A CASE STUDY FOR WATERPROOFING BELOW-GRADE WALLS SHORED WITH CONTINUOUS SOIL MIX TECHNOLOGY USING A BENTONITE WATERPROOFING SYSTEM

By

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INTRODUCTION

The development of a seven-story office building with a four-story underground parking garage, located adjacent to the Alaskan Way viaduct just south of downtown Seattle posed unique challenges. The project was situated on a sensitive site with specific soil conditions and a high water table. The team identified early on the need to develop strategies to minimize the risks associated with the site conditions both during construction and over the long term. The site conditions along with the project requirements were all considered in the selection of the appropriate shoring system and waterproofing system for the structure.

SITE HISTORY

The project is located on the waterfront in a historical location just south of downtown Seattle in an area that has been reclaimed from Elliot Bay as part of multi-phased re-grading conducted at the turn of the century. In the 1880s a wharf was located on the site containing a sawmill, offices, laundry facility, and tar warehouse as well as the Queen City Boiler works. Fill for the site that was deposited in the late 1800s includes sawdust from the sawmills, wood planks and pilings, ship ballast, and brick and wood burn debris from the Seattle fire. The site is now located less than a ½ mile from Elliott Bay, subjecting the groundwater level to tidal fluctuations.

SUBSURFACE CONDITIONS

Due to the history and location of the site near the waterfront, the existing subsurface soil conditions consisted of three separate layers of varying conditions; deep fill overlying loose and soft marine deposits with very dense glacial soils encountered below the marine deposits. The first layer of deep fill extended down to between 25 and 35 feet below the current ground level was scattered with wood and debris as well as being subject to a very high water table and fluctuating tide.

Below the layer of fill and extending down to between 30 and 40 feet below the existing surface was a thin layer of marine sands and silts from the former bottom of Elliot Bay.

These marine deposits are typical of the waterfront area and include loose sand and soft sandy, clayey silt. The fill layer and marine deposit layer that consist of soft and loose materials were not suitable to support the structure.

Beyond the marine deposits lies the third layer of ground conditions, a layer of dense glacial sand and silts. This layer, which was located beyond the marine deposits which terminated at a depth of 30 to 40 feet, consisted of glacially overridden layers of dense sand and hard clayey silt that were suitable for support of the structure. At the depth of the excavation a till-like material of very dense silty sand with gravel was expected.

Water was encountered within the site at three levels with the first occurring at approximately 6 to 11 feet below the existing ground surface and with the lowest extending below the bottom of the excavation depth.

Given the high organic content of the fill some amounts of methane gas were also present within the site and needed to be accounted for in the design of the subgrade structure. For the most part, the organic fill was located below the water table. Therefore, long term degradation of the material is very slow, and thus the methane production is also slow. The geotechnical survey also noted pockets of petroleum contamination in the fill soils, likely a result of scraps contaminated with wood and debris from the wharf and sawmill used in the fill.

PROJECT REQUIREMENTS

The project consisted of a seven-story office building with 4 stories of underground parking at a maximum depth of 43 feet below the existing ground level, with an additional 6 feet toward the center of the site for elevator and sump pits, resulting in an average excavation depth of 36 feet below the water table.

In addition, the proposed structure and site were located in an area with adjacent buildings, roads, and utilities that were sensitive to settlement. The proposed structure required removal of portions of the foundation at the adjacent eight-story building directly to the north of the site. The southern footing line of the adjacent building was supported on pile caps and a series of timber piles. Approximately 1/3 of the piles and pile caps required removal during excavation and replacement with a new row of micro piles to extend below the current timber piles.

CONSTRUCTION CONSIDERATIONS AND SHORING SELECTION

The primary geotechnical concerns included the following:

- Excavating the site below the groundwater table and providing a permanent waterproof system for the underground parking.

- Addressing lateral and uplift hydrostatic pressures on the foundation and waterproofing system.
- Dewatering of a 43 foot deep excavation site adjacent to settlement-sensitive structures.
- Mitigating base heave at the bottom of the excavation within a ground water aquifer.

Excavation of the site below the water table required either significant construction site dewatering or, where dewatering of the entire site was not practical, the use of a shoring wall that acted as a watertight cut-off wall. Dewatering of the entire site for a fully drained shoring system was not practical because it would drain the water table of the surrounding sites down to a level that would have severe off site impacts resulting from settlement of previously buoyant soils. This led to the determination that the shoring system would need to provide a water cut-off to allow for dewatering of the soils within the excavation site. The dewatering of the site was required to keep the water table below the level of excavation to allow for removal of the wood infill and to maintain a safe and dry working environment.

