

DESIGN AND CONSTRUCTION CONSIDERATIONS FOR THE USE OF SLURRY WALLS TO CONSTRUCT WATER RESERVOIRS IN THE DENVER FORMATION

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Continued population growth combined with limited water resources in the Denver area has resulted in the conversion of a number of mined out gravel pits in the area into municipal water storage facilities. The use of slurry walls provides a cost effective means of isolating groundwater to convert these pits into efficient water storage facilities. Design considerations include: stability, underlying bedrock conditions, backfill mix design and earthwork requirements. Installation issues during construction include: trench stability considerations when excavating through relatively clean sand and gravel deposits in potentially high groundwater conditions; keying into three to ten feet of fractured claystone, siltstone or sandstone that makes up part of the Denver Formation, and quality assurance procedures to assure a proper groundwater barrier is constructed. The paper concludes with two brief case histories to illustrate how these considerations are applied

Introduction

As a result of the continual growth of population in and around Denver, combined with the shortage of water and associated water rights issues, the need for municipal water storage continues to increase in this area.

Because of its geology and surface deposits, the Front Range of Colorado is also home to a large number of sand and gravel pits. Local population growth helps to further increase the need for these locally available aggregate sources for the construction projects.

The combination of these two conditions lends itself to the conversion of former gravel pits, once considered a liability requiring significant reclamation bonding into much needed and valuable municipal water storage facilities. A gravel pit lake water storage facility, without attached water rights, is selling at approximately \$4,000 per acre-foot.

One of the requirements of this conversion is to line these gravel pits to comply with state requirements to protect various surface and groundwater rights. The use of slurry walls provides a cost-effective means of meeting these liner requirements.

Over the past several years, Envirocon has installed approximately a half of dozen slurry walls in this area for this application, and in total, several dozen slurry walls have been installed in the greater Denver area.

Why Slurry Walls

Sand and gravel deposits in the area typically vary in thickness from 25 to 75 feet deep. Using

standard and specially modified long-stick excavators, these depths are ideal for the installation of cost-effective soil-bentonite slurry walls to act as vertical seepage barriers to prevent the lateral movement of groundwater within the unconsolidated soil. These walls essentially form the sides of the required reservoir lining. In addition to lower cost when compared to more conventional lining approaches, slurry walls can be installed in a relatively short time frame and are less impacted by inclement weather conditions, normally associated with the construction of clay liners.

Slurry walls are non-structural subsurface groundwater barriers. These walls are constructed using the slurry trench method of construction where a trench is excavated under a bentonite slurry and is "keyed" into the underlying bedrock. The slurry acts to keep the trench open during excavation operations until a mixture of blended soil and bentonite clay is used to backfill the trench and create the final underground vertical groundwater barrier.

Underlying these sand and gravel deposits is the Denver formation. This formation consists of claystone, siltstone, and sandstone. The non-weathered portion of this formation acts as a natural lining for the reservoir.

Design considerations

In designing a slurry wall, key items to consider include the following:

- Plan alignment;
- Horizontal and vertical alignment;
- Stability analysis;
- Bedrock key;

- Seepage analysis;
- Backfill mix design, and
- Technical specifications

Plan alignment of the slurry wall will be limited by such factors as the property line, overhead and underground utility locations, proposed reservoir structures (i.e. spillways) and typically be located a minimum of 15 feet from any existing slopes into the interior of the mined gravel pit. This 15 foot requirement is a minimum for access for the excavator, but may need extended based on slope stability considerations. Location of the plan alignment toward the property line allows for an increase in quantity of sand and gravel available for additional mining and an increase in the final reservoir capacity.

Wherever possible, the alignment should be such that the slurry wall backfill can be mixed along the side of the trench, thus reducing double handling of the backfill and associated costs. To allow for this, a 25 to 50 foot wide mixing platform bench is constructed on either side of the trench alignment. When combined with minimal access along the other side of trench, a total work bench of 40 to 60 feet wide is required. If plan alignment restrictions prohibit this configuration, excavated soils can be trucked on-site to a central location, blended with bentonite, and then hauled back to the trench for backfilling.

