bingham fluid is defined as the resistance of initial flow of the fluid or the stress required to move the fluid; it is the shear stress extrapolated to a shear rate of zero. The viscosity of bentonite fluids depends on the concentration of bentonite suspended in the slurry and the fluid sand and fines content, which typically increases the viscosity. Bentonite slurries for temporary support of deep excavations have the following fundamental functions:

(i) the removal of drill spoil and the maintenance of particles in suspension; for this function, it is beneficial to keep the YP and thus the apparent viscosity of the slurry as low as possible to make the cleaning and pumping process of the slurry as easy as possible, and
(ii) stabilising the excavation, from both a global and localised perspective.

The YP of the bentonite slurry is critical for both functions and is therefore the most important parameter when assessing the behaviour of bentonite support fluids.

Polymer fluids are best described using the power law model with shear thinning behaviour. Polymers have no YP and thus, without the addition of additives, cannot build a watertight membrane with the same efficiency as filter cakes for bentonite fluids. Modern polymer fluids can form a thin and rather unstable membrane but currently, it is very difficult to calculate the stability of polymer-supported temporary deep excavations. Polymer fluids are generally defined as shear thinning fluids, which implies a reduction in apparent viscosity with increasing shear rates. The power law model is suitable to describe shear tinning behaviour (where K is the flow consistency index and n is the flow behaviour index):

$$\tau = K\gamma^n \qquad [6]$$

For n = 1, the fluid will behave like a Newtonian fluid.

Substituting Eq. 6 into Eq. 4, the apparent viscosity of a power law fluid with shear rate γ is expressed as follows:

$$\eta = K\gamma^{n-1} \tag{7}$$

The model displays shear thinning behaviour if $n < 1$ (polymer-based fluids) and shear thickening behaviour for $n > 1$. It is important to emphasize that each fluid type follows a different rheological model. Hence, the behaviour and performance parameters (including QA) are different for each fluid type.

TEMPORARY STABILITY OF BENTONITE-SUPPORTED DEEP EXCAVATIONS

The rheology of drilling support fluids also influences the stability of a deep excavation. In soil formations with low permeability (e.g. clay), drilling support fluids might not be necessary, and the excavation could be carried out safely in dry conditions or by using a steel liner firmly embedded in the foundation layer (e.g. hard clay or rock). The assessment of the temporary stability of a deep excavation might not be required unless layers of granular and permeable soil are present which increase the risk of fluid losses. In such ground conditions, borehole excavations and trenches for diaphragm walls should follow the basic principle that the positive pressure head inside the excavation must always be higher (by ~20 kPa) than that outside the excavation; the fluid level inside the excavation must always be ~2 m (~6.5 ft) above the groundwater level.

The stability of temporary deep excavations constructed in granular or layered ground conditions supported by bentonite fluids is based on the following filtration and blocking mechanisms which will occur, to achieve stress equilibrium inside the soil formation: (i) surface filtration, (ii) deep filtration and/or (iii) rheological blocking.

Surface filtration

Surface filtration assumes that the filter cake is formed at the inside of the temporary excavation and that a stable and impermeable filter cake is formed by the filtration of clay particles through the surface of the borehole/trench wall. The wall is sealed and hydrostatic pressure from inside the excavation can be exerted on the wall surface without increasing the pore water pressure in the soil formation; thus, subsequent slurry loss or loss of stability is avoided (Fig. 6).

