Polymer systems for fluid supported excavations

Citation for published version (APA):
Lam, C., Jefferis, S., & Troughton, V. (2011). Polymer systems for fluid supported excavations. In *Geotechnical issues in construction: short paper series and 2nd conference held on 2 November 2009, at CIRIA, London* (pp. 7-12). Construction Industry Research and Information Association. http://www.ciria.org

Published in:
Geotechnical issues in construction

Polymer systems for fluid supported excavations

Stephan Jefferis, Environmental Geotechnics, Viv Troughton, Stent Foundations, and Carlos Lam, University of Oxford, discuss the history and formulation of excavation fluids before examining developments in the field and their implications for the construction process

Introduction

Excavation support fluids are used in a wide variety of civil engineering operations including piling, diaphragm walling, slurry tunnelling, horizontal directional drilling, oil and water well drilling, drilling site investigation boreholes and the formation of cut-off walls and drainage walls.

In each of these applications the role of the fluid is to keep the hole open until a permanent element (concrete, lining etc) is installed. This paper will focus on the use of polymer excavation fluids for piling though polymers can and have been used in all the applications cited except for low permeability cut-off walls, which remain an area of need and opportunity.

A brief history of excavation fluids

The concept of excavation under a bentonite slurry to form a continuous structural wall was advanced by Christian Veder in 1938 (Xanthakos, 1979) though the use of supporting muds in well drilling is much older. Boyes (1975) notes that a French engineer, Fauvelle, is credited with the first use of circulating fluid to remove drill cuttings in 1845. Veder (1963) reviews some of the work in the field and the laboratory, and states that the first applications of early diaphragms were for solving issues such as "for impermeable cut-offs below earth dams in deposits of sands and gravels with large boulders" (depths of about 40 m) and for "making a reservoir watertight" using a wall of maximum depth 35 m and area 38 000 m2. These walls would have been backfilled with concrete and Veder noted that the first experimental diaphragms were carried out in 1950 "using circular concrete elements partly embedded one in another" (though Xanthakos, 1979 notes that concrete test panels were inserted in linear trenches in the 1940s). Hajnal et al (1984) report that both Veder and Lorenz "obtained relatively smooth diaphragm walls" in 1950. It seems that the concept of the concrete diaphragm wall was well established by the late 1950s. However, before that there had been major developments in cut-off walls backfilled with soil. The first slurry supported trench excavation is believed to be that used to stabilise levees on the Mississippi River in 1945 using technology developed in the oil well drilling industry (Kramer, 1946). The fluids used for excavation support in early applications were based on clays and especially montmorillonite (bentonite) clay in the high swelling sodium form.

Bentonite producers have responded to the evolving experience in specifying and using excavation slurries and to meet the requirements of the civil engineering industry polymer modification of bentonites has become regular practice. Today many bentonites are significantly polymer modified at the time of production though the purchaser/user may not be aware of this. Polymer modification can enable bentonites of moderate activity to develop sufficient properties for use in excavation support and/or to develop systems with high rheological properties (viscosity and gel) that tend to be used in horizontal directional drilling.

Polymers may be added to bentonite slurries at the time of use as well as at the time of production, though such additions should be limited to systems requiring specialist properties such as horizontal directional drilling. If polymers are added to bentonite at the time of use the polymer/bentonite systems should be based on proven slurry formulations. Injudicious mixing of bentonite and polymer in the field can produce systems with properties worse than either system alone.

Pure polymer systems have been tried at intervals over the last 30 years. Early polymer systems tended to be based on naturally derived products such as carboxymethyl cellulose and xanthan and guar gums. These products were tried as pure polymer systems but nowadays are generally used only in conjunction with bentonite or natural clay dispersed into the slurry from the formation being excavated. Naturally derived polymer materials tend to be readily biodegradable and should be used in conjunction with a biocide.

The advent of synthetic polymers has allowed the development of fluid systems with designer properties using blends of different types of polymer product. Despite this many synthetic polymers offered for use in construction are simply partially hydrolysed polyacrylamides. These polymers have some useful properties but much more can be achieved. Tailored systems for particular soils and construction processes are perfectly practicable. However, if such systems are to be commercialised industry support is vital.

Synthetic polymers tend to be more resistant to biodegradation than natural products and there should be no need to use a biocide. Synthetic polymers can be repeatedly reused so that there is no need to dispose of any liquid until the end of a job. However, repeated reuse requires appropriate slurry management. Fresh polymer should be added to the fluid after each use as polymers are sorbed onto soils so that the concentration of active material drops with use. With hindsight it is clear that several past failures have stemmed from insufficient use of polymer.