Vertical alignment should minimize the depth of the slurry trench excavation to bedrock. Additionally this alignment should maintain a working bench a minimum of 2 feet above the water table, and if not later tied into a clay dike above the slurry wall, installed to an upper elevation above the anticipated high water level. The vertical alignment should also be based on establishing a good firm, wide temporary working bench based on the overall planned earthwork operations of the site.

Based on the proposed horizontal and vertical alignment of the slurry wall, two-dimensional stability analyses should be performed at critical cross-sections of the interior slope into the gravel pit plus any exterior slopes where the slurry wall is installed on a perimeter dike. Temporary, long-term, drained and undrained reservoir conditions should be evaluated.

An adequate factor of safety in the 1.3 to 1.5 or greater range against critical failure surfaces intersecting the slurry trench should be maintained. Based on this analysis, the location of the slurry wall may need to be pushed back further from the top of the slope to prevent such condition. Typical stable side slopes within the proposed reservoir are in the 2H:1V (horizontal to vertical) to 3H:1V range or shallower. It is not uncommon for the existing gravel pit to have steeper interior slopes as a result of the mining operations. If necessary, the interior slope may need ballasted by placing granular fill into the pit below the water table, and/or the construction of structural fill above the existing water level.

In accordance with State Engineer Guidelines for Lining Criteria for Gravel Pits (1999), the amount of acceptable groundwater inflow into a completed reservoir should not exceed $0.03 \text{ ft}^3/\text{day}/\text{ft}^2$ ($1 \times 10^{-5} \text{ cm}^3/\text{cm}^2/\text{sec}$) multiplied by the length of the perimeter wall in feet multiplied by the average vertical depth of the perimeter wall, plus $0.0015 \text{ ft}^3/\text{day}/\text{ft}^2$ ($5 \times 10^{-7} \text{ cm}^3/\text{cm}^2/\text{sec}$) multiplied by the area of the bottom of the natural bedrock bounded by the perimeter wall.

Given that the condition of the underlying bedrock is beyond the control of the slurry wall design professional and that the typical slurry wall backfill has a maximum permeability of $1 \times 10^{-7} \text{ cm}/\text{sec}$, an important seepage design consideration is the depth of penetration or "key" of the slurry wall into bedrock. Weathering and fracturing of bedrock and its ability to transmit groundwater typically decrease with depth into bedrock. A typical key into bedrock to achieve acceptable seepage parameters is 3 feet. However, based on localized conditions, keys up to 10 feet into bedrock may be required to meet acceptable groundwater inflow.

On the opposite end of the spectrum, a very hard competent sandstone unit of the Denver formation may be encountered near the bedrock surface and refusal of the excavation into bedrock may be encountered. As reported by Huzjak et al. (2004), locations where bedrock excavation exceeded the excavation refusal clause, (unable to excavate 1-foot depth over 20-foot long segment for 1 hour) refusal was allowed. These areas should be noted during construction, and based on the extent, additional analyses may be required to determine if this condition would adversely impact the overall infiltration into the reservoir. Typically, where

bedrock refusal is encountered, it is a better, less weathered and less fractured bedrock than normally encountered in the key.

Given the critical nature of the key, during the design phase, core borings and pressure testing of the bedrock along the wall alignment is warranted. During construction, a design representative to log actual key materials during slurry wall excavation is also warranted. Based on the original core borings, this individual can make the determination if the key should be advanced further.

Also during the design phase or prior to construction, a backfill mix design should be performed to determine the necessary soil-bentonite (SB) mix required to meet the performance objectives. Typical SB mix requirements include:

- Maximum permeability of 1×10^{-7} cm/sec.
- Maximum particle size of 3 inches.
- Minimum 1% bentonite, by dry weight.
- When placed, a slump of 4 to 6 inches.
- Density at least 15 pounds per cubic foot greater than the bentonite slurry in the trench.

The excavated trench spoils comprise the major source for the SB backfill. If available, on-site clayey borrow soils may be used as a source of additional fines (materials finer than #200 sieve). Fine-grained materials (clays or silts finer than the #200 sieve) are valuable in SB backfill as a means to plug pore spaces and also to provide a gradation that is resistant to hydraulic instability. A minimum preferred fines content of 15% is desirable.

Because the typical soils found at these sites, primarily consist of sand and gravel, an additional 2% dry bentonite must be added to the SB mix to achieve the permeability requirements. This is in addition to the bentonite slurry added to the SB mix for workability to produce a required slump of 4 to 6 inches. This slurry addition adds another 0.5 to 1% bentonite, for a total bentonite added of 2.5 to 3% by dry weight.