1. Fluid:

2. Membrane: $S = SH - W$

3. Wedge: $S_H = 0.5 * \gamma_F * H_1^2$
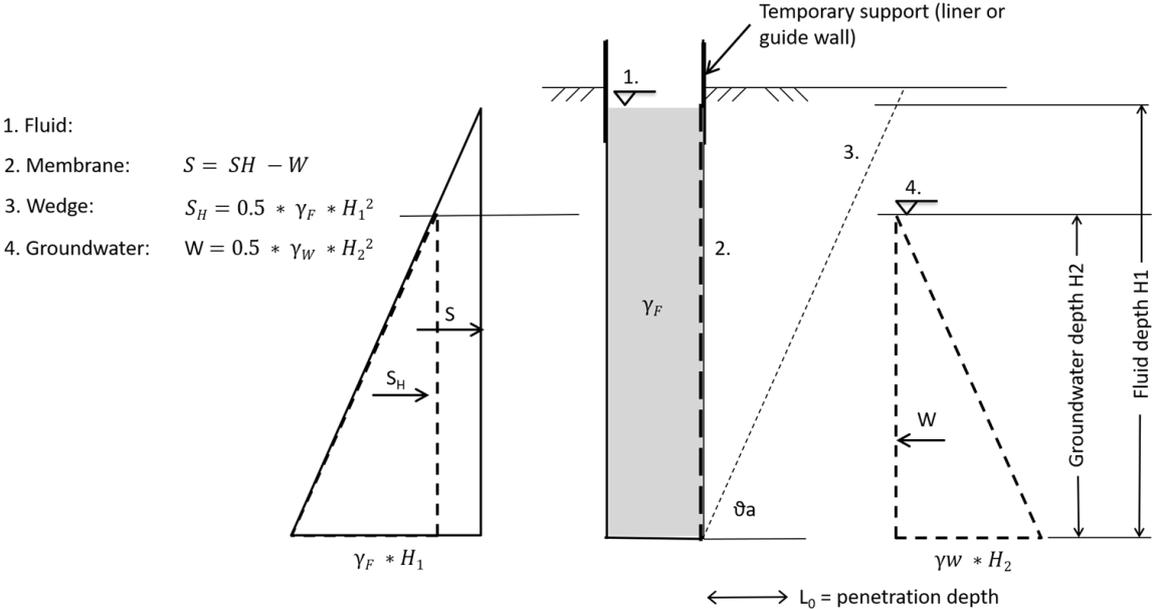
4. Groundwater: $W = 0.5 * \gamma_W * H_2^2$

Fig. 6. Basic external pressure equilibrium for fluid-supported deep excavations with a filter cake (surface filtration) following DIN4126-2013

278

During the initial contact between the freshly excavated wall and the bentonite fluid, the fluid will penetrate through the trench or borehole wall into the soil formation. The initial rate of fluid loss is high but decreases rapidly in granular soils with small voids, as the bentonite particles are filtered out along the wall. Even if the bentonite particles are significantly smaller than the voids in the granular soil, due to bridging effects, the bentonite filter cake will be built up quickly and fluid losses will abate.

Surface filtration can also occur in coarser material (e.g. coarse sands) with larger voids, as the bentonite slurry must contain fine sands in suspension, which will assist in blocking the voids.

Deep filtration (or stagnation of fluid penetration)

If the voids grow larger again (as in gravels), deep filtration is likely to occur. Deep filtration (Fig. 7) is a process where the bentonite slurry penetrates the soil formation over a distance 's'. Eventually, the pores and voids are slowly blocked and clogged with slurry and suspended sand and fines which causes further fluid penetration into the soil formation. The process is more complex than surface filtration and some fluid losses should be expected until stress equilibrium is established. The penetration depth 's' may extend several metres into the soil formation. This influences the shear strength of the soil and should be considered in the selection of design parameters.