The shoring walls needed to provide temporary lateral support to the adjacent loose fill soils while also providing a relatively watertight cut-off wall and providing stability for the adjacent structures, streets, and utilities. The shoring walls were also required to extend 25 feet below the depth of the excavation in order to limit the risks of seepage and base heave resulting from the deep aquifer. A variety of shoring options were considered and rejected including:

- Typical shoring walls with soldier piles and lagging. It was determined that this system was not practical for the project due to the soft and wet nature of the fill and marine deposits.
- Sheet piles that consist of interlocking sheets of steel that are vibrated into the soil. These were not selected due to the depth of the excavation and the risk of interference and blockage of the sheets by existing fill debris.
- Secant piles that are constructed by drilling overlapping shafts and filling to form a continuous concrete wall. This system was originally planned and bid for the project but was determined to be expensive, slow, and unable to provide a suitable surface for the waterproofing installation.

The final system selected was a cutter soil mix (CSM) shoring system. The CSM shoring wall is a modified soldier pile system that makes use of overlapping soil-cement panels to construct a strong and relatively watertight wall. CSM technology mixes the soil in situ with a cement and bentonite slurry, creating a solid and cohesive block. For this type of shoring wall, two sets of vertically mounted cutting wheels rotate on a horizontal axis creating a rectangular soil-cement panel. The mixing is performed using mixing paddles attached to the augers that are slowly driven into the ground. Refer to Photo No. 1 for a view of the soil mix wall installation process. As the auger is rotated, the cement slurry is added through the hollow stem of the auger shaft. The mixing paddles are located above the auger to blend the soil and slurry. The slurry also helps break up the soil and lubricate the equipment as well as helping bring spoils in the mixture to the surface. A continuous wall is achieved by overlapping the panels, which are constructed in alternating sections. Steel sections similar to conventional soldier pile walls are also driven into the panels as soon as the soil-cement mix is installed but still wet. The strength of the soil walls can be tailored to specific project and site conditions. A CSM wall with a compressive strength of 200 psi was designed for this project.

Image 1 – CSM shoring wall installation in progress

Another benefit of the CSM over secant pile walls was the method in which the drilling equipment essentially chewed through any underground obstructions. This allowed the CSM wall to maintain a straight vertical plane by limiting the effects of encountering subsurface obstructions. Pre-trenching of the site perimeter was also conducted prior to the CSM wall installation. This allowed for removal of most of the fill layer and any obstructions within this layer that may have caused imperfections and flaws in the finished CSM walls.

CSM shoring was selected for a number of reasons including price, schedule, the ability to provide a solid and generally watertight wall that allowed for dewatering of the excavation site without causing any settlement of the adjacent soil and the ability of the excavation equipment to cut into obstructions in the soils. The use of the soil mix technology provided a shoring wall that was adequately strong and watertight. In order to provide adequate lateral support of the CSM shoring walls, tie-backs anchors were installed as the excavation proceeded. These tie-backs were installed in steel sleeves that were pre-installed in the steel soldier beams that were driven into the CSM wall while it was still wet. These sleeves allowed the drilling of the tie-backs without damaging or causing water flows at the CSM wall. In some areas where tie-backs could not be installed due to underground obstructions, such as adjacent structures and utilities, steel whalers were installed for lateral support. The steel whalers consisted of horizontal steel I-beams welded to the vertical steel soldier piles at the face of the CSM walls. These whalers were removed as the structural concrete walls and floor slabs were installed.

The structural engineer designed a five-foot thick concrete mat slab with 680 tension pile tie-downs to permanently resist the hydrostatic water pressure acting on the foundation once the site dewatering system has been shut off.

BELOW-GRADE WATERPROOFING

Several different below-grade waterproofing systems were evaluated based on the project requirements: the use of a CSM slurry wall system, the desire to use a shotcrete-applied structural concrete foundation wall, the hydrostatic conditions, and the possibility of methane and petroleum contamination present in the fill soils. Due to the proximity of the site to the Puget Sound, the site groundwater table was found to be approximately six to eleven feet below the top of soil. The four story below grade parking structure was about forty-five feet below grade. A temporary dewatering system was utilized during the excavation and construction of the foundation system. The dewatering system was deactivated once the structure was in place.