In addition to all of the above requirements, the SB mix should be simple to mix and place in the field and be economical.

The preparation of technical specifications and construction quality assurance/quality control (QA/QC) documents should be prepared by qualified and experienced professionals familiar with such projects so that these documents will assure the work will be performed properly, yet not overly restrictive resulting in increased costs to the client. Specific details to be addressed should include:

- Site preparation
- Slurry mixing and hydration
- Trench excavation
- Backfill preparation
- Backfill placement
- Site cleanup

Guide specifications are available from a variety of resources, including those from the Colorado Department of Natural Resources (2000).

Bentonite materials are governed by American Petroleum Institute (API) Specification 13 A and consist of standard oil field grade 90 yield (90 barrels of bentonite slurry per ton of bentonite) sodium bentonite powder. Large deposits of this material is mined and processed in the adjacent state of Wyoming.

Construction

Prior to construction of the slurry wall, a minimum 40 to 60 foot wide work platform must be constructed along the entire slurry wall alignment. This platform must be capable of supporting 75 to 125 metric ton class excavators. Since the trench will be filled with a bentonite slurry during trenching operations, the platform must be fairly level throughout the wall alignment. A maximum slope along the alignment should be less than 2% and preferably within 1%. For trench stability purposes, the platform elevation should be a minimum of 2 feet above the groundwater.

A bentonite slurry mix plant area should be accessible for the delivery of bentonite on tractor trailers and include a slurry holding/hydration pond to provide sufficient storage capacity of bentonite slurry. Often the water within the gravel pit may be used as the water source. A small jet shear type mixer is used to initially hydrate the bentonite and several centrifugal type 6 to 8 inch diameter pumps are used to recirculate the slurry within the pond and transfer

the slurry to the trench via 4 to 6 inch diameter HDPE lines.



Slurry Pond

Based on the depth of excavation, the slurry wall is excavated using either a standard excavator for depths less than 35 feet or large modified excavators with extended boom and sticks for depths up to 85 feet. In order to properly key into the Denver formation, a rock ripper type bucket is used. During excavation, the trench is filled with a bentonite clay slurry to maintain trench wall stability. The level of the slurry in the trench is maintained within several feet of the work platform.



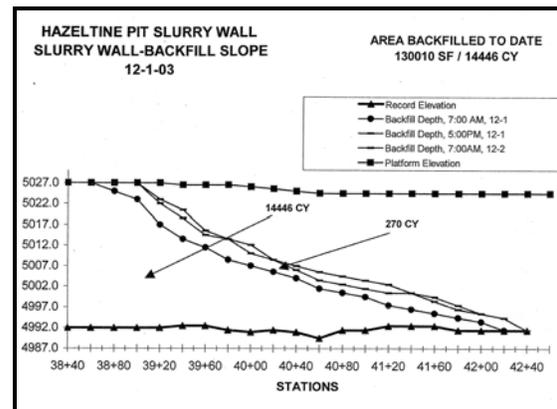
Rock Ripper Bucket

SB backfill is typically blended adjacent to the trench using a mixture of excavated spoils, clayey borrow soils, bentonite slurry and dry bentonite. Blending is accomplished using a dozer and/or a second excavator.



SB Backfill Blending

After blending, the SB backfill is placed within the trench where the previously placed backfill has stacked to work platform elevation. This allows the front face of the existing backfill to push forward within the trench without trapping slurry or sediments within the final backfill. A 4 to 6 inch slump consistency backfill will assume a backfill slope within the trench in the 6H:1V to 10H:1V range. To minimize the amount of open trench (filled with slurry), the toe of the backfill is usually kept within 30 feet of the toe of the slurry trench excavation.



Slurry Wall Backfill Profile

During excavation and backfilling operations, soundings using a weighted tape measure are conducted every morning and evening to profile the backfill and the excavated area of the trench. Additionally, throughout the day, soundings will be performed to determine the top of competent bedrock and final depth of the bedrock key. The trench hand will also assist with sample

collection of slurry and backfill material for QA/QC testing, and samples of the bedrock material for the oversight engineer to verify key material.