1. Fluid:

2. Fluid penetration: $S = (SH - W) * As/A$

$s = (H1\gamma_F - H2\gamma_W) / fs0$

3. Wedge: $S_H = 0.5 * \gamma_F * H_1^2$

4. Groundwater: $W = 0.5 * \gamma_W * H_2^2$
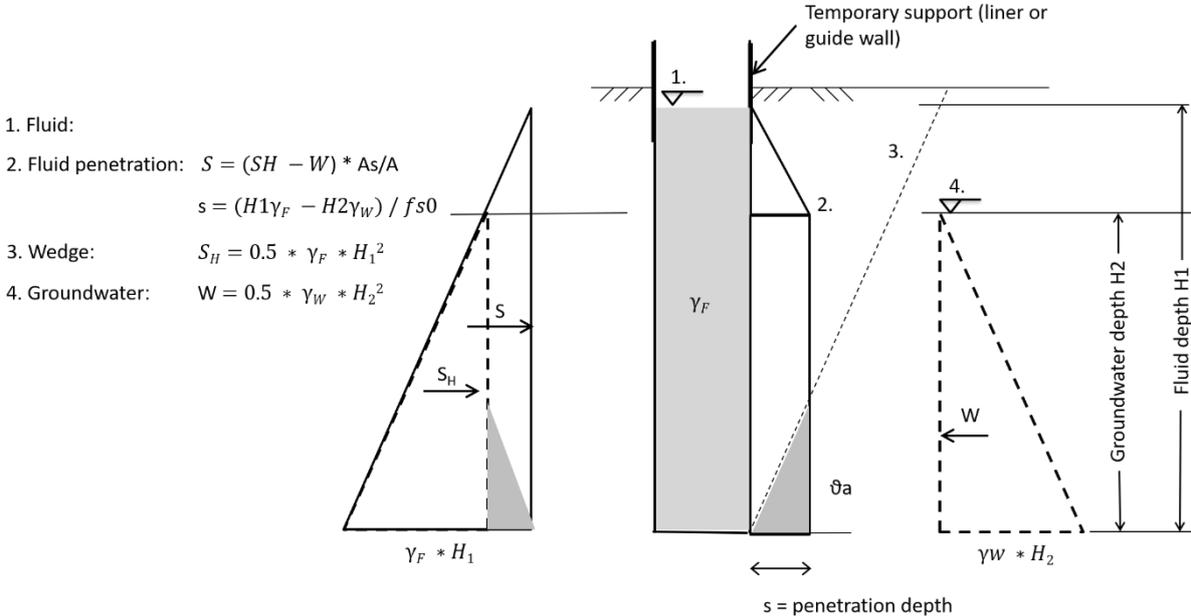
s = penetration depth

Fig. 7. Basic external pressure equilibrium for fluid-supported deep excavations based on stagnation of the fluid penetration into the soil formation (deep filtration), following DIN 4126-2013

Rheological blocking

Rheological blocking is a third mechanism that occurs in very coarse soil conditions where the bentonite fluid penetrates the soil formation until the shear stresses between the (loaded) fluid and the soil particles restricts further flow. The stability principles from Fig. 7 could be applied; however, the mechanism relies on shear stress between the particles and the fluid (and its sand content) rather than on filtration.

Rheological blocking is likely to occur in gravel or cobble layers and the penetration depth 's' could reach several metres into the soil formation. The soil is saturated with bentonite fluid and the achievement of stress equilibrium will take time. The pressure head inside the temporary excavation must be monitored and topped up regularly with fresh polymer fluid. Saturation of the soil with bentonite fluid affects the internal friction angle of the soil and is likely reduce the shear strength of the soil formation, which also reduces the shaft capacity of bored piles or barrettes.

Standardised approaches for the determination of bentonite fluid properties can be found in DIN 4126-2013 and the interaction with the ground can be described as one of two scenarios: (i) the formation of a filter cake and no fluid loss/penetration into the soil (Fig. 6) or (ii) the penetration of the fluid inside the formation, blocking the voids over a distance 's', until equilibrium is achieved (Fig. 7).

The second scenario can be assessed with the help of an existing pressure gradient fs_0, which represents the decrease in fluid excess pressure over the penetration distance 's' into the soil formation. The existing pressure gradient can be calculated from Eq. 8 (Müller-Kirchbauer, 1977), as follows:

$$fs_0 = \Delta p \, / \, s \qquad\qquad\qquad [8]$$

Where fs_o = existing pressure gradient, Δp = fluid pressure (pressure at the borehole wall at depth 's') and s = penetration depth

Saltwater, peat or chemicals in the ground or ground water can rapidly reduce the pH level of the drilling fluid, which may affect it's viscosity. Fluid losses into sand or gravel formations are governed by fluid viscosity, and reduced viscosity might lead to higher than expected fluid losses.

The use of water as a drilling support fluid might follow the method for rheological blocking if sufficient fines are available inside the excavation. However, fluid losses when using water are expected to be very high and the stability of the excavation is likely to be very low.

TEMPORARY STABILITY OF POLYMER-SUPPORTED DEEP EXCAVATIONS

Deep excavations constructed under polymer support fluids in cohesive ground conditions are likely to perform in a stable manner if the polymer concentration is monitored and modified as required.

In granular ground conditions, simple and pure polymer fluids without the addition of additives are likely to behave like water. Significant and ongoing fluid loss can be expected, which is likely to cause instability issues for temporary deep excavations.

For polymer fluids with additives, the mechanism of deep filtration or rheological blocking is likely to occur and achieves stress equilibrium inside the soil formation. The soil is saturated with (loaded) polymer fluid and the achievement of stress equilibrium might take some time. The pressure head inside the excavation must be monitored and topped up regularly with fresh product. The saturation of the soil with polymer might only marginally affect the soil angle of internal friction (Lam and Jefferis 2018).

Some polymer manufacturers claim that their product is capable of building a thin membrane that acts in a similar way as a bentonite filter cake. Further research is required to develop a feasible concept that fully explains the mechanism of building such membranes which help to achieve equilibrium in the soil formations (Lam and Jefferis 2018).

In summary, most design concepts to achieve temporary stability of boreholes or trenches are based on bentonite-supported deep excavations (Huder 1972; DIN 2013). More research and collaboration between drilling fluid suppliers, contractors and consultants is required to develop guidelines to assess the temporary stability of polymer fluid-supported trenches. The EFFC–DFI document (2019) is a first step in this direction and contains a variety of very useful information but also some knowledge gaps.