DUAL MEMBRANE SYSTEM

At the perimeter of the below-grade foundation walls, where there is conditioned space (storage rooms, electrical rooms, and other rooms) where water migrations is not desired, a dual waterproofing system was recommended. A dual membrane assembly typically consists of a waterproofing membrane sandwiched between the shoring wall and the structural below-grade foundation walls; in conjunction with an integral hydrophobic additive added to the concrete structural walls. The hydrophobic additive restricts capillary action making the concrete a secondary waterproof barrier. The advantage of this dual membrane system is that there is a primary and secondary waterproofing system – a 'belt and suspenders' approach.

The installation of the dual membrane system was found to be economically unfeasible, and the owners determined that they were willing to accept a higher risk of water infiltration and used a single system. The owner determined that some moisture on the walls in the parking garage would be acceptable but that liquid water running down the walls was not.

Several of the waterproofing systems that were considered for the dual waterproofing system were not selected for a single membrane system. These included a reinforced cold applied waterproofing membrane. Minor imperfections in the shoring wall would need to be filled with grout to create a smooth and even substrate to receive such a membrane. If a large amount of imperfections occurred in the CSM wall, the use of an asphalt/felt protection board mechanically attached to the CSM wall could be used as a smooth substrate.

Another system considered was a spray-applied liquid waterproofing membrane intended for blindside application. The use of two layers of geotextile fabric installed over the

CSM shoring wall would provide an appropriate substrate onto which the membrane would be sprayed. The membrane thickness would be a minimum of 100-mil dry film thickness at both horizontal and vertical surfaces. The use of the spray-applied membrane was eliminated due to the reliance on the membrane applicator to maintain a uniform thickness and quality of the installation and the limited warranty available with this system. The risk of installing the membrane improperly was significantly higher when compared to a sheet product.

A self-adhesive membrane was considered, but these membranes were deemed better suited to positive side application and would require a very smooth CSM wall substrate. In addition, concerns were raised about the use of a shotcrete wall against the membrane, which can cause damage to the lapped seams.

In the end, preference was given to a ‘sheet good’ membrane that would be fully adhered to the structural walls. Sheet membrane products are produced in a controlled environment where quality can be monitored and maintained. A fully adhered membrane would minimize any lateral water movement between the membrane and the substrate should the membrane be breached; therefore, water leaks are generally easier to isolate and locate for repairs.

One sheet good option considered was a single ply 80-mil thick PVC membrane. For the single ply PVC system, membrane lap joints are typically heat welded. A second layer of the PVC membrane would have to be installed at the vertical walls as a protection course and a high density polyethylene sheet (HDPE) loose-laid over the PVC membrane at the slab as the protection course. The PVC membrane also required that the shoring wall be smoothed to avoid puncturing of the membrane by any sharp protrusions.

BENTONITE MEMBRANE

In the end, a two layer bentonite membrane system was chosen because it met project requirements. This system included two layers of bentonite with the first layer

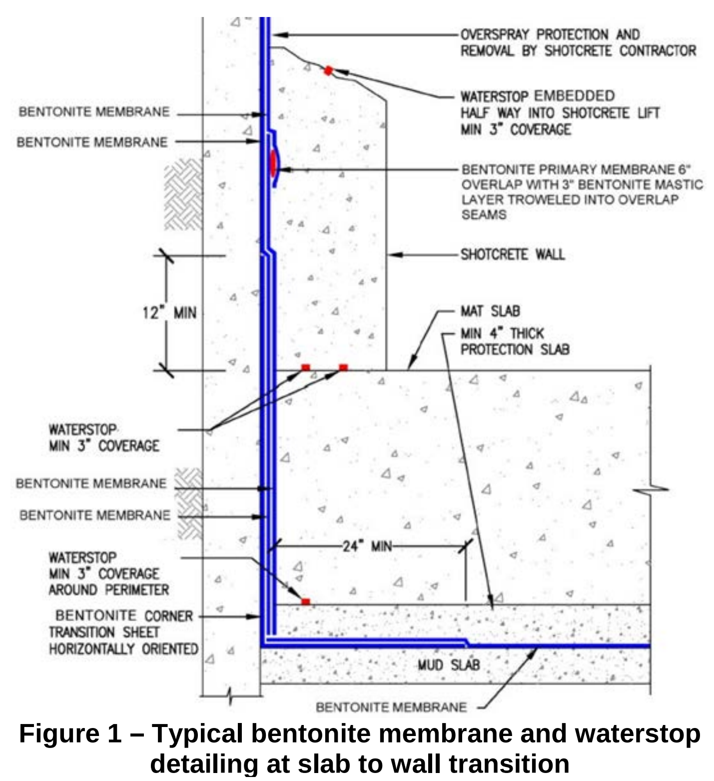

Figure 1 – Typical bentonite membrane and waterstop detailing at slab to wall transition

