PARSONS BRINCKERHOFF

GENERAL GUIDELINES FOR DESIGN AND CONSTRUCTION OF CONCRETE DIAPHRAGM (SLURRY) WALLS

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OF
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I. INTRODUCTION

This guide was developed to assist designers in evaluating the suitability of concrete diaphragm walls (slurry walls) for earth support for project application, to provide an understanding of common construction issues, and provide guidance on construction inspection requirements. The objective of this guide is to help designers confirm that major items associated with the design and construction of slurry walls have been addressed on their project and to provide guidance for field inspection staff. The guide includes lessons learned from numerous slurry wall projects designed and/or overseen by PB. The designer is not bound to follow these guidelines, but should refer to these guidelines on projects that may use slurry walls.

Although this guide is considered comprehensive, it is likely that each project will have its own site specific issues that may not be addressed in this document. Since additional experience will be gained and technologies will evolve, the suggestions and direction provided herein should be confirmed for current relevancy.

For each project application it is essential that this guide not be considered a replacement for proper quality control/quality assurance procedures. Rather it should be considered an additional tool for the designer and field inspectors.

These guidelines were developed under the supervision of Ray Castelli and Bob Rawnsley. It is requested that any comments or errors be sent to either Castelli@pbworld.com or Rawnsley@pbworld.com .

II. GENERAL CONSIDERATIONS

A. Selection Process

1. Description of Concrete Diaphragm Walls (Slurry Walls): This guide is limited specifically to issues associated with Conventional Reinforced Concrete Diaphragm Walls and Soldier Pile and Tremie Concrete Walls, both as described below.

   a. Conventional Reinforced Concrete Diaphragm (CRC) Walls: The most common type of slurry wall is the Conventional Reinforced Concrete Diaphragm Wall. In this type of wall the reinforcing cage is designed to span vertically with no structural continuity between adjacent panels. Temporary endstops are generally used to form the ends of panels in lieu of permanent soldier piles. Internal steel members or secondary reinforcement bars may be provided within the main reinforcing to provide internal beams which act as wales or additional reinforcing around openings. Wall widths of 18 inches to 48 inches are typical, with 36 inch wide walls being the most common. Wider walls are available, but are not as common.

   b. Soldier Pile and Tremie Concrete (SPTC) Walls: Soldier Pile and Tremie Concrete Walls are walls primarily reinforced with vertical wide flange steel sections. Reinforcing cages can be installed between the steel soldier piles to provide additional stiffness or to permit a wider spacing of soldier piles. SPTC walls tend to be stiffer than CRC walls and sometimes better facilitate construction of moment connections within the excavation. SPTC walls also provide significant construction benefits when working in restricted headroom areas. Wall widths are similar to the CRC wall.

      - With Reinforcing Cages: When reinforcing cages are incorporated into a SPTC wall, the cage is designed to span horizontally, transferring load to the soldier piles. This permits a wider spacing of soldier piles and decreases the number of steel soldier piles and corresponding panel joints.
      - Without Reinforcing Cages: SPTC walls can also be constructed without a reinforcing cage. A common spacing of the soldier piles for this condition is on the order 4 to 6 feet on-center.

2. Other Types of Concrete Diaphragm Walls: Two other types of concrete diaphragm walls are Pre-cast Panels and Post Tensioned Panels. Pre-Cast Panels and Post Tensioned Panels are considered specialty walls and are therefore, only discussed briefly below. They require detailed investigation prior to confirming their use is appropriate for a specific project.

   a. Pre-Cast Panels: This type of wall includes the use of pre-cast panels set in slow-set cement slurry. The benefit of this type of wall is an excellent finish surface and the potential for a more positive watertight joint with the use of rubber waterstops at panel joints. Similar to the traditional cast-in-place slurry wall, watertightness is subject to workmanship and long term deformations. Other disadvantages of pre-cast panels include cost, transportation and handling size limitations.

b. Post Tensioned Walls: Post tensioned slurry walls are simply traditional slurry walls with post tensioning tendons installed vertically for the entire length of wall. Post tensioning increases bending resistance, permitting wider spacing between bracing levels. Added cost and more complicated construction procedures are disadvantages.