STABILITY PROBLEMS DURING CASING INSTALLATION AND EXTRACTION

Adequate seals for temporary or permanent steel casings in rock formations are critical to keep the pile excavation dry and to avoid potential influx or soil or water through the base of the excavation, especially if the fluid levels and the associated pressure head inside the excavation are inadequate and the rock is fractured allowing groundwater inflow. If groundwater inflow occurs, it is advisable to fill up the pile excavation to stabilise the borehole and to proceed with wet tremie concrete placement.

Temporary steel liners are typically used to stabilise the top section of fluid-supported pile excavations. It is important to consider stability problems during casing installation, as they might affect the temporary stability of the excavation as well as the final load settlement performance of the pile.

Regardless of the type of drilling support fluid selected, the installation and extraction of steel liners can cause significant long-term defects and short-term stability problems. Fig. 8 shows some common stability issues related to the installation of steel liners, which include the destabilisation (or 'blow-out') of water-saturated granular soils during casing installation. If the pressure head inside the casing is insufficient or drilling is advanced too far below the toe of the liner, blowouts can occur and may result in areas of reduced soil stiffness and stability around the pile shaft. The water-saturated soil around the pile shaft and below the base of the pile excavation is drawn into the excavation, destabilising the area around the shaft and below the pile toe. These blowouts will affect the base capacity and the shaft friction performance of the pile, regardless of the selected drilling fluid type. Blowouts are likely to occur in combination with high fluid losses, such as may be encountered like drilling under water or basic polymer fluids. Fluid levels will drop rapidly inside the excavation, causing subsequent stability issues. Drilling too far below the toe of the liner can also result in blowouts. Blowouts can result in excessive concrete overconsumption in the destabilised area, as shown in Fig. 8.
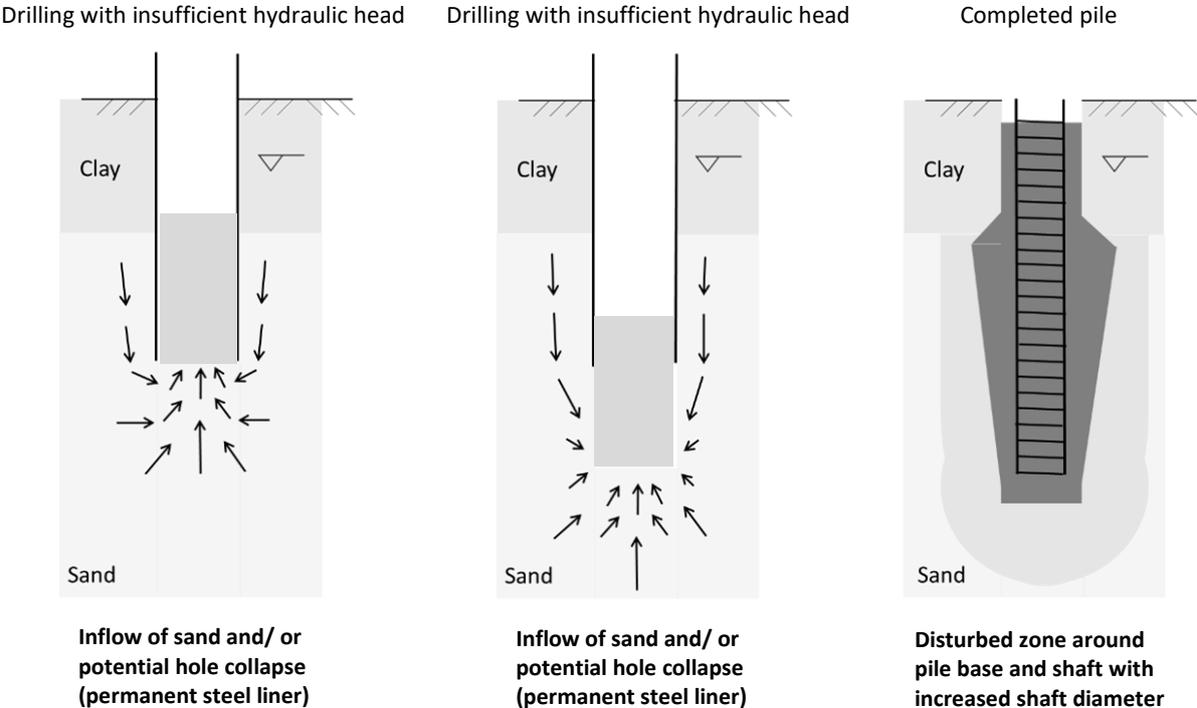