consisting of a polymer alloy bentonite clay encapsulated in a geo-membrane panel. The second layer of bentonite is similar to the first layer, except one side has a high density polyethylene liner on one side of the membrane panel. When the bentonite clay is hydrated the material swells. The first layer of bentonite membrane was mechanically attached directly to the shoring wall with minimum end and side laps of 4-inches to form a continuous waterproofing membrane. The second layer of bentonite was installed in a similar fashion, except that the laps were sealed with bentonite mastic. Refer to Figure 1 for the typical detailing of the bentonite membrane and waterstop.

One assembly discussed included the installation of the bentonite membrane between two layers of drainage board. This option was eliminated due to the need for the bentonite to be securely fastened to a solid and smooth substrate and the requirement of the bentonite panels to be in direct contact with and bonded to the structural concrete.

Samples of the soil and groundwater were provided to the bentonite membrane manufacturer to conduct testing, the results confirmed that the salt and other contaminants within the soil and water were acceptable levels and would not affect the performance of the bentonite system. In addition, the use of the HDPE liner against the CSM wall limited leakage of any methane gas into the parking garage.

CONSTRUCTION CONSIDERATIONS

During the course of the design and construction of the below-grade foundation, a number of specific conditions related to the site conditions, CSM shoring wall and two layer bentonite waterproofing system were identified that needed to be addressed.

SHOTCRETE

The structural concrete foundation walls were installed by shotcrete application. The pressure of the shotcrete, if applied correctly, aids in pressing the bentonite membrane against the CSM shoring wall resulting in a well-confined membrane that is fully bonded to the foundation wall and that will expand when it encounters moisture to fill the space between the CSM shoring wall and shotcrete foundation wall.

The installation of the shotcrete posed specific conditions that were required to be considered and addressed during installation. These items included:

- Damage of the membrane during installation of the re-bar cage, which then limited access to the membrane for repair.
- The height of the floors, which resulted in the shotcrete applicators being located below the height of the shotcrete while also avoiding spraying at an angle up toward the bentonite membrane lap joints.
- Achieving adequate coverage and consolidation of the concrete behind all the re-bar in order to provide a solid surface to confine and adhere to the membrane.

- Patching and sealing around re-bar structural ties through the bentonite membrane.
- Limiting and removing overspray of the shotcrete onto adjacent areas of bentonite membrane that would result in inadequate bonding of the bentonite membrane to the structural concrete.
- Striping off a minimum 2-inch wide section in each vertical and horizontal termination of the shotcrete lifts to provide a smooth substrate for application of a bentonite waterstop at each cold joint.

COLD JOINTS

A bentonite waterstop was installed around all penetrations and at all horizontal and vertical cold joints within the structural foundation slab and walls. This waterstop provided a secondary line of defense against water leaks at the concrete joints. The bentonite waterstop was provided with a minimum 3-inch concrete coverage to avoid blowouts of the concrete caused by swelling of the waterstop. The waterstop was adhered to the concrete substrate using a water-based adhesive, and then fastened every 12 inches on center to ensure the waterstop would remain in place under the pressure of the shotcrete application.

SLAB WATERPROOFING

The waterproofing system was required to extend under the mat slab and all sump and elevator pits and to be tied into the wall panels in order to provide a continuous watertight assembly. Refer to Image 2 for an overall view of the bentonite membrane over the "rat" slab and tie-down anchor penetrations. A two layer rat slab was utilized with a single layer of bentonite membrane sandwiched between the slabs after drilling of the tension piles through the bottom slab was completed. The top slab was used to provide a smooth and dry surface for the installation of the waterproofing membrane with the top layer providing a protection layer for the membrane as well as a solid working surface for equipment staging and the placement of the steel reinforcing for the 5 foot thick mat slab. The top layer of the rat slab as well as the mat slab were provided with sodium bentonite based waterstops installed at each cold joint as a secondary line of defense against water infiltration at the joints.

