CONSTRUCTION OF FULL-SCALE SHAFT SEALS IN CRYSTALLINE ROCK

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ABSTRACT

The Underground Research Laboratory (URL) was constructed to investigate concepts related to geological disposal of used nuclear fuel. This involved investigating the rock mass by undertaking in situ experiments using a multi disciplinary technical approach. The decision was made in 2003 to close the URL. Part of the closure process involved installing seals in the access and ventilation shafts at locations where they intersected an ancient thrust fault (Fracture Zone 2 – FZ2). FZ2 is an active hydraulic pathway in the Lac du Bonnet batholith and this feature is the dominating structural and hydrogeological feature at the URL site. Above FZ2 the groundwater has a low salinity and is dominated by surface-related processes. With increasing depth in the batholith, surface-related effects decrease and the salinity of the groundwater increases to 90 g/L total dissolved solids. The decision to install the seals was made as part of the due diligence for the site closure to ensure that the saline groundwater located at depth down strike and below the thrust fault would not enter the closed underground openings and mix with less saline shallow groundwater. The construction of each seal involved the installation of a heavily reinforced low alkalinity concrete component keyed into the surrounding rock. The concrete supported and restrained a central clay-sand component, which was capped by an unreinforced concrete component. The clay-sand component spans the exposure of the thrust fault in each shaft.

This paper describes the construction of the main shaft seal and the ventilation shaft seal. The construction of the shaft seals at the URL was part of the Nuclear Legacy Liabilities Program (NLLP) being funded by Natural Resources Canada (NRCan).

1. INTRODUCTION

Construction of Atomic Energy of Canada Limited's (AECL's) Underground Research Laboratory (URL) began in 1982 and was completed in 1990. Following the construction phase, the experimental phase began, and continued until 2003 when closure of the facility was announced. The closure phase continued until 2010 when the underground access points were sealed at surface. The URL was situated in the Lac du Bonnet Batholith, in eastern Manitoba near the Whiteshell Laboratories (Fig 1). The Lac du Bonnet Batholith is a relatively complex structure, with evidence of multiple magma injections. The granite ranges from fine-grained (intrusive mafic rich granite dykes), to medium-grained (the main body of the batholith) to coarse-grained (pegmatite dykes).

The URL consisted of two major levels (240 and 420 Levels) and two drilling stations (130 and 300 Levels) accessed by a 443 m deep shaft. The upper part of the shaft from surface to the 255 m depth is rectangular (2.8 x 4.9 m) and the lower part is circular and 5 m in diameter. An exhaust air vent raise/escape way connects the surface and 240 Level and the 240 and 420 Levels. Raise boring was used to excavate both ventilation shafts. The access shaft and the majority of the tunnels were excavated by drilling and blasting. The shaft raises and tunnels totaled about 2.5 km in length.

During excavation of the main and ventilation shafts, an ancient thrust fault (Fracture Zone 2 – FZ2) was intersected (Fig 2) at approximately 271 m to 275 m depth in the main shaft and 265 m to 268.5 m in the ventilation shaft. FZ2 is an active hydraulic pathway in the Lac du Bonnet batholith and this feature is the dominating structural and hydrogeological feature at the URL site. It has a dip of about 25° to 30° and appears controlled by foliation in the batholith [1]. Above FZ2 the groundwater is younger (meteoric to glacial age), and less saline (<2 g/L TDS – total dissolved solids content), and is dominated by surface-related processes. With increasing depth in the batholith, surface-related effects decrease and the groundwater is older, with salinity up to 90 g/L TDS. The fracture zones at the URL act as primary conduits for water movement in the batholith and have surface discharge points to the west of the URL site.

The shafts penetrating FZ2 provide a possible route for the shallow-sourced, less saline groundwater and the deeper, higher salinity groundwater to mix more quickly than would occur in the absence of these openings. As part of the due diligence for the site closure, a decision was made to install seals in these excavations in order to reduce the possibility of any significant mixing of these groundwaters.