Formulation of excavation fluids

The advent of synthetic polymers has allowed many innovations in fluid supported excavations though substantial potential for further developments remains. However, there is a large amount of experience in the specification and use of bentonite slurries so why change? Why consider non-clay systems? The prime purpose for any change of excavation support fluid should be to achieve improvements in one or more of the following:

- health and safety
- the end product
- economy including improving pile performance by reducing overbreak
- the construction process
- the sustainability of the process/product
- to eliminate problems of materials shortages (for example, good quality bentonite may not continue to be available).

Considering just one of these, economy, a well-designed and maintained support fluid can pay for itself and much more if overbreak is reduced or if the pile length can be reduced because of better end bearing or wall friction.

Conventional bentonite based excavation fluids will have a density of about 1.02 g/ml when freshly mixed but this density will increase in use as fines from the excavation become suspended in the fluid. Bentonite slurries do not inhibit fines dispersion from the ground – indeed they tend to promote it. During excavation, densities may rise to over 1.25 and specifications should set an upper limit on density of the excavation fluid before concreting so as to enable its full displacement by concrete. Because of spoil suspension if bentonite slurries are to be reused a soil/slurry separation plant normally is required. Separation plants are substantial and costly pieces of equipment.

In-use, the density of bentonite slurries will be significantly above that of water. This will contribute to the stability of the fluid supported excavation. However, recent experience with piling, diaphragm walling and slurry trench excavations shows that excavation stability is seldom a problem provided that the fluid level is maintained at about 1 m or more above the groundwater level – it is not essential to maintain a high fluid density to ensure stability.

Low specific gravity excavation fluids

The recognition that water density fluids can be used to stabilise many excavations has allowed revolutionary developments in fluid support technology and these have been pioneered by KB International LLC an American polymer manufacturer in conjunction with Balfour Beatty Ground Engineering Ltd. Despite this pioneering work the subtle features of low density systems are seldom fully appreciated and the current generation of polymers is often used inappropriately. To enable a better understanding of polymer behaviour research is being undertaken at Oxford University with support from the UK Engineering and Physical Sciences Research Council (EPSRC), Balfour Beatty Ground Engineering Ltd and KB International LLC.

Water-density polymer fluids are pure solutions of polymer in water rather than solid (bentonite) – water slurries. A key feature of polymer fluids identified from the research is that the polymer system should be designed to prevent dispersion of fines from the soil into the fluid. If dispersion is not inhibited the fluids will become native soil – water slurries that may be quite unsuitable for construction operations.

Unfortunately, slurry users have not always appreciated that low density polymer based systems allow/require different working practices to clay based systems. In particular the polymers developed for use in low density systems should not be used for higher density systems or mixed with bentonite to form clay/polymer systems. The use of low density systems permits:

- the use of polymers, which inhibit dispersion of fines from the excavated soil
- production of drier arisings (inhibition of dispersion results in coarser, more free draining arisings)
- use of the excavation hole (pile bore) as a settling tank for solids settlement
- use of in-hole slurry cleaning chemicals to promote settlement of any fines that have become dispersed in the fluid
- development of a thinner filter cake (or effectively no cake) on the walls and base of the excavation. This can improve bearing capacity (promoted by lower solids content and lower pressure differential with the groundwater because of lower density)
- the filter cake to be designed to be collapsed/destroyed by the calcium ions in cement improving concrete/soil bond
- inhibition of swelling of the in situ soils and so improved soil/concrete bond.

In addition to these aspects of low density systems the following requirements are essential for all support fluids. The fluid should not damage the setting and hardening of concrete, damage concrete-steel bond or be lost to the ground to an excessive degree.

The construction process

The principal stages of all fluid supported excavation processes are:

1. Preparation of excavation fluid (bentonite slurry – solid-liquid system or polymer fluid – solution).
2. Hole excavation.
3. Check on the fluid properties in-hole and if necessary carry out slurry cleaning or replacement.
4. Concreting or other insertion of a permanent element (eg a borehole lining or a tunnel lining).
5. Fluid conditioning for reuse.
6. On completion of the works, treatment of slurry and disposal.

Preparation of the excavation fluid

- for bentonite slurries, the bentonite concentration is typically in the range of 25 to 50 kg per cubic metre of water (2.5 to 5 per cent). The actual concentration depending on the source and quality of the bentonite, the specification for the works and the soil type(s) to be excavated. Typically a bentonite slurry is prepared in a dedicated plant that will include a high shear mixer, hydration tanks and a slurry recirculation system. A bentonite slurry does not develop its properties immediately on contact with water, some time for hydration should be allowed between mixing and use. The hydration time will depend on the type of bentonite and the level of shear in the mixer. Typically a bentonite slurry will be allowed to hydrate for a few hours before use so hydration tanks are an important feature of bentonite use
- in contrast polymer fluids typically are used at a concentration of 0.5 to 2 kg/m^3 (0.05 to 0.2 per cent), that is at about 25 to 50 times less than bentonite. High shear mixing is not only not required but should be avoided as the polymers for excavation work are of high molecular weight and can be easily damaged (Lam *et al*, 2010). Powdered polymers can be mixed with a simple venturi eductor though direct sprinkling into flowing water can be employed but this can be wasteful as full wetting-out of the polymer is unlikely to be achieved. The hydration is quite rapid, a few minutes to about half and hour. As a result, hydration tanks are not necessary and the fluid can be used immediately. Emulsion polymers can develop their properties effectively immediately but the oil and surfactants present in emulsion systems can make them inappropriate for some construction applications. As polymers are used at concentrations of the order of 25 to 50 times lower than bentonite the site footprint for storage and mixing is minimal compared with that for bentonite.