Image 2 – Bentonite waterproofing membrane installed over rat slab and sealed around tie-down penetrations

SLAB TIE-DOWNS

Sealing was needed around each of the 680 tension piles through the waterproofing membrane. Each of the piles was required to be located within a sleeve, which allowed the piles to move freely in the slab, without allowing water seepage into the sleeves, as the structure settled. In order to address these requirements a detail was developed by the team that consisted of a 12-inch diameter core hole in the rat slab with a PVC sleeve extending from the bottom of the nut and metal washer plate to the top of the protection slab. A #14 re-bar was then installed through the sleeve to allow the bar to go under tension under hydrostatic pressure with a movement of 1/8-inch to ¼-inch. The anchor tie penetrations through the membrane were flashed with a target patch of the bentonite membrane. The field membrane was lapped over the target patch and the penetration sealed with a cant of bentonite mastic. Waterstops were wrapped around each PVC sleeve at three different heights above the substrate. The PVC sleeve was primed prior to the installation of the waterstop and the waterstop was secured with a zip tie or similar device. Bond breaker was then coated over the remaining surface of the sleeve to prevent adhesion of the slab to the sleeve but the coating was not applied at the areas of the waterstop. Once construction of the entire structure was complete the top of each tie down anchor head was grouted over prior to turning off the dewatering system. Refer to Figure 2 for the bentonite waterproofing membrane patching around the tie- down penetrations.

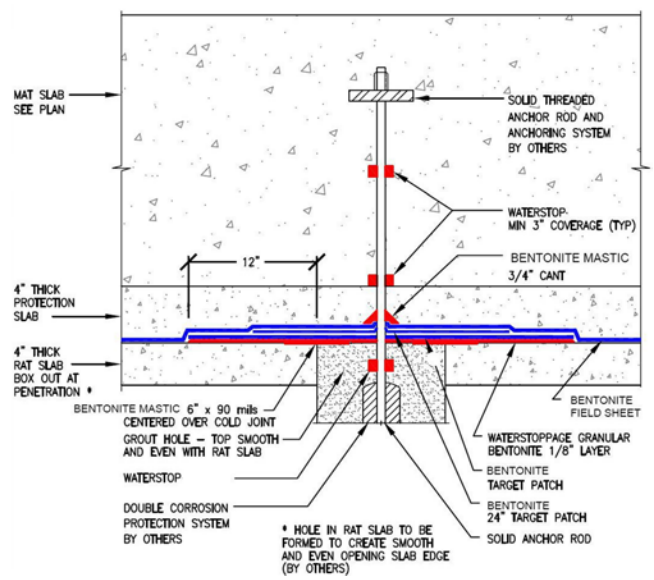

Figure 2 – Bentonite slab waterproofing around tie-down penetration

PREPARATION OF THE CSM WALLS

In order for the bentonite to perform effectively the membrane must be in intimate contact with the shoring wall. The shoring wall substrate was required to be prepared either with a layer of shotcrete that was troweled smooth or by filling any voids or large areas of rock pockets with

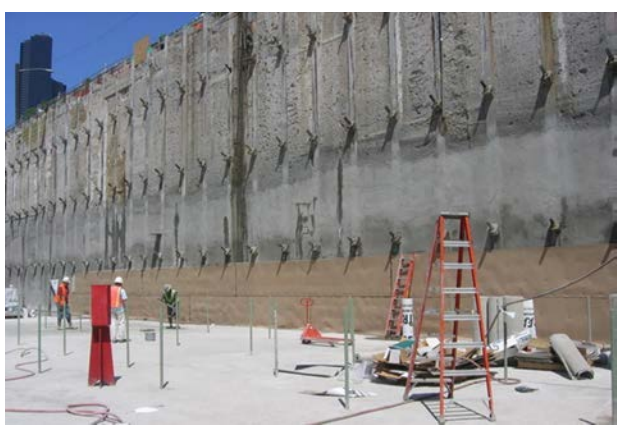

Image 3 – Overall view of CSM shoring wall with section smoothed and prepared for receiving bentonite membrane

grout. Any fins, ridges or other protrusions at the shoring wall were ground down to level and smooth. Refer to Image 3 for a general view of the CSM wall with a section smoothed and ready to receive the bentonite waterproofing.