3. Applications for Slurry Walls: Slurry walls are used at sites where one or both of the following requirements or site conditions exist:

a. Groundwater Control: Slurry walls are used at sites where a relatively watertight excavation support wall is required. This situation may occur when: 1) groundwater lowering outside the excavation may lead to potentially damaging settlement of nearby structures or other facilities, 2) dewatering of the site is not practical, i.e., adjacent to an open body of water, and 3) where seepage gradients initiated by dewatering options may risk migration of an existing contamination plume. With penetration into an underlying stratum of low permeability, or with sufficient penetration below the bottom of excavation, a slurry wall may provide an effective barrier preventing or limiting potentially damaging groundwater drawdown from occurring outside the excavation and provide a stable and relatively dry excavation.

b. Increased Stiffness: Slurry walls are commonly used in urban settings where it is required to minimize ground displacements outside of the excavation to decrease the risk of damage to existing structures and other facilities, and to eliminate the need for underpinning of nearby structures. Although stiffness of the support system is primarily controlled by the spacing of the bracing, slurry walls are considered relatively rigid as compared to steel sheeting or soldier pile and lagging excavation support systems.

4. Advantages/Disadvantages of Slurry Walls

Slurry walls have many benefits, including:

- The ability to be installed in low headroom conditions.
- The ability to be installed through stiff/dense soils and rock.
- The ability to support large vertical loads.
- The ability to resist high bending moments.

Advantages of using slurry walls include:

- Slurry walls provide a ‘watertight’ system (in comparison to soldier pile and lagging support systems)
- Slurry walls can be used for both the permanent and temporary support.

- Slurry walls permit the use of top-down construction techniques which shortens the duration of surface disruption and permits early construction of above grade works.
- Slurry walls are stiffer than other types of walls.
- Slurry walls often eliminate the need for underpinning existing structures.

Disadvantages of using slurry walls include:

- Higher cost, when used for temporary support only.
- The need for specialty equipment and contractor.
- Slurry walls require a large lay down area for staging, cage assembly, slurry desanding, spoil storage, cranes, and slurry plant.

Other ‘watertight’ wall systems, including steel sheeting, secant pile walls and tangent pile walls, all provide reasonable groundwater control and are considered acceptable alternatives of support for the typical excavation in regard to groundwater control. However, where unusually strict groundwater control requirements exist, or where a very stiff excavation support system is needed, slurry walls are the preferred system. Selection of the wall system, however, should also consider local practice and client preference.

A summary table of the various attributes of different wall systems is provided in Appendix A.

5. Temporary vs. Permanent Slurry Wall: The primary reasons for incorporating the slurry wall into the permanent structure design is cost and site constraints (eg. constricted right-of-way in urban areas). In making the decision to incorporate the slurry wall into the permanent structure, the designer should assess the overall performance criteria of the project. Of primary importance is the anticipated watertightness of the permanent wall and the long term effects seepage may have on the structure’s architectural finishes, mechanical and electrical systems, structural integrity of the completed structure, and long term maintenance concerns. Watertightness performance criteria for the permanent structure may dictate if slurry walls are an acceptable choice as a permanent wall. Slurry walls are generally considered to provide acceptable permanent groundwater control for structures such as transportation tunnels, underground garages and most building basements. Slurry walls are not always completely watertight and some long term seepage should be planned for. Watertightness of slurry walls is generally governed by two items: soil permeability and workmanship during slurry wall construction. A secondary cause of leakage is the lack of a positive waterproofing membrane on the exterior face of the slurry wall, allowing seepage to develop over the life of the structure. Such seepage may result from deformation of the slurry wall caused by future excavation or new loads adjacent to the slurry wall or due to thermal deformations from air temperature change; thermal deformations are particularly a concern in highway tunnels where air exchange is frequent. For structures that require a true watertight support wall, such as research

facilities, electric vaults, etc., it may be prudent to consider slurry walls for temporary support only.

