Construction of a cement-bentonite slurry trench

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ABSTRACT: The design and implementation of a remediation measure aimed at impeding seepage from an existing residue facility was carried out. The design called for the construction of a cement-bentonite slurry cut-off trench, using the under-slurry construction technique, combined with a conventional subsoil drain. The aim of this paper is to present the investigation and design aspects briefly with the main focus being the implementation phase and the lessons learnt during implementation as a case study. This paper documents the process followed during construction to ensure that the design objective was met, considering the challenges faced during implementation.

1 INTRODUCTION

A comprehensive investigation was undertaken in 2006 to determine the amount of seepage emanating from existing residue facilities with the aim of establishing the relative contribution of each facility. As part of the investigation, remediation measure recommendations were made. This paper focusses on the remediation measure proposed to impede seepage from an existing residue facility.

As with most construction projects, challenges were encountered during the implementation phase. Seeing that a cement-bentonite slurry cut-off trench is relatively novel in South Africa, this paper aims to elaborate on the lessons learnt during the construction phase to assist other geotechnical practitioners who may come across a similar project in their careers.

The implementation phase commenced mid-2022 and was completed in early 2023.

2 INVESTIGATION

A comprehensive geotechnical investigation was carried out in 2006 which comprised the excavation and profiling of test pits as well as the drilling of auger holes. The test pits and auger holes provided information regarding the seepage from the facility under consideration as well as the ground conditions in order to comment on suitable remedial measures. Of the two methods of investigation, the auger holes were drilled closer to the facility.

A total of four auger holes were drilled along the alignment of the proposed cut-off trench with 13 test pits excavated to the east of the auger holes. Figure 1 presents the position of the test pits relative to the auger holes which were drilled along the edge of an existing access road surrounding the facility.

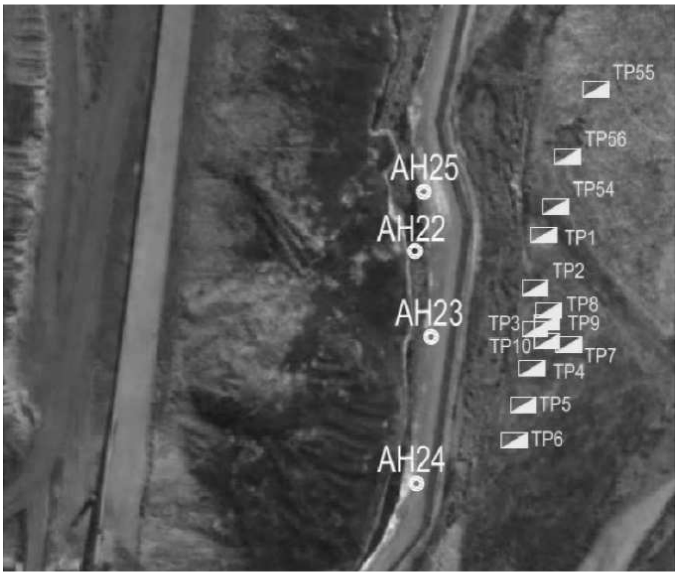

Figure 1. Locality of the auger holes and test pits

The site is underlain by between 1.5 m and 2.5 m of medium dense to firm, clayey sand / sandy clay fill of varying origin underlain by either firm to stiff silty clay alluvium or medium dense to dense, clayey coarse sand, residual dolerite to about 4.0 m depth. Soft rock dolerite underlies the alluvial and residual dolerite horizons below 4.0 m depth.

Seepage was encountered from about 1.9 m depth. The water level in the auger holes varied between 2.4 m and 3.9 m depth soon after drilling was completed. The sidewalls remained stable with no indication of sidewall collapse noted in the auger profiles.

It must be noted that auger holes were not drilled along the entire alignment of the proposed cut-off trench alignment. No further investigation work was conducted along the portion of the cut-off trench alignment which was not covered by the auger holes.