Image 4 – Sample of CSM shoring wall prior to being prepared as an acceptable substrate

The CSM shoring walls, although intended to be flat and relatively smooth, were often wavy and had voids. Refer to Image 4 for view of voids and inconsistencies in the face of the CSM wall. It was determined that the waviness of the walls would not be an issue but that the bentonite needed be installed in direct contact with the substrate and any voids larger than 2- inches would require smoothing. A similar CSM shoring wall was reviewed and it was determined that approximately 10% of the surface of the shoring wall would likely require smoothing. This allowed for the shotcrete structural concrete to be applied directly against the membrane to confine the bentonite.

WATER SEEPAGE

As was expected, the CSM wall did not provide a completely watertight cut-off wall. Water seepage from the perimeter water table was common at joints in the CSM and especially at the tie-back anchors. Refer to Image 5 for typical seepage down CSM wall. In order to maintain a clean and safe work area as well as keeping the bentonite products from significant hydration and damage, this water needed to be controlled as much as possible. A temporary system of gutters was installed at the upper levels of tie-backs to prevent the majority of the water from dripping down the walls and onto the slab. These gutters were not able to capture all the water and other methods of addressing the water were needed. This included vacuuming ponding water from work areas and heat drying the concrete substrate at the

Image 5 – Water seepage through CSM wall at tie-backs

perimeter walls prior to installation of the waterstop at the horizontal cold joints at floor slabs and shotcrete foundation walls.

In addition to water seepage down the face of the bentonite membrane and onto the floor slab, water seeping in behind the bentonite membrane prior to installation of the shotcrete foundation walls resulted in bulging of the membrane away from the CSM walls. The pockets of water pooling behind the bentonite membrane would be enough to resist the pressure of the shotcrete from confining the bentonite between the CSM and shotcrete. This confinement was needed for the bentonite to perform properly. Releasing the water from behind the bentonite membrane was required and was achieved by cutting drainage slots into the membrane at intervals along the base of the floor lines a minimum of 12-inches above the slab. On the day of shotcrete, these slots would be vacuumed as dry as possible to eliminate any pockets of water trapped behind the membrane and then patched with 2 layers of 12-inch by 12-inch bentonite patches set in bentonite mastic.

TIE-BACK DETAILING

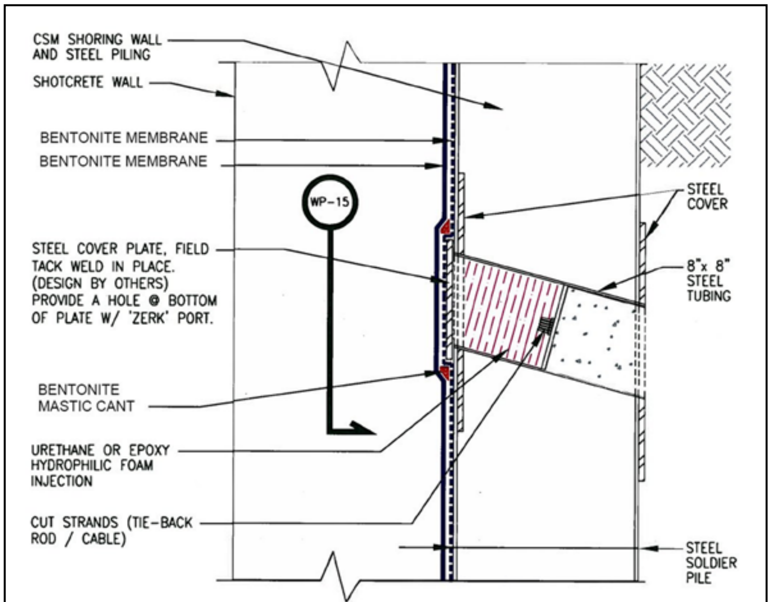

Figure 3 – Tie-back cut-off and sealing at bentonite membrane

De-stressing and cutting off the tie-back anchors resulted in the tie backs being inboard of the exposed side of the shoring wall. The recessed areas were to be grouted flush and smooth with the CSM shoring wall. This condition allowed the bentonite membrane to be patched directly over the grouted tie-back anchors without a preformed boot over the tie-back. Due to the hydrostatic pressure at the tie-backs, a significant amount of water infiltration was experienced once they were cut-off. As a result, tie-backs were cut-off just prior to patching the bentonite over it. The drainage slots through the membrane at each floor line allowed water from the tie-backs that entered behind the membrane to be removed. Rapidly expanding spray foam water cut-off was used at the tie-backs to stop gushing water and to provide a smooth surface around the tie-backs. The bentonite patches consisted of one patch of the HDPE lined bentonite membrane installed between the two field membranes and a second bentonite patch installed over the face of the field membrane with all edges sealed with a 3-inch strip of bentonite mastic and fastened at 6- inches on center around the perimeter. Refer to Figure 3 for detailing of the bentonite membrane at the tie backs and Image 6 for photographs of the tie-back cut-off process.