2. SEAL CONCEPT

The seal concept adopted for the URL shaft seals consists of two keyed, conical frustum shaped, concrete components that confine a central blended clay-sand component. This shape was selected in order to provide mechanical restraint to the clay and also to facilitate cutting off the excavation damaged zone (EDZ) associated with the shaft walls. The concrete used is a low-pH, high performance concrete (LHHPC) designed to have a reduced chemical influence on adjacent clay materials by reducing the long term alkalinity (with a pH reaching ~9.8) and essentially eliminating free portlandite after curing [5]. The design and materials used as shaft seal components were based on the design concepts and lessons learned from the Tunnel Sealing Experiment (TSX) [6][7].

In the main shaft, the conical frustum shaped concrete components are 3-m-thick and increase from a 5-m to 6-m diameter (Fig 2) and confine a 6-m-thick swelling clay section. In the ventilation shaft, the concrete components are 2-m-thick and increase from 2 m to 2.5 m in diameter. The central clay component of the main access shaft seal consists of a mixture of Wyoming bentonite and sand-sized aggregate (40:60 mass ratio) that had a target dry density of 1.8 Mg/m^3 using conventional dynamic compaction techniques. Due to the smaller diameter of the ventilation shaft pre-compacted blocks composed of 70% Kunigel V1 bentonite and 30% sand having an initial dry density of approximately 1.9 Mg/m^3 were installed instead. Kunigel VI is recognized as having a lower swelling clay content relative to Wyoming-type materials (~48% versus >75%). These blocks were the same type as were used in the TSX and once hydrated provided an effective seal [7]. These bentonite-sand materials both provide a substantial self-sealing capacity to the installation and will minimize groundwater flow and mass transport from the fracture zone to the underground openings.

Backfilling below the shaft seals was not a regulatory requirement of the URL closure. The area below the seal locations was intentionally progressively flooded as decommissioning activities advanced. This was done to prevent the formation of a large air pocket that could become pressurized and cause damage to the seals. Flooding reached approximately 2 m below the bottom of the formwork prior to seal installation. Seepage from FZ2 and water from operational wetting of shaft set timbers during installation was anticipated to fill the remaining volume.

3. INSTALLATION OF THE SHAFT SEALS

3.1 Pre-installation

The installation of the seals was part of the closure project of the URL. The closure was managed by first decommissioning rooms furthest from the access shaft and retreating back to the access shaft. Closure and removal of the underground furnishings began on the 420 Level. Grouting was undertaken immediately around the access and ventilation shaft to reduce groundwater inflow into the main access and ventilation shafts at the intersection of FZ2 and the seal locations [2]. It was not expected that the grouting would fully seal the fracture zone at the shafts; its purpose was only to temporarily reduce inflow into the shafts via FZ2 making seal material placement less challenging. Approximately 1.1 m^3 and 1.95 m^3 of grout were injected into the fracture zone at the ventilation and access shafts respectively. Based on average water inflows collected at the shaft FZ2 location during operations at the URL and collection of distinct water inflows post-grouting the inflow rate was reduced from approximately 0.5 m^3 per day to 0.22 to 0.25 m^3, a reduction of approximately one-half.

During the later part of the closure work 420 Level, the lower ventilation shaft between the 420 and 240 Levels had the escape ladder system hoisted and cut into manageable sections for slinging to the surface. Work then progressed up the shaft to approximately the 255 m depth in the shaft. The main shaft sets and services were too large for hoisting and were cut in place before hoisting. This cleared the shaft walls for work to install the shaft seals at the FZ2 intersections.

As the 420 Level closure was completed, a working platform known as a Galloway stage was installed in the shaft (Fig 3) to facilitate removal of the shaft furnishings (steel and wood framing). The Galloway stage was a three-decked work platform designed with removable "wings" to allow the shape to be adapted to the change in shaft configuration of circular (443 m depth (shaft bottom) to 255 m depth) to rectangular (255 m depth to surface). The lowest deck was designed to detach and become the formwork for the lower concrete component of the shaft seal. A similar smaller unit was employed in the ventilation shaft. Unlike the main access shaft, the ventilation shaft was approximately 3° from vertical to allow proper angling of ladders; this required the mobile staging in the ventilation shaft to have steel runners to facilitate movement.