6. Comparison of CRC and SPTC Walls

   a. Conventional Reinforced Concrete (CRC) Walls: CRC walls are the most commonly used type of slurry wall. Following are the primary advantages of CRC walls over SPTC walls.

      - Panel Joints: When properly constructed, the concrete to concrete interface between CRC panels has been observed to provide a better seal against groundwater inflow than the concrete to soldier pile interface of SPTC walls. In addition, CRC panels have typical joint spacing in the range of 9 to 25 feet whereas SPTC walls may have spacing on the order of 4 to 6 feet between soldier piles. Therefore CRC walls greatly reduce the number of potential leak locations.

      - Corrosion: The absence of structural steel at panels joints in CRC walls eliminates the concern for long term corrosion at the panel joints should leaks develop over the life of the structure. Invert slabs and roof connections provide a second source of leakage. In CRC walls these connections are usually made with steel reinforcing, providing some structural redundancy which reduces the impact of corrosion if leaks develop. Corrosion at localized, high capacity connections of SPTC walls is a significant issue.

   b. SPTC Walls: SPTC walls provide the following advantages over conventional reinforced concrete walls:

      - Site Constraints: Site constraints that may influence a choice between SPTC and CRC walls include lay down area and vertical headroom. The relative ease of splicing soldier piles provides SPTC walls with a clear advantage in areas of restricted headroom. Although reinforcing cages can also be spliced during lowering into the trench, it is less practical and more time consuming than splicing soldier piles, and therefore should generally be considered in isolated cases only. Construction and hoisting of the reinforcing cages for a CRC wall require significantly more lay down area than SPTC walls.

      - Structural Requirements: Structural requirements may dictate the need to use SPTC walls in lieu of CRC walls. SPTC walls can be designed to provide greater stiffness than typical CRC walls and may accommodate larger vertical wall spans, horizontal loads and moments associated with deep excavations and long roof/ invert spans.

B. Site Investigations

Geotechnical subsurface investigations for slurry wall projects include the same elements common to foundation and retaining wall structures. Reference is made to FHWA Manual on Subsurface Investigations (1997) for a general description and procedures for geotechnical subsurface investigations. A typical investigation program might include test borings drilled at approximately 100 to 200 feet on center along the proposed slurry wall alignment. In instances where subsurface conditions are expected to vary significantly, more closely spaced borings may be warranted to permit a more precise estimate of reinforcing cage and soldier pile lengths prior to panel excavation. Depths of borings should initially be estimated to extend at least to a depth equivalent to 1.5 times the depth of proposed excavation or 10 feet into rock, whichever is shallower. For instances where end bearing is critical, borings may be drilled at each panel location before or during slurry wall construction to confirm top of rock elevation and the quality of the rock. However, in most cases the added cost of drilling at each panel location is not justified as top of rock and rock quality can normally be confirmed in the field during panel excavation. Following is a brief description of specific parameters that are applicable to the construction and temporary design of slurry walls:

1. Groundwater Conditions: In assessing groundwater conditions, of primary importance are groundwater elevations, pressure, artesian pressure and salinity in each soil stratum along the entire alignment. This information is necessary to:

    - Determine minimum slurry elevation during slurry wall excavation to avoid groundwater infiltration into the slurry trench that could destabilize the trench excavation.
    - Establish temporary groundwater pressures.
    - Analyze the potential for seepage beneath the slurry wall.
    - To allow the contractor to determine the appropriate type of slurry.
    - To permit the contractor to determine if additives are required for the slurry mix.

2. Soil and Rock Data: In addition to clearly identifying the type, density and stiffness of each soil stratum anticipated to be encountered, the investigation program is used to obtain soil samples for laboratory testing. Grain size, permeability of granular soils, and strength of cohesive soils are important soil properties necessary for evaluating soil performance during panel excavation, slurry mix design, estimating rates of excavation, determining design earth pressures and estimating wall, ground, and existing building deformations. These data are also useful in assessing the potential for base instability and groundwater drawdown outside the site resulting from seepage beneath the wall.