Image 6 – Tie-back removal, capping to prevent water seepage, and bentonite patching over tie-backs

FASTENING OF THE MEMBRANE

The selection of appropriate fasteners for securing the bentonite panels to the CSM shoring wall was considered, and the use of low velocity fasteners with metal washers was determined to be appropriate for securing the waterproofing membrane to the slurry wall. With the resulting seepage through the CSM at joints and tie-back anchors the bentonite membrane did become damp in some areas. The membrane needed to be securely fastened to the wavy areas in the CSM wall. As a result, a number of these fasteners with washers were either sunken into the softened membrane or pulled out where inadequately driven into the CSM wall. Identifying and patching these minor holes in the membrane prior to installation of the shotcrete foundation walls became one of the most common conditions reviewed during construction.

POST CONSTRUCTION

Upon completion of the building and tie-in of the bentonite membrane to the horizontal waterproofing membrane, water was observed seeping through the below grade foundation walls into the parking garage. Possible causes were considered and investigate work was conducted in an attempt to review the conditions of the bentonite membrane between the CSM shoring wall and the foundation wall. A number of concrete core samples through the foundation walls were taken and visually examined. A small number of concrete cores showed areas of poor concrete consolidation; however, the majority of the concrete core samples were found to be well consolidated. At one core sample the bentonite membrane was not adhering to the face of the core due to the shotcrete overspray on the bentonite membrane. The other core samples showed that the bentonite nonwoven geotextile fabric side was either partially bonded or not bonded to the concrete; while others had the bentonite membrane fully bonded to the substrate.

It was determined by the design team, contractors and bentonite manufacturer, that as a result of differential movement between the shoring wall and the shotcrete foundation walls that there were areas where the bentonite membrane was not adequately confined; as a result the performance of the waterproofing was not realized. Both settlement of the CSM shoring wall and structural deflection of the structural foundation wall were considered as potential contributors. Shrinking of the post-tensioned floor slabs in the underground garage was also identified as a potential source of the deflection of the structural walls. Ultimately the exact nature of the differential movement was not conclusively proven.

A bentonite-based grout was injected at the three levels of the below grade parking garage to seal the voids between the foundation wall and the shoring wall. These treated areas were monitored by the design team, contractor and bentonite manufacturer and were completed without any major difficulties. It was interesting to note at one area there was a gap between the below grade walls and the CSM shoring wall that allowed a minor amount of the bentonite-based grout to progress up the walls and in one instance enter behind the stone cladding, move under the sidewalk and move into the interior insulation through an abandoned electrical conduit. This was mitigated by using a lower pressure at the injection ports and creating relief ports at the upper parking level. Once grout was flowing out the relief ports, the injection process was stopped.

Once the bentonite-based grout injections were completed, the last few minor areas of seepage were treated with a urethane grouting techniques. The final result was a dry parking garage complete with a 10 year manufacturer's warranty.

CONCLUSION

The CSM shoring wall system provided an innovative and effective approach that accommodated the unique constraints of this site. Even with the use of the CSM shoring wall to provide a water cut-off for excavation and dewatering of the site, complete dewatering of the site was not possible.

The two layers of bentonite membrane were found to be the most appropriate waterproofing system to meet the requirements of the project and to address the limitations of the CSM shoring wall. As a result, site specific detailing was required for the bentonite system installation to address the challenging hydrostatic conditions.

The use of post-tensioned floor slabs and a shortened curing time for the floor slabs may have contributed to the voids created between the CSM shoring and foundation walls. Considerations should be given to potential differential movement between the shoring and foundation walls for property line waterproofing system.

For the bentonite to perform properly, it must be confined; in this case between the shoring and foundation walls. Nonetheless the bentonite-based grouting employed and the use of urethane injection techniques to seal the CSM shoring and foundation wall voids were effective in providing a fully watertight garage.