Although a repository shaft would likely be entirely backfilled and sealed, potentially using a variety of materials, backfilling was not a mining regulation requirement for closure of the URL. It was therefore decided not to backfill those regions below the location of the shaft seals. This meant that the seals at the URL had to be self supporting; therefore, the lower concrete component was designed to support the mass of all materials above. This made the mechanical strength requirements of the seal equal or greater than that which would be needed for a shaft where backfill had been installed. Once the shaft sets had been removed to 255 m depth in the shaft, the 420 Level, was intentionally flooded using water from the URL minewater retention pond and boreholes intersecting groundwater in the upper part of FZ2 with relatively low salinity. The rate of water inflow to the URL was only approximately 4 m^3 per day and so it would take many years to naturally flood the regions below the plug leaving no opportunity to test seal effectiveness. An unflooded shaft would also see the formation of a pressurized gas pocket under the seals.

3.2 Excavation and formwork

The shaft walls were mechanically excavated to key the conical frustum shape for the cast-in-place concrete components into the rock. Hitches were also excavated to allow support beams to be installed below the lower concrete formwork. The clay section was not keyed.

The horizontal perimeter of each 0.5 m deep key was drilled and reamed to separate it from the surrounding rock mass without inducing discernible mechanical damage to the rock. This depth was based on the typically measured hydraulically active depth of the EDZ at the URL of 0.5 m [4]. A greater depth was not desired as the excavation (particularly above FZ2) could intersect the holes used to grout FZ2 in advance of seal installation. The horizontal section of the concial frustum provided a clean cut-off for the excavation of the remaining key volume. The angled portion of the keys were drilled and blasted. The amount, type of explosive used, and blast hole pattern drilled, were designed to minimize blast induced fracturing to the surrounding intact rock mass. The configuration of the excavation work for the main access shaft is shown in Figure 4.

In the ventilation raise, the rock had been partly coated with shotcrete in the area of the seal. Two strips of the shotcrete were removed to permit the clay-based material to contact the rock wall to improve the sealing capability of the installation.

After excavation was complete, the lower formwork deck of the Galloway stage was rockbolted to the shaft walls. The formwork deck was constructed of a welded grid of structural steel H beams overlain by a steel plate deck. Two steel I-beams spanning the shaft and extending into the hitches in the shaft walls were then installed. The beams were bolted and welded to the deck for further support.

3.3 Concrete placement

The lower concrete component in each seal was designed to support its own mass and the material above it (including a full hydraulic head) once cured without support of the lower formwork. The LHHPC is a blend of two binders and one filler (cement powder, silica fume and ground silica) as well as sand and aggregate. Normally these materials are only blended at mixing time as moisture in the sand and aggregate would cause premature setting of the concrete. For the URL seals, the sand and aggregate were oven dried to evaporate all water and then pre-blended with the binder and filler components and bagged prior to mixing. The 1 m^3 (~2165 kg) bags of blended material were wrapped in plastic to prevent moisture uptake and shipped to the URL site. This approach greatly reduced the requirements for onsite material handling and allowed the concrete preparation to be done more effectively. During concrete mixing the bags of pre-blended mix were moved to the front of the 2 m^3 mixer and hoisted over top of the mixer using an overhead crane. Mixing with water and superplasticizer required a minimum of ten minutes. The mixer discharged the blended concrete into a concrete pump that moved the concrete to the shaft collar into a bottom dump bucket that in turn was used to transport the concrete down the shaft to the seal location. A flexible rubber chute attached to the bottom of the bucket allowed the concrete to be directed as required during placement. For the ventilation shaft seal, the concrete was emptied into the hopper of a second concrete pump located underground that moved it across the level to a hopper that supplied a slick line to the seal location (Fig 4). Table 1 shows the volume and total time required for each pour.

3.4 Clay-based material placement

3.4.1 Main shaft

The material installed between the concrete components in the main shaft consisted of in situ compacted, clay-based material with 40% dry mass of Wyoming sodium bentonite (200 mesh gradation), and 60% uniformly graded, water-washed sand (<2% of 200 mesh size). The target installed dry density of this material was 1.80 ±0.05 Mg/m^3.