Trench Hand Sounding Slurry Trench

Quality control testing of the bentonite slurry and SB backfill in the field are governed by API and ASTM standards. Field equipment includes:

- Mud balance to determine the density of the bentonite slurry and backfill;
- Filter press to determine the filter cake characteristics of the bentonite slurry;
- Marsh funnel to determine the relative viscosity of the bentonite slurry;
- Slump cone to measure the consistency of the backfill, and
- # 200 sieve used for wet sieve analysis to determine the percent fines in the backfill



Field Testing Equipment

Case History – Hazeltine Water Storage

In February 2004, Envirocon, working in conjunction with GEI Consultants completed the Hazeltine Slurry Wall project in Henderson, Colorado. This work was performed for Denver Water which provides municipal drinking water for the city of Denver and many surrounding communities.

The Hazeltine project is located adjacent to the South Platte River a few miles north of Denver. The slurry wall surrounded three mined out gravel pits, was 14,480 lineal feet long and ranged from 27 to as much as 85 feet in depth (528,274 square feet of slurry wall face). The purpose of the wall was to create a single water storage facility out of three adjoining gravel pit lakes. Work also included the installation of 9,000 lineal feet of upgradient perforated HDPE infiltration pipe of varying diameters from 12 to 24 inches and 16 manholes.

During construction of the Hazeltine project, crews faced two challenges. The first was the extreme depth of the slurry wall, up to 85 feet deep. The second challenge was created by the fact that one of the pits had been excavated right up to the edge of the South Platte River and a 55 foot wide slurry wall working platform needed to be constructed. To build this working platform at Hazeltine, Envirocon placed and compacted 286,000 cubic yards of fill and then successfully excavated the slurry wall through the platform fill material.



Slurry Trenching Operations (white bags are dry bentonite for backfill mix)

Three Envirocon slurry wall excavation crews constructed the three mile long slurry trench

using Caterpillar 365, Komatsu 1100 and Komatsu 750 excavators. The larger excavators equipped with long booms and sticks were used for the deeper portions of the trench. Multiple slurry wall crews allowed Envirocon to complete the Hazeltine project in five months.

During construction of the cutoff wall, the water level within the gravel pits began to rise. To facilitate groundwater infiltration testing for state approval, Envirocon successfully pumped approximately 170 million gallons of water from the newly formed Hazeltine reservoir for discharge to the South Platte River.

Case History – Miller Reservoir – Phase I

In 2006 Envirocon, Inc constructed the foundation for an earthen dam and SB cutoff wall for the Denver Water Board. The cutoff wall isolated the 550 acre water pit from ground water encroachment for a future surface water storage impoundment. Envirocon worked closely with the owner's consultant Kumar and Associates, who provided design, construction oversight and QA services.

The scope of work included over 75,000 cubic yards of earthwork to prepare the slurry wall platform and to act as the base for a future earthen dam to be constructed on top of the slurry wall to further increase the water storage capacity of the proposed reservoir; 3,000 lineal feet of 12 inch perforated HDPE drainline to intercept groundwater infiltration from an adjacent canal located at an elevation above the slurry wall platform; installation of 218,000 vertical square feet of SB slurry wall through overburden soils and a 3 feet bedrock key, and the draining of the reservoir of over 200 million gallons of water following installation of the slurry wall.

On site select fill was used to construct a portion of the platform, so that the platform could later be used as the base of an earthen dam. Select fill consisted of a clay material with low permeability and contained 60% fines passing the #200 sieve. Portions of the platform required additional earthwork to allow for the ability to side mix SB backfill adjacent to the trench.

The slurry wall was 8,050 feet long with a maximum depth of 40 feet. Envirocon mobilized

an owned Komatsu PC750 hydraulic excavator with an extended boom and stick configuration capable of excavating up to 60 feet. The excavator bucket was equipped with specialized rock ripper teeth to facilitate excavation of the bedrock key.



Komatsu PC 750 Excavator with long boom and stick

Envirocon had to physically drain the eastern side of the site due to large amounts of water infiltration from the adjacent irrigation canal prior to installation of the workpad and slurry wall. This condition needed to be rectified to eliminate elevated groundwater conditions which created trench stability concerns.



Draining operations from canal infiltration

Despite severe winter weather at the end of the project, the project came in slightly ahead of schedule and under budget for the client.

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