Hole excavation

The excavation process with polymer fluids is similar to that with bentonite slurries. Care should be taken to avoid dispersion of the soil into the fluid and also with the cleaning of the bottom of the pile hole before concreting. This is good practice for all excavation fluids. Excavation tools and practice should be tailored to particular soils and fluids but discussion on this is beyond the scope of this paper.

Checking fluid properties

An important part of the research at Oxford is the development of test procedures for polymer fluids and the development of the associated specifications. Few of the test procedures used for bentonite slurries were developed specifically for the civil engineering industry. Most have been "borrowed" from the oil industry and are not optimal for polymer systems let alone bentonite slurries. Once the research is complete, findings on testing and specification will be published.

Concreting

Generally, concreting under polymer fluids is similar to that under bentonite slurries though once further research has been completed some optimisation of concrete mix designs will be possible.

Slurry/spoil separation

Bentonite slurries do not inhibit dispersion of soils, ie they do not inhibit the breaking up to clods of excavated soil into individual soil particles, gravel, sand, silt and clay, and they tend to promote it. So in use, and especially with reuse, bentonite slurries often accumulate fines becoming dense and viscous so compromising proper displacement of the slurry by concrete during the concreting phase. To allow slurry reuse it is necessary to separate the fines from the slurry using purpose designed separation plant that typically will include scalping screens, hydrocyclones and dewatering screens. Often the separated fines are discharged as a wet mass that is unsuitable for reuse and can require treatment or blending with drier material before reuse. The preferred option is reuse, which is seldom achieved. Often disposal is required that can be problematic because in the UK liquid wastes cannot be disposed to landfill.

It is with respect to soil dispersion that appropriately designed polymer systems are most distinct from bentonite. Polymer fluids can be designed to inhibit the dispersion of cohesive soils so that the excavated material remains as clods with little tendency for the fines to disperse to form a slurry. Even in sands, the excavated material may appear no wetter than naturally in the ground. The soil behaves as if wrapped in a plastic bag with little penetration of the polymer fluid into the excavated soil. This can greatly simplify reuse of the arisings. The inhibition of soil dispersion brings a further substantial benefit, as there is no need for slurry separation plant.

However, the fluid activity should be maintained. In use the polymer is sorbed onto the soil and lost from the system. It is of important that the concentration of polymer in the fluid is maintained at a sufficient level. If the polymer concentration is not maintained soil will start to disperse into the polymer fluid to form a soil-water slurry. This dispersion will expose more soil surface area permitting further sorption of the active polymer material and ultimately the system will become a water-native soil slurry not a polymer fluid. At this stage, it will have lost all its beneficial properties and become a thick, solids laden slurry unsuitable for construction work.

With a polymer fluid, at the end of excavation and before concreting any soil that has been dispersed into the slurry can be settled using a flocculating agent added directly to the excavation and the solids allowed to settle in the hole for removal with a cleaning bucket. Alternatively suspended solids can be settled in a simple holding tank.

Fluid conditioning for reuse

As discussed, an important requirement for slurry re-conditioning is the separation of suspended soil from the slurry so as to reduce the slurry density and prevent it becoming too thick and viscous. However, for both bentonite slurries and polymer fluids there is a problem of loss of active material during slurry use. For bentonite slurries, bentonite will be lost to the filter cake and with the fines in the separation plant. In both these processes bentonite and water will be lost so that although there will be a reduction in the slurry volume there will be little change in the bentonite concentration in the remaining slurry. However, the concentration will be reduced by dilution of the slurry by water associated with any soil dispersed into the slurry. This reduction in bentonite concentration will be partially compensated by fresh bentonite slurry added to make up for the losses during excavation and the losses in the soil/slurry separation plant. Typically this added fresh slurry will maintain the concentration of bentonite in the slurry at an acceptable level. However, it should be recognised that the in-use bentonite concentration in the slurry will be lower than the as-mixed concentration. Problems can occur with excessive dilution of the slurry during repeated reuse if make-up volumes are small (see the worked example on slurry dilution in Jefferis, 1991).