3 DESIGN

3.1 *Design basis*

Due to physical site constraints, a cement-bentonite slurry trench was preferred as conventional excavation with slope battering would not have been possible. For the cut-off trench to perform as per the design, the design consisted of two elements. The first being the cement-bentonite slurry cut-off trench which was designed to impede seepage. The second element being a subsurface drain capable of intercepting the increasing water table on the upstream side of the cut-off.

3.2 *Cement-bentonite slurry cut-off trench*

3.2.1 *Trench dimensions*

A cut-off trench typically takes the form of a narrow, vertical trench. Considering the subsurface profile evident from the geotechnical investigation, the cut-off trench was designed to be continuous from surface to bedrock. Based on the results of the investigation, the maximum depth of the trench was specified as 7.0 m from ground level or refusal at shallower depth, whichever comes first.

To rule out any uncertainty regarding the definition of refusal, refusal was taken as the contact between intermediate excavation and hard rock excavation as done with a minimum 25-ton excavator (or larger) with tines in good condition.

The width of the trench was specified as 0.6 m or greater. The reason for this is that the 0.6 m was deemed sufficient for the wall to act as an impermeable barrier. However, tendering contractors could elect to construct a thicker wall if they only have access to excavators with larger buckets. This ultimately meant that a larger contingent of contractors could tender for the project. In terms of payment, the bill of quantities was set up such that the contractor would be paid for the cross-sectional area of wall constructed on a vertical plane through the centreline of the trench. Hence, payment for the construction of the wall was independent of the bucket width. The trench was designed to be 819 m in length.

3.2.2 *Construction technique*

A major concern with the construction of a cut-off trench is the probability of side wall collapse, seeing that open excavation by means of excavator was specified. For this project, the fill horizon encountered during the investigation posed the greatest risk as manmade fill horizons typically tend to be prone to side wall collapse.

The design called for the use of the under-slurry technique which entails keeping the excavation filled with fresh cement-bentonite slurry during the excavation works. The water from the slurry suspension bleeds into the pervious sides of the trench and leaves behind a thin, densely packed collection of colloidal particles, often referred to as a "filter cake". The hydrostatic force of the slurry acting in combination with the filter cake, provides stability to the sides of the trench. The filter cake also provides the primary contribution to the overall low permeability of the completed cut-off wall.

3.2.3 *Slurry mix design*

A mix design was proposed at tender stage on the proviso that mix design tests would be conducted by the successful contractor soon after contract award to confirm the correct mix. The proposed mix comprised a self-hardening cement-bentonite slurry which contains a minimum of 7% of bentonite in the slurry (measured as the weight of dry bentonite to the weight of water) and 25% cement (measured as the weight of dry cement to the weight of bentonite-water slurry). It must be borne in mind that the cut-off trench was not designed to be a structural element.

The bentonite specified for this project was a sodium bentonite which comprises naturally occurring, powdered, sodium cation exchanged clay mineral composed primarily of montmorillonite (bentonite) with minor amounts of quartz. Further to the above, the bentonite had to meet other criteria, such as Free Swell, Filtrate Loss, Moisture Content, and grading requirements.

Much like the bentonite, a specific type of cement was also specified for the project, namely CEM II \ B-V. The reason being that this cement type has a high fly ash content which assists in making the mix pumpable. Considering the fact that the trench was 819 m long, pumping the mix over long distances could be a challenge, hence the requirement for a pumpable mix.

Other requirements for the slurry mix were as follows:

- Only potable water could be used for the mix.
- The bentonite had to hydrate for at least 24 hours prior to adding the cement.
- Mixers capable of achieving a strong shearing action were required to give superior performance

and rapid hydration (i.e., colloidal mill mixer, side-winder mixer, venturi flume etc.).
- A 0.5 m over dig (overlap) into the previous day's work was required to ensure a continuous trench with no joints which could compromise the performance of the trench.