Drilling with insufficient hydraulic head   Drilling with insufficient hydraulic head   Completed pile

Inflow of sand and/ or potential hole collapse (permanent steel liner)   Inflow of sand and/ or potential hole collapse (permanent steel liner)   Disturbed zone around pile base and shaft with increased shaft diameter

Fig. 8. Selected stability problems related to rotary bored piling methods with steel casings

When using steel liners, especially when excavating granular soil below the groundwater table, it is of fundamental importance to maintain the minimum required fluid level inside the casing to ensure that the fluid pressure inside the casing is always greater than the earth and external water pressure. This is particularly important in tidal areas or regions with artesian groundwater conditions. The latter case can de-stabilise the pile toe, even if the fluid levels inside the casing are 2 m or more above the groundwater level. Stability calculations and potential additions of fines into the bentonite slurry might be required to increase the density of the mineral drilling fluid (e.g. by adding barite or similar) to achieve stress equilibrium. The density of polymer-based drilling fluids cannot be increased by adding minerals and their use in artesian groundwater conditions is therefore not recommended.

The placement of concrete inside the temporarily supported borehole can also cause stability problems. Concrete is heavier than the excavated soil and it applies higher lateral (active) pressure onto the borehole wall or trench than the excavated material. In particular, more fluid concrete mixes apply more

lateral pressure onto the excavation face. In granular ground conditions, the passive resistance of the borehole wall is typically sufficient to resist these pressures. However, in very soft soils or peat layers, the concrete might slump into the soft soil formation because of the low lateral passive resistance of soft soil layers. Excessive concrete overconsumption might be the consequence, and, in some instances, it might be impossible to cast concrete to surface level as the lateral passive resistance of a soft layer is lower than the active lateral concrete pressure. Peat soils can lose their stability rapidly, which might even cause partial collapse of the freshly poured deep foundation element.

The extraction of temporary steel liners using vibrators should be carried out carefully, especially if highly workable concrete is used to cast the pile shafts. The vibration energy transmitted through the casing into the fresh concrete can cause a reduction in shear resistance of the fresh concrete. This might lead to a potential decrease in the yield stress of the fresh concrete, reducing the resistance of the concrete to prevent the larger aggregates from sinking in the fresh concrete. As a result, segregation of the fresh concrete may occur, with consequent effects on concrete strength and durability of the pile shaft.

INTERACTION OF DRILLING FLUIDS WITH CONCRETE

The placement of tremie concrete in fluid-supported deep excavations is a complex process and it is considered to be the reason for the majority of defects found in deep foundation elements. Concrete characteristics and performance criteria are different from those of normal class concrete and international guidelines (Concrete Institute of Australia 2012; Joint EFFC–DFI Concrete Task Group 2018) should be followed.

The principle of concrete flow inside a fluid-supported deep excavation is complex. Two theories, plug flow and bulging flow, have been used to describe the flow behaviour of tremie concrete inside a fluid supported deep excavation (Joint EFFC–DFI Concrete Task Group 2018). The flow pattern of fresh concrete largely depends on the rheology of the fresh concrete placed inside a pile or panel, as shown in Fig. 9. Tremie concrete, designed more closely to self-compacting concrete (SCC) characteristics, might exhibit plug flow behaviour, whereas concrete designed more closely to normal class concrete is likely to exhibit bulging flow.
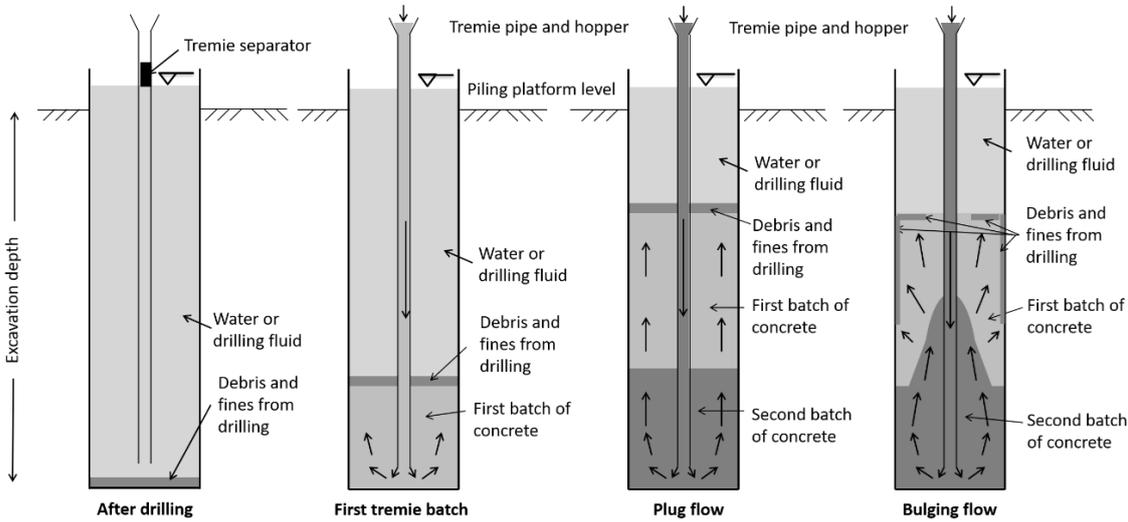