For polymer fluids particular care should be taken to maintain the polymer concentration as polymers also can be sorbed onto soils, especially fine soils. Polymer concentration will decline in use, especially during excavation. So it is important to maintain the fluid viscosity at the supplier's recommended value to confirm that sufficient active polymer is present. The amount of polymer used should be monitored to confirm that appropriate concentration is being maintained – regular "topping-up" of the fluid with polymer should be the standard practice. Using insufficient polymer can be a false economy. If the active polymer concentration is low, soil will begin to disperse into the fluid so promoting further polymer sorption with the result that the fluid performance rapidly degrades. If the viscosity drops, further polymer should be added to the fluid. Fresh polymer fluid also may be added to make up for losses of volume, for example, as a result of fluid spilled from the excavation tool. In addition to monitoring polymer fluids for viscosity it is important to monitor density to ensure that uncontrolled soil dispersion has not occurred.

Fluid disposal on completion of the works:

For bentonite based system the slurry either should be disposed as a liquid (perhaps as a soil amendment) or it should be solidified by pressure filtration or some other procedure. Options for bentonite disposal are becoming progressively more limited because of increased/improved environmental regulation and the cost of disposal of the used slurry can be significantly higher than the original cost of bentonite purchase and slurry production.

For a well managed low density polymer fluid, the solids content will be low, however it will be viscous. The polymer effect can be reduced by dilution or it can be destroyed with calcium hypochlorite, which is readily available as a swimming pool treatment. Domestic bleach (sodium hypochlorite) also can be used though calcium hypochlorite, a solid material is often simpler to use. Once the polymer has been destroyed any remaining suspended solids will be settle readily settleable. After settlement of solids and with appropriate consent from the sewerage undertaker disposal to foul sewer should be acceptable. With a properly managed and maintained polymer fluid there should be no need to dispose of any liquid during a job. The only disposal required will be at the end of the job.

Conclusions

Modern polymer excavation fluids are different from bentonite slurries. Further research will develop a fuller understanding of soil-polymer interactions and the mechanisms by which polymers systems provide improved performance over bentonite slurries including improved pile performance and stability in loose and caving grounds. The work will develop the necessary theoretical basis for specifications for the use of polymer fluids on site. The early findings of the research are that in a properly managed and maintained system, polymers have many potential advantages over bentonite including:

- small site footprint for fluid operations
- simpler mixing
- reduced requirements for fluid storage as polymers do not require the hydration stage that is necessary for bentonite
- elimination of soil/slurry separation plant
- repeated fluid reuse provided the polymer concentration is maintained
- no disposal of excavation fluid during a job
- at the end of a job simple disposal of fluid to foul sewer after slurry dilution or breaking with calcium hypochlorite and residual solids settlement
- reduced overbreak and improved shaft friction and toe performance
- overall significant economies.

The next stages of the work will include optimisation of polymer slurries for diaphragm walling – especially with hydromills to maximise plant performance and also for slurry tunnelling to reduce the effects of fines dispersion and the tendency of some clays to stick to parts of the tunnelling machine and clog it.

References

BOYES, R G H (1975) *Structural and cut-off diaphragm walls*, Applied Science Publishers, London (ISBN: 0-85334-607-0)

HAJNAL, I, MARTON, J and REGELE, Z (1984) *Construction of diaphragm walls*, Wiley, John & Sons, Incorporated, USA (ISBN: 978-0-47110-002-7)

JEFFERIS, S A (1991) "Grouts and slurries", *The Construction Materials Reference Book*, Doran, D K (ed), Butterworths, UK pp 48/1–48/24

KRAMER, H (1946) "Deep cutoff trench of puddled clay for earth dam and levee protection" *Engineering News Record*, Vol 136, **26**, Technical Information Center, U. S. Army Engineer Waterways Experiment Station, Vicksburg, pp 76-80

LAM, C, JEFFERIS, S A and GOODHUE, K G (2010) "Observations on viscosity reduction of PHPA polymer support fluids". In: *Proc int conf sessions of GeoShanghai 2010, 3–5 June 2010, Shanghai, China, Deep foundations and geotechnical in situ testing (GSP 205)*, R Y Liang, F Zhang and K Yang (eds), ASCEM, Geo Institute, Reston, VA (978-0-7844-1106-3)

VEDER, C (1963) "The excavation of trenches in the presence of bentonite suspensions for the construction of impermeable and load bearing diaphragms", In: *Proc Grouts and drilling muds in engineering practice, symposium of the British National Society on Soil Mechanics and Foundations Engineering, Institution of Civil Engineers, London*, pp 181-188

XANTHAKOS, P P (1979) *Slurry walls, McGraw Hill Publishers*, London (ISBN: 978-0-07072-216-3)