3.2.4 *Other considerations*

Achieving a depth of 7.0 m using a conventional excavator is unlikely and hence, the design incorporated a 2.5 m wide by 0.8 m deep capping cut into the natural ground level to create a working platform from which the slurry trench could be excavated. This meant that the excavator only needed to achieve an excavation depth of 6.2 m.

During the drying process, the slurry level would tend to lower, and cracks open up to a limited depth on the surface of the trench. Hence, it was required that the trench be topped-up and cracks be filled with fresh slurry for a period of 10 days after placement to allow the slurry to cure.

As mentioned earlier, the slurry trench was not designed to function as a structural element. Considering the fact that the trench was to be built along an access road, the trench could not be left open for long as the road had to be returned to service as soon as possible. After the above-mentioned 10 days, the backfilling of the 0.8 m deep cut had to commence to form a structural cap over the cement-bentonite cut-off. Seeing that it was unlikely that the slurry would have set by this stage and gain sufficient strength to support the backfill, the design incorporated a layer of geogrid that had to span over the slurry trench. The geogrid allowed the backfilling process to continue unhindered from a safety and constructability point of view.

3.3 *Subsurface drain*

Seeing that the cut-off trench is impeding the flow of the water, it was expected that the water table would rise to the extent that it could overtop the trench. Hence, a subsurface drain was designed on the upstream side of the trench with an invert elevation to intercept the water prior to this happening.

The southern end of the cut-off trench was designed to start at an existing manhole where an existing subsurface drain terminated. The northern end, an existing sump structure constructed years before which was connected to a downstream network of pipes and manholes.

The drain was designed to tie into these two existing structures to complete the existing drain system around the facility under consideration. The fall of the system was to the north, into the existing manholes and pipes downstream of the existing sump.

The drain designed comprised of 600 mm diameter concrete culvert pipes. To allow seepage water to seep into the main pipe system, the culvert pipes were installed with a 10 mm gap between each pipe. The joint was wrapped in a geotextile to prevent ingress of fines. The purpose of this pipe was to both convey water reporting from the existing system upstream of the tie-in point and to collect seepage alongside the cut-off.

To further assist in intercepting and conveying seepage water, the design incorporated two geotextile wrapped, 160 mm diameter perforated pipes placed on either side of the 600 mm diameter culvert pipes in the same trench. The design included a series of 1.5 m diameter manholes into which the culvert and perforated pipes reported. The manholes were stationed at each significant direction change and/or at 100 m spacing (maximum) to allow for maintenance of the system.

On the upstream face of the trench excavation, the design called for a geocomposite drain consisting of a geonet wrapped in geotextiles. Seeing that the seepage was reporting to the drain from the upstream side, this geocomposite drain was aimed at intercepting the seepage and leading it directly to the perforated pipe. Refer to Figure 2 for a typical detail of the subsurface drain relative to the cut-off trench.

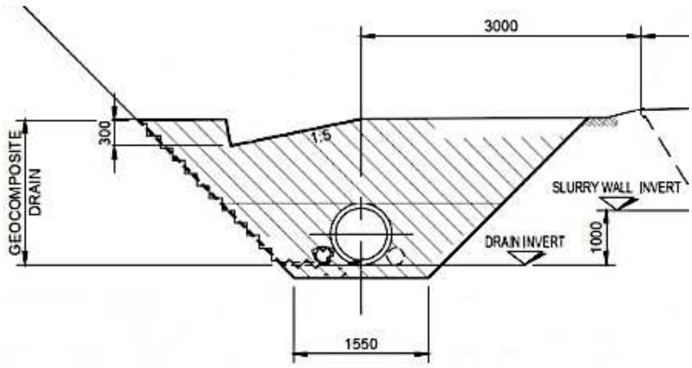

Figure 2. Typical detail of subsurface drain (not to scale)

4 IMPLEMENTATION OF CHECKS AND BALANCES

For most geotechnical engineering designs, the quality control and quality assurance (QA/QC) aspects are critical to the successful implementation of the design. In the case of this project, a number of measures were put in place to monitor the works. Note that the QA/QC measures for the toe drain are not discussed below as it is regarded as conventional civil engineering works for which QA/QC procedures are well established.