The clay-based material used in the shaft was prepared on surface at the URL using a truck mounted, small batch concrete mixing plant (Fig 6). The sand and clay were put into hoppers on the truck and gates at the base of the hoppers controlled the material volume being supplied to a mixing auger. The amount of water needed to achieve the required mixture moisture content was added through a spraying nozzle where these two materials were blended using a screw-type auger. The auger fed the blended material into bags that were stored in a warehouse until needed. During seal construction, the clay-based material was transferred into a bottom-dump concrete bucket with a maximum capacity of 2000 kg that was lowered into the shaft by a hoist and discharged at the seal. The material was then manually spread using rakes and shovels.

Two electrically powered vibratory rammer compactors were used to compact the clay-based material and a smaller electric compactor (an impact hammer) was used to compact the perimeter region where the larger compactors could not operate effectively. Preventing groundwater seepage from entering the region where clay-based material was being installed was a critical issue during placement and compaction. This was made easier by the grouting work done in advance of seal installation. Plastic sheeting was installed to catch and direct seepage from above the seal to water collection rings were it was drained to a collection point for pumping. In addition to water entering from the upper shaft there was water entering the excavation via the fracture zone itself. The major groundwater seepage from FZ2 was originally encountered in the southwest quadrant of the shaft, where the fracture zone was lowest along the shaft wall. The inflow rate decreased noticeably from the initial 0.25 m^3/day as the clay elevation increased and the lowermost inflow locations were sealed by the clay. With installation of the clay, the inflow shifted location along the fracture zone just above the level of clay installation until the fracture zone was completely covered.

In the early stages of clay installation groundwater seepage proved problematic and temporary formwork was installed along the southwest quadrant area to isolate the inflow location. This consisted of readily removable wooden sections that extended to a height of 1.0 m above the lower concrete seal. Groundwater seepage was directed to the cribbing area using polyethylene sheets and it drained past the concrete until the clay was placed, into the as-yet incompletely flooded lower shaft (as anticipated, the shrinkage of the concrete as it cures resulted in a hydraulic connection to the lower shaft). A hydraulic connection past the concrete was not an issue as the concrete is expected to play a purely mechanical function in seal performance. This cribbing was left in place until clay-based material height reached the elevation of the main seepage locations (Fig 7). The volume behind the formwork was then filled and compacted using a small, high-energy pneumatic impact hammer as the formwork was removed.

Installation of the clay component of the shaft seal, required 25 working days (one 10-hour shift/day) from 2009 October 06 to 10 November. This included time needed to install an array of monitoring sensors in and around the clay-based material. The total mass of 40:60 bentonite-sand material placed in the clay component was approximately 217 tonnes and in total, 104 lifts were installed. The total volume of the clay seal segment installed in the shaft was approximately 107 m^3 and an average dry density of 1.81 Mg/m^3 was achieved.

3.4.2 Ventilation shaft

The ventilation shaft seal contains pre-compacted blocks composed of 70% Kunigel V1 bentonite and 30% uniformly graded, water washed sand. The blocks were sized at approximately 0.36 m x 0.10 m x 0.17 m to permit hand placement, which was suitable in the confined space of the ventilation raise. Examination of the blocks prior to their use found approximately 3.4% volumetric shrinkage and a slight reduction in their gravimetric water content after 12 years of storage, but they were still suitable for this application. The clay blocks were installed a series of layers. Each layer required an average of 47 blocks and was rotated about 30º clockwise from the layer below it in order to reduce the likelihood of piping between the layers along a continuous joint. Pre-crushed blocks and powdered 40:60 bentonite-sand mixture was used to fill any gaps between the blocks and the rock wall as installation progressed. A small impact hammer was used to compact the filling material. The quantities of placed materials were recorded to calculate the seal as-placed density. Samples were taken in the course of clay seal installation to provide a record of as-placed water content.