Fig. 9. Tremie concrete flow and deposit of debris and fines from insufficicent base cleaning inside a deep foundation following plug flow or bulging flow (Larisch 2019).

The placement process and flow pattern of the first load of concrete is similar under both theories. Initially, the open-ended tremie pipe fills with water or drilling fluid as it is lowered into the excavation to ~300–500 mm (~1-2 ft) above the final excavation level. The tremie separator (e.g. rubber ball or vermiculite plug) is placed inside the top of the tremie pipe, before the first charge of concrete is discharged into the hopper. As the tremie concrete flows down the tremie pipe, divided from the drilling fluid by

the tremie separator, the base of the pile excavation experiences some flushing from the fluid displaced from inside the tremie pipe. This fluid flushes debris and remaining fines off the base, dispersing them temporarily a few metres above the pile base. As the fresh concrete reaches the bottom of the tremie pipe, it hits the clean base of the deep excavation, spreading from the centre towards the edges of the deep excavation. When it reaches the borehole walls, the fresh concrete begins to flow upwards, pushing and passing through the reinforcement cage and rising upwards along the borehole wall. Debris and fines dispersed temporarily from the base quickly settle on top of the fresh concrete from this first batch.

As the initial plug of fresh concrete (including the contaminated layer of debris and fines on top of its surface) is pushed and placed along the borehole wall during bulging flow, contaminated concrete can sometimes be found inside the concrete cover zone or along the reinforcement cage, which has the potential to cause defects because of inclusions and related durability issues (Fig. 10). During bulging flow, accumulation of debris from the contaminated layer is likely to occur independently of the selected pile diameter. Thinner layers of contaminated concrete might deposit at greater depths.

Consequently, tremie concrete should be designed with the aim of exhibiting plug rather than bulging flow to avoid deposits of contaminated concrete along the borehole wall (cover zone) and/or along the reinforcement. The layer of contaminated concrete can be removed from the surface of the raising concrete column after completion of the pour, if pure plug flow occurs. In the author's experience and based on numerous observations of concrete pours and analysis of a large variety of defects in bored concrete piles, a combination of both flow patterns is likely to occur in most applications. Depending on the consistency of the concrete supplied, different batches might exhibit different flow patterns. To minimise the thickness of the layer of debris, thorough base cleaning prior to concrete placement is vital to reduce the risk of defects caused by depositing this layer along the borehole wall or reinforcement cage.

Interaction of polymer-based fluid systems with fresh tremie concrete and its admixtures

Insufficient bonding between the pile reinforcement and the hardened concrete in polymer-supported bored piles was observed by the author on a number of piles in the Asia Pacific region several years ago. Even though the root cause of the issue, as shown in Fig. 10 (centre), has not been fully examined, it is likely that the lack of bond between reinforcement bars and concrete was caused by a thin layer of polymer fluid that was not displaced by the fresh concrete. This phenomenon might be related to a chemical reaction between the fresh concrete and the polymer fluid (or its additives), preventing the complete displacement of the thin layer of polymer fluid from the reinforcement bars.

Fig. 10. Uncontrolled concrete setting (left), insufficient bond with reinforcement bars (centre) and inclusion of sand or silt caused by an insufficiently cleaned pile base (right)

Other defects have been observed by the author, where fresh tremie concrete experiences rapid set, right after placement in polymer-supported deep excavations (Fig. 10, left). In all instances, the projects were located in tidal areas with saline (ground)water conditions and a polymer system with various additives was used. In all cases, the concrete mix design incorporated modern superplasticisers based on PCE technology, which may have reacted with some of the additives in the polymer system or the chemicals contained in the groundwater. It is recommended to assess the compatibility of the polymer fluid (and its additives) with the proposed concrete mix design during laboratory and field trials prior to commencement of construction. Similar defects have not been observed when bentonite fluid was used.