4.1 *Pre-implementation*

The first measure put in place to ensure that the cement-bentonite slurry mix was suitable for this project was a set of testing conducted on a variety of mixes to obtain the optimum mix. After the contract was awarded, the successful contractor had to undertake the testing which entailed filling four 200-liter drums halfway with bentonite-cement mixes in which the ratio of the cement to the bentonite-water slurry was varied to 15%, 20%, 25%, and 30%, respectively.

Prior to adding the cement, the following tests had to be conducted on the mixes:

- Mud Density Balance as per ASTM D4380 (2020) at 20°C < 1 100 kg/m3
- Viscosity by Marsh Cone as per ASTM D6910M (2019) at 20°C to be between 30 s and 90 s.

After the cement was added, density and bleeding tests were conducted on the cement-bentonite slurry. The density of the cement-bentonite slurry was measured again (Mud Density Balance at 20°C). The bleed also had to be measured 24 hours after mixing by carefully pouring the slurry into a measuring cylinder up to the 1000 ml mark whilst ensuring that no air was entrapped in the cylinder. The top of the cylinder then had to be sealed off and left for 24 hours. The volume of set cementitious slurry in the cylinder had to occupy at least 980 ml. Based on the trial conducted, the optimal mix design comprised 25% cement to 7% bentonite measured as the weight of dry cement to the weight of bentonite-water slurry.

4.2 *During implementation*

During the implementation phase, the contractor prepared checklists aimed at prompting the contractor to take certain measurements or interventions during construction of the trench.

During the slurry trench excavation, the contractor recorded the elevation of the trench working platform at 1 m intervals and the corresponding depth of the excavated trench at each point. From a frequency perspective, the depth was measured immediately after excavation took place as well as two hours later. Depth readings were also taken at the end of each day and on the following day at the edge of the overlap excavation made into the previous day's work. All measurements were recorded against the applicable chainage and submitted for review.

Over and above the depth recordings, the contractor had to complete a daily batching checklist which recorded the required information for the slurry batch prepared for the day's work. The tests discussed in Section 4.1 had to be conducted for each and every batch prepared, and the results recorded in the abovementioned checklist for approval.

4.3 *Post implementation*

On completion of a section of trench, the contractor took a block sample of completed slurry wall at 200 m intervals. The block sample was sent to an accredited geotechnical laboratory to undergo flexible wall permeameter tests to confirm the permeability of the slurry wall and the uniformity of the permeability over the length of the trench. The results of these tests were not available at the time of writing.

5 LESSONS LEARNT

A retrospective assessment of the project is deemed necessary in order to learn from challenges experienced and how these can be better managed in future projects.

5.1 *Safety considerations*

The health and safety of personnel working on a construction project is of utmost importance. In the case of this project, two critical safety elements were highlighted. The first of which being the batching plant and the second being the actual trench construction.

The cement was delivered to the site in 1-ton bulk bags. During the mixing process, the cement was added to a tank containing the hydrated bentonite. Due to the scale of the mixing process, multiple bags of cement had to be mixed into the hydrated bentonite prior to pumping the mix. To do this, the bags were lifted by a forklift and then positioned over the hatch situated at the top of the tank. In order to release the cement, the batch plant operator had to reach under the bag to untie the release mechanism under the bag. This action was not identified as a safety risk during the planning stage as the contractor did not fully disclose his/her planning for the works. This risk only became known when the first batches were being mixed, and immediately flagged as an unsafe action considering the weight of the bag suspended above. To address this risk, the batching process was halted, and appropriate risk assessments carried out to determine the way forward.

The second safety concern was the trenching itself. The reason being that the cement-bentonite slurry takes at least 10 days to set. Hence, the risk of a person falling into the trench and potentially drowning was a concern. This does not only apply to the contractor's personnel during working hours but to other personnel in the area that might venture onto site after hours or over weekends. To mitigate this risk, the trenches were hard barricaded by means of scaffolding sections to prevent unauthorised access as far as possible. Appropriate signage was also installed to highlight the risk of the deep excavations.