Minor groundwater seepage of approximately 0.003 m^3/day was encountered during installation of the clay seal in the ventilation shaft. Such a low rate of seepage did not require any remedial measures. It took seven working days (seven 8 hour shifts) to complete construction of the clay seal. A total of 1870 Kunigel bentonite-sand blocks in 40 layers were installed. The total volume of the clay seal was approximately 13 m^3 and a dry density of 1.85 Mg/m^3 was achieved.

4. NEXT STEPS

The seals are now slowly hydrating as the natural groundwater regime is re-established at the URL. Water will continue to enter the shaft mainly from intersected fractures above FZ2. Flooding to above the 240 Level is estimated to take 7.6 years with complete shaft flooding taking an additional 3 years. These numbers are estimates that depend on climatic conditions and interactions with groundwater movement in the near-surface rock mass. Monitoring of the groundwater recovery is being undertaken as part of the closure activities. Groundwater recovery along with monitoring of the hydraulic, swelling and strain behaviour of the main shaft seal are reported as part of the Enhanced Sealing Project funded by the the Nuclear Waste Management Organization (NWMO – Canada), Agence Nationale pour la gestion des Dechets Radioactifs (ANDRA - France), Posiva Oy (Finland) and Svensk Kärnbränslehanertring AB (SKB - Sweden).

5. SUMMARY

Shaft seals were successfully installed in the main access shaft and ventilation shafts during the closure of AECL's URL. The seals were a composite design with clay-based material restrained by massive concrete components that were keyed into the rock to provide restraint and additional frictional resistance against movement from swelling pressure. The installation of the seals was conducted as part of the due diligence of returning the site to its original groundwater flow regime. The seals have the additional demonstration benefit of showing the practicality of installing at full-scale, a seal with similarities to one expected to be used at an actual repository.

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Table 1. Concrete pour information.

Location	Volume (m^3)	Time (hours)
Lower Component Main Shaft	70	26
Upper Component Main Shaft	67	23
Lower Component Vent Shaft	13	6
Upper Component Vent Shaft	12	4

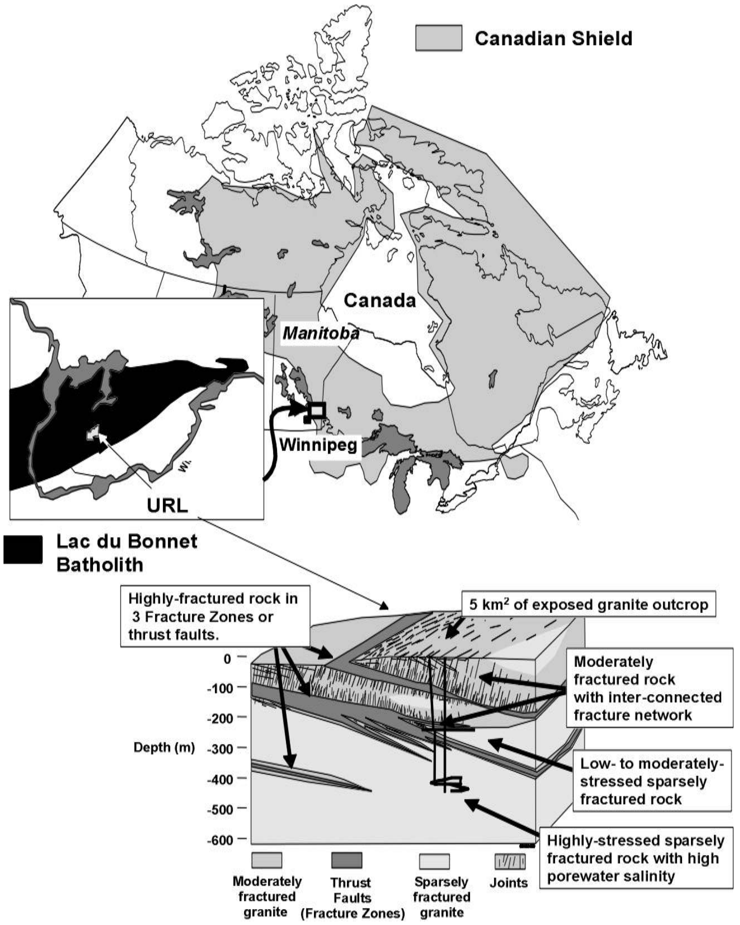

Figure 1. Location and geology of the URL site.