DESIGN CONSIDERATIONS FOR PILES INSTALLED UNDER SUPPORT FLUIDS

Drilling support fluids can largely influence the load settlement performance of a deep foundation element. Insufficient fluid management can also cause defects in bored piles and diaphragm wall panels.

For deep foundation elements designed with base load transfer, it is critical that the base is free of debris and soil particles before concrete placement commences (Haberfield 2013). This is particularly important for the design of rock socket and end-bearing piles. The performance of end-bearing piles in soil formations can also be influenced externally, by reducing the stiff-ness of the soil below the pile base (e.g. blowouts), or internally, by debris and fines at the pile base (inside the excavation), which will increase the deformation necessary to fully activate the base resistance..

Drilling below the toe of the liner and subsequent blowouts can significantly reduce the base capacity of a pile, especially in saturated granular soils. Artesian groundwater pressure might soften the pile base and these effects need to be taken into consideration when assessing the base capacity of a bored pile.

In polymer-supported deep excavations, the cleaning process is carried out inside the excavation after typically allowing, the fines and drill spoil to settle at the pile base. Thorough cleaning of the pile base is very important when using polymer fluids for end-bearing piles. The use of sufficiently cleaned bentonite fluids for end-bearing piles might reduce the risk of excessive layers of debris and fines settling at pile base, as some of the fines are held in suspension. Nevertheless, base cleaning is critical for all end-bearing piles, more so when using polymer support fluids.

Shaft resistance for bored piles excavated under bentonite fluids is likely to decrease in cohesive ground conditions (e.g. clay or shale) if the soil is sensitive to swelling. Several publications make recommendations about potential reduction factors for skin friction in cohesive soil for bentonite-supported piles (FPS 2006, Lam and Jefferis 2018). The use of polymer fluid systems (with additives) or hybrid fluids (bentonite/polymer mixes) in cohesive ground conditions is unlikely to reduce the shaft resistance if the minimum polymer concentration is maintained and this process is documented sufficiently.

In granular ground conditions, bentonite fluids form a filter cake to stabilise the temporary excavation. Depending on the void space of the granular soil, deep filtration or rheological blocking might occur as well. The latter will create a penetration depth 's' of bentonite fluid around the pile shaft, which potentially decreases the shear strength of the original soil formation. This decrease needs to be considered in the assessment of the shaft resistance. Most of the bentonites used for construction purposes are sodium-activated bentonites, which normally form thin and strong filter cakes. In the past, some less expensive, low-quality calcium bentonites formed soft and thick filter cakes, which acted as a layer of soft clay between the pile shaft and the surrounding soil, severely decreasing the shaft capacity of the pile. The effects of the bentonite filter cake on load capacity in permeable and impermeable formation are discussed in the literature (Lam et al. 2010; Jefferis and Lam 2013) and it is recommended to allow for some reduction in shaft resistance when using bentonite fluids, not just in clay but also in granular soils.

The use of advanced polymer fluid support systems in granular soil conditions seems to have very little impact on the shaft resistance of piles (Lam et al. 2010). If the polymer fluid can stabilise the deep excavation, it seems likely that the shaft resistance is not greatly affected. Other than the clay particles in bentonite fluids, which might create a 'slip layer' between the sand particles, polymer strands simply bind fines and soil particles, which may reduce the void space in the close vicinity of the pile shaft. Pure base polymer fluids will not support temporary excavations in granular soil conditions and therefore their impact on load settlement behaviour is not discussed any further.

The use of water as the sole drilling fluid is recommended to clean the base and side wall of the rock socket if conditions are suitable for water-based drilling fluid to be used. Bentonite slurries might leave smear on the rock socket surface, which has the potential to significantly reduce the shaft resistance unless the socket walls and base are mechanically cleaned. The impacts of polymer are less severe but potential reductions in shaft friction should be considered. Regardless of the drilling fluid to support the

entire deep excavation, cleaning of rock socket side walls should always be done in combination with suitable cleaning tools (e.g. with attached brushes).

The use of water in cohesive ground conditions will reduce the shaft capacity, especially in swellable clay or shale formations. In granular ground conditions, the stability of the temporary excavation might not be achieved by water and therefore no recommendations about long-term design effects are made.