Safety considerations are overlooked in some cases by no fault of the parties involved as some risks only become apparent when the activity is taking place. A lesson learnt is to undertake regular risk assessment meetings with all parties involved to talk through the contractor's methodology in order to identify risks that could lead to delays or worse, injury or death. This should especially be the case for non-conventional works.

5.2 *Equipment selection*

The batch plant was situated at the northernmost end of the trench which meant that the slurry had to be initially pumped for a distance of about 800 m to the southernmost point. Although all precautions were taken to increase the pumpability of the mix (high cement content, cement specified contains high amount of fly ash etc.), the contractor experienced severe challenges in pumping the mix.

The original plan was to have a single centrifugal pump at the batch plant sized to pump the volumes required to the extremes of the trench. This proved unsuccessful. Several options were considered, such as installing a booster pump midway in the pipeline, pumping the mix into a cement truck that would then discharge into the trench etc. The option eventually implemented was to switch the pump type from a centrifugal pump to a positive displacement pump designed to pump slurry over long distances. This intervention proved successful.

A valuable lesson learnt is that contractors should, as far as possible, consult the designers, equipment manufacturers, other contractors, experts in specific field etc. in order to choose and specify the appropriate equipment for the project. This item potentially also speaks to the appointment of an experienced and reputable contractor for the specific project to lessen the risk posed to the project and ultimately, the client.

5.3 *Depth variation*

The trench excavations started from the southernmost point (Chainage 0 m) moving towards the north (Chainage 818 m).

Up to about Chainage 425 m, the trench refusal depth stayed more or less consistent at about 4 m below platform level (i.e., 0.8 m below ground level). From Chainage 425 m onwards, the refusal depth varied considerably.

Isolated zones of shallow refusal were identified during the trenching, examples of which being Chainage 248/249 m and 269 m. Upon closer inspection, the depth records showed that the refusal depth suddenly decreased from 3.1 m (Chainage 247 m) to 2.0 m and 1.8 m (Chainage 248 m and 249 m, respectively) whereafter it increased again to 4.0 m (Chainage 250 m). A similar occurrence was noted at Chainage 269 m.

In contrast, zones were also encountered which exceeded the 6.2 m maximum trench depth, to the extent that the excavator did not reach refusal in some zones (Chainage 784 m to 813 m).

To investigate the causes of the shallow refusals, a series of tests pits were excavated adjacent to the zones where the shallow refusal occurred. In some cases, a horizon containing cobbles and boulders were encountered on top of which the excavator refused. In other cases, manmade materials at shallow depth caused the shallow refusal (abandoned buried concrete slabs etc.).

In terms of remedial works, diversion cut-off trenches were constructed around the cause of the shallow refusal to ensure that the cut-off was continuous in length and depth to ensure the integrity and functioning of the cut-off trench. In areas where refusal was not reached, the working platform was lowered by an additional 0.7 m in order to achieve refusal.

The above-mentioned does not really constitute a lesson learnt as the necessary QA/QC measures were in place during implementation which made it possible to track the trench depths daily. Without these records, these zones of shallow refusal or non-refusal would have been missed, and the functioning of the trench would have been impaired. This does prove the importance of QA/QC measures, the diligent application of these measures by the contractor and engineer on site and further investigation of areas of non-conformance.

Further to the above, it was also found that informing the contractor of the purpose of the works they are performing, benefits the project as the contractor has a better understanding of why they are performing the work and what the end-goal is. The fact that the contractor has a set of construction drawings and bill of quantities does not mean that they fully understand the design and project intent.