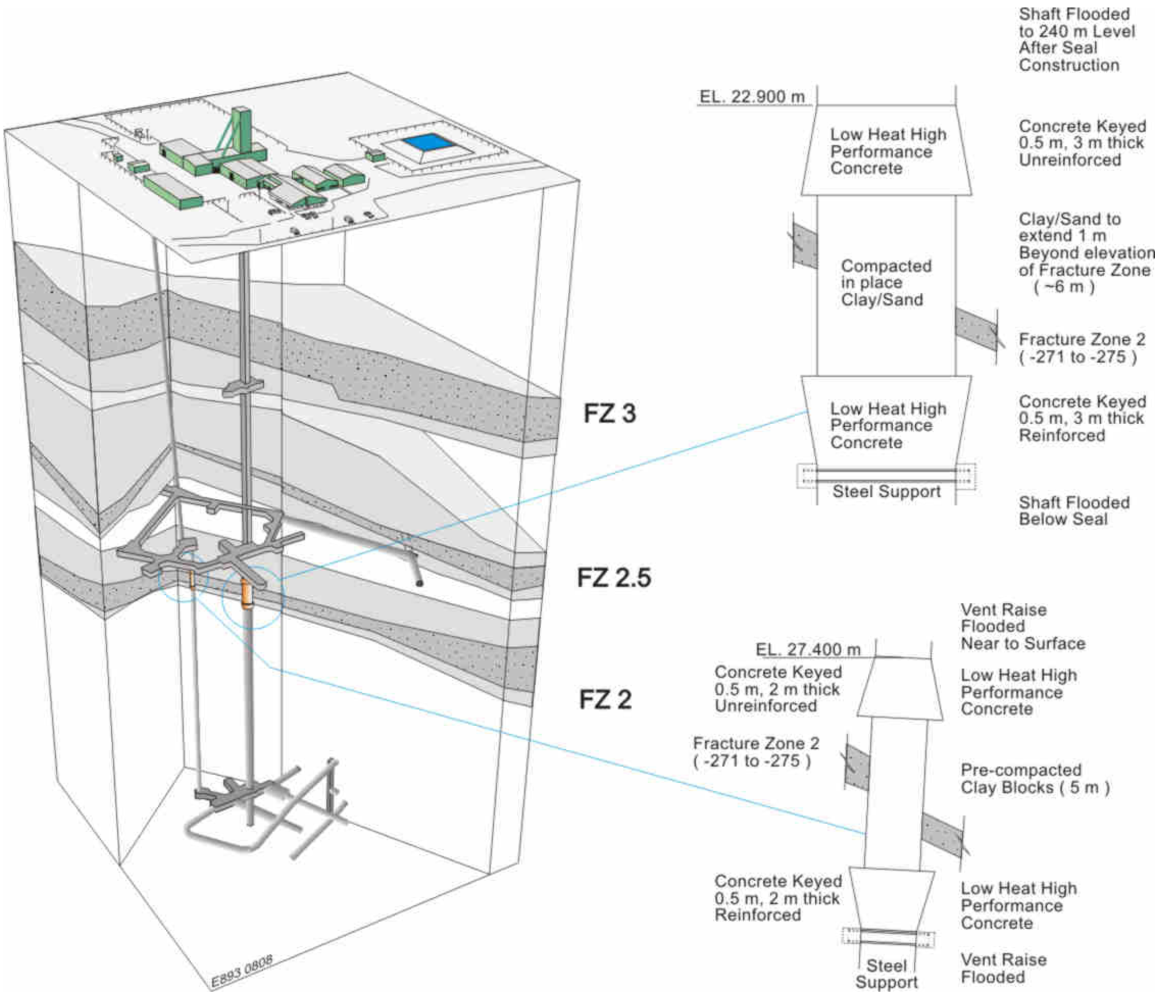

Figure 2. Layout of the URL showing locations of shaft seals.