Contamination of the fresh concrete by sediments from an insufficiently cleaned pile base can cause sand or silt particles to settle inside pile shafts, between reinforcement bars (Fig. 10) and/or inside the concrete cover zone along the borehole wall. Defects in the cover zone are typically not able to be detected by state-of-the art pile integrity testing methods, such as cross-hole-sonic logging or low-strain integrity testing (Larisch 2011) as this surpasses their capabilities. Recently developed pile integrity testing methods like thermal integrity profiling (TIP), which is based on the measurement of the concrete hydration temperature, may help to detect and assess likely defects in the cover zone in the future.

SUMMARY

Drilling support fluids can efficiently stabilise deep excavations. However, it is important to select the correct fluid support system for the project-specific ground conditions and the construction environment. Designers of deep foundations should be aware of the basic working principles and associated construction and stability risks of different support fluids as such fluids can influence the shaft and base capacity of deep foundation elements.

Water has had the longest history as a support fluid and is most suitable for the support of temporarily or permanently lined bored piles with rock sockets. In granular ground conditions water will be lost inside the formation, and in cohesive soil the water molecules might react with clay or shale and cause swelling and softening of the borehole walls.

Bentonite support fluids are mineral based and are designed to keep drill cutting in suspension. During the drilling process, fines and drill cuttings are suspended in the fluid, which must be cleaned outside the excavation. Bentonite storage tanks, mixers and silos require a large set-up area of the construction site. Bentonite can be best described as a Bingham fluid. In granular soil conditions, bentonite fluids typically achieve very stable temporary excavations by the mechanisms of surface filtration, deep filtration and rheological blocking. Depending on the thickness of the filter cake, some reduction in design shaft capacity might be required. In swelling cohesive ground conditions, bentonite support fluids are not recommended as the free water molecules are likely to react with swellable clays or shales and cause swelling and softening of the borehole wall, which will reduce shaft resistance and the stability of the open deep excavation during construction. Bentonite fluids can be enhanced by the addition of small amounts of polymer (hybrid fluids) to prevent clay swelling and softening.

Polymer support fluids follow the power law with respect to their rheological behaviour; they do not have a yield point. Unlike bentonite support fluids, they flocculate fines and drill cuttings to quickly settle to the base of the excavation where they can be collected by purpose-built cleaning tools. The cleaning process for polymer supported deep excavations is typically much faster than for bentonite fluids and can be done inside the excavation. No fluid de-sanding or de-canting equipment is required to externally remove drill cuttings. The space requirements for polymer farms are thus much lower.

Base polymer fluids do not build a filter cake and in granular soil conditions they can be used with additives to create a thin membrane to establish equilibrium in the soil formation by deep filtration and rheological blocking of the sand particles trapped within the polymer fluid. Even though the polymer fluids penetrate into the soil formation which surrounds the deep excavation, no (major) impacts on the shaft resistance are expected.

Polymer systems work very well in cohesive ground conditions as clay swelling is prevented by the polymer chemistry. However, similar to hybrid fluids, the polymer concentration must always be main-

tained at a minimum level to ensure the system remains in equilibrium. Not all polymer fluids are suitable for construction applications and the use of polymer systems (with additives) is highly recommended over the use of pure polymer fluids without additives.

The installation of temporary or permanent steel liners for the surface support of fluid-supported excavations can cause severe stability problems if the positive head is not maintained inside the temporary excavation. Blowouts below the pile toe can severely impact the end-bearing performance of the pile.

The key consideration to achieve a stable temporary excavation is the maintenance of a positive fluid pressure head inside the excavation. The fluid level inside the deep foundation excavation should be maintained at least 1m (3.5 ft) for bentonite and 2 m (3-7 ft) for polymer, above groundwater level. Tidal influences and the effects of the insertion of the digging and cleaning tool also need to be considered.

Recycling of used bentonite fluids can be very difficult and expensive. Typically, the used bentonite fluid is collected by sucker trucks on site and spread out off site over a large area for drying or disposed of in a suitable approved liquid landfill. When it is dried it will be collected and stored in landfills. Recycling is much easier for polymer fluids. Used polymers can be used as surface stabilisation and dust suppression on earthwork projects to assist with dust control. Most polymers will disintegrate and return to water. Disintegration can often be accelerated with the use of bleach. Prior to treated fluid disposal, the fluid needs to be tested and, depending on the test results, can be recycled accordingly.

General performance criteria and QA requirements for different drilling support fluids are provided a number of good practice industry guidelines (FPS 2006, AASHTO 2010, ICE 2017, EFFC-DFI 2019).

Stability calculations for polymer fluids to support deep excavations are complex and some key parameters used for the calculation of bentonite supported deep excavations (e.g. yield point) are not applicable for polymer fluids. Therefore, well established stability calculations used for bentonite supported excavations should be used with great care for polymer-based fluids.

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