5.4 *Detailed investigations*

As mentioned in Section 2, the investigation included auger drilling of four boreholes along the alignment of the proposed trench, concentrated along the southern portion of the trench between Chainage 0 m and 300 m. The results of the investigation yielded that refusal could be expected from about 4 m to 5 m depth, and this was the case for the first 425 m of the trench. Thereafter, the depths varied considerably. Upon further investigation, the following two causes were ascribed to the shallow or non-refusal:

- Change in geology. The first 425 m of the trench was underlain by dolerite bedrock whereas the remaining 400 m was underlain by sandstone/siltstone bedrock. Although the exact contact could not be determined, it is likely that the bedrock level increased to the north as the geology changed from dolerite to sandstone/siltstone.
- A portion of the trench alignment to the north passed through what is thought to have been a historical landfill site. It is likely that the shallow refusal on manmade materials is as a result of the presence of this landfill and abandoned concrete etc.

As is the case for many projects, a more detailed investigation could have pre-empted some of the challenges experienced with depth variations. In this case, the investigation technique (auger drilling) was suitable. However, the extent of the investigation should have been extended along the entire proposed alignment of the trench. It could well be that at investigation stage, it was not known that a slurry cut-off trench would be the preferred solution. However, a follow-up investigation could have been commissioned during the detail design phase to better inform the detail design phase and highlight any risks that could jeopardise the successful completion of the project.

5.5 *Unavailability of materials*

During the design stages, South African cement manufacturers were readily stocking and supplying CEM II \ B-V cement. At the time of contract award, which was about two years later, none of the cement manufacturers had stock of this cement and were not planning to produce this cement in the near future. Several mitigations were discussed, such as blending other cement types with commercially sourced fly ash, to replicate the CEM II \ B-V variant. Fortunately, one of the cement manufacturers committed to supplying this cement, albeit in bulk (by tanker or 1-ton bags).

The aforementioned speaks to the safety considerations discussed in Section 5.1 as the batch plant was originally designed for the use of 50 kg cement bags and not 1-ton bulk bags. Due to this shortage, the batch plant design had flaws which resulted in safety risks to personnel when the type of supply changed after completion of the batch plant.

A lesson learnt is that if there is a considerable time delay between design completion and construction, the client, engineer, and contractor should take it upon themselves to determine whether the products and materials specified in the technical specification are readily available in the market. If not, plans can be made ahead of time to potentially mitigate the risk posed to the project.

5.6 *Loadshedding*

During the closing stages of the implementation phase, South Africa was facing Stage 6 loadshedding for extended periods of time. Loadshedding entailed the planned interruption of the supply of electricity to areas in order to protect the national grid. Stage 1 meant that 1000 MW of capacity had to be shed with 1000 MW added per stage, meaning that 6000 MW of capacity was being shed during Stage 6.

A risk not identified at tender stage was that some materials may not be readily available in the market as loadshedding could affect the production and supply of certain materials.

Unfortunately, the bentonite supplier contracted by the contractor encountered severe shortages of bentonite due to loadshedding. The mines responsible for mining the bentonite were severely impacted by loadshedding to the extent that the waiting period was in the order of one month towards the end of the project. The lesson learnt is to always have a back-up supplier for a particular product just in case the main supplier cannot supply the material, for whatever reason (not only loadshedding).

6 CONCLUSIONS

The design and implementation of a remediation measure was carried out to impede seepage from an existing residue facility.

The design called for the construction of a cement-bentonite slurry cut-off trench, using the under-slurry construction technique, combined with a conventional subsoil drain. The slurry trench had to be installed to refusal on bedrock. The subsoil drain comprised a combination of culvert pipes, perforated drainpipes and geotextiles with the aim being to intercept the water table dammed up behind the newly installed slurry cut-off wall.

A series of quality control and quality assurance measures were implemented during the various parts of the implementation phase aimed at ensuring that the cut-off trench ultimately serves its purpose as an impermeable barrier.

As with most construction projects, challenges were experienced during the implementation phase. The construction of cement-bentonite slurry cut-off trenches in South Africa is novel. Hence, the lessons learnt during the project have been presented in this paper as a case study.

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