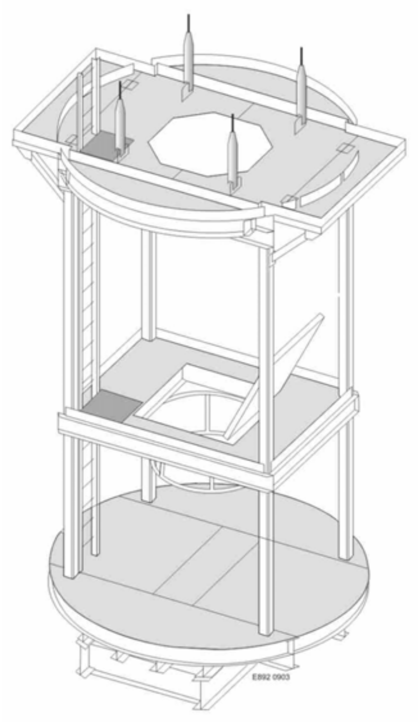

Figure 3. Galloway Stage used in main shaft closure activities.

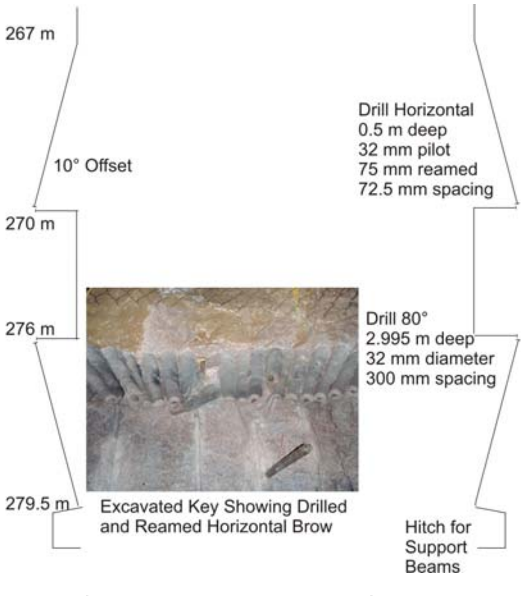

Figure 4. Excavation of the main access shaft with inset photo showing a segment of the completed key.

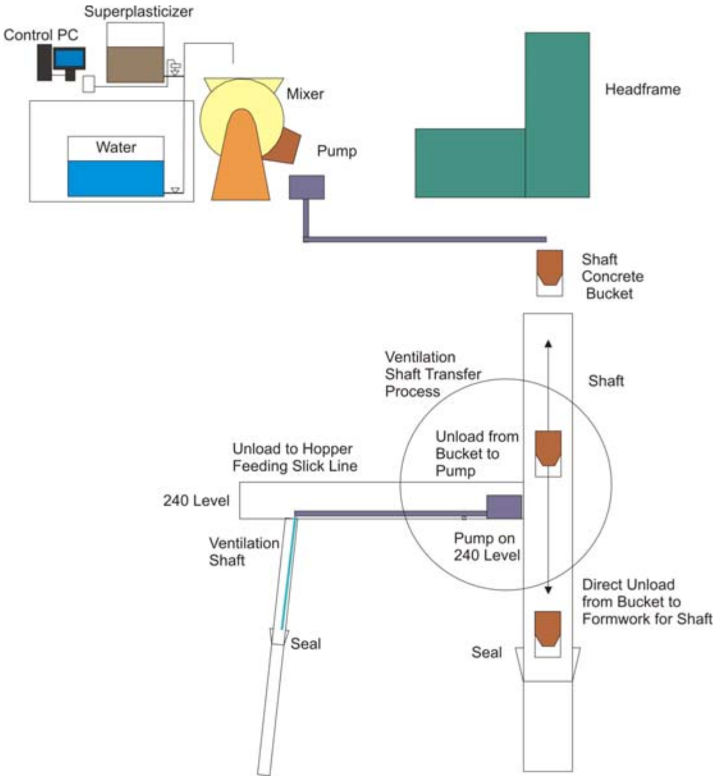

Figure 5. Concrete material movement.

Figure 6. Clay mixing and compaction.

Figure 7. Seepage control measures, cribbing (left) and water collection (right).