    In soils suspected of containing boulders/cobbles a detailed assessment should be made of the likelihood of encountering these materials. This assessment may be performed by in depth research of local case histories and field investigations such as localized test pits and continuous roto-sonic sampling.

    Rock strength, mineralogy, and rock quality designation (RQD) data are all valuable parameters for aiding the contractor in selecting its preferred method and equipment for rock excavation. For walls requiring embedment to rock, it is important that an adequate top of rock profile be established along the slurry wall alignment.

3. Existing Foundation Conditions: The contractor needs to assess the impacts of existing structure foundations on slurry trench stability, surcharge loads, and clearances for guidewall and slurry wall construction. Research of existing building foundation records complimented with test pit explorations should be performed. Demolished structures that once occupied the site should be included in this research to better assess the likelihood of the contractor encountering obstructions. Obstructions are a major concern to the slurry wall contractor and should be fully addressed in the design and contract documents, with special attention given to the method of payment for removal of obstructions.

4. Utilities: Research of existing and abandoned utilities complimented with test pits to accurately locate sensitive utilities and utilities located in the immediate vicinity of proposed slurry wall work should be performed. Abandoned utilities interfering with the slurry trench should be removed and capped. When feasible, existing utilities should be relocated. When relocating utilities outside of the slurry wall limits, consideration should be given to the potential adverse impacts of slurry wall excavation and future slurry wall deformation.

   On occasion, utility relocation may not be an option and the utility is required to be supported in place. This situation is known to have occurred on at least two PB projects, Shot Tower Station in Baltimore, and Post Office Square in Boston, both cases involved slurry wall interference with a high voltage electric line. Different solutions were used for each case.

   For Shot Tower Station, slurry wall construction was terminated on each side of the utility. Jet grouting with soldier pile and lagging was then used to fill the gap. Following completion of general excavation, the gap was infilled with a cast-in-place concrete wall.

   For the Post Office Square project, slurry wall excavation was performed on each side of the utility with a cable bucket. Following excavation of these initial slots, it was possible to slide the bucket laterally beneath the utility to remove the remaining small column of soil. Two steel reinforcing cages were installed, one on either side of the utility. The unreinforced concrete between the cages was considered similar to a typical panel joint.

5. Contamination: In areas of suspected contamination, an environmental assessment of the contaminants known or suspected to be present should be provided to the slurry wall contractor for slurry mix design and determining any special requirements for material handling and disposal.

III. DESIGN OF SLURRY WALLS

A. Design Analysis

The design analysis of slurry walls can be divided into two components, temporary/short term conditions and permanent/long term conditions. There are many options and procedures for analyzing slurry walls, as with all earth support systems, and it is not the intent of this guide to dictate the method to be used. Rather, it is intended to provide general direction as to what level/type of analyses might be appropriate.

1. Earth Pressures: For many cases, employing traditional earth pressure design and empirical correlations for wall and ground deformations are appropriate for slurry wall design. The tributary area method, continuous beam method, and beam on elastic foundation method are all considered acceptable methods. In congested urban settings, slurry wall deformations are critical and often warrant more sophisticated analyses. Numerical analyses require detailed knowledge of soil properties and groundwater conditions, and must assume a detailed sequence of construction. Numerical analyses require significant experience in the collecting, processing and evaluation of data. If a structure requires numerical analyses, all work related to the analysis should be planned and performed under the supervision of a person with extensive experience in the modeling of underground structures. It is common practice to compare the results of each numerical analysis with empirical data to confirm the results are reasonable. Projects that warrant a numerical analysis will also likely warrant a sophisticated monitoring program to confirm the accuracy/assumptions of the analysis. For a more thorough presentation of design procedures, refer to the FHWA manual on "Earth Retaining Structures" (Munfakh et al, 1999)

   a. Temporary Earth Pressure: Temporary earth pressures are those that would be anticipated during excavation and in the period of time following completion of excavation to completion of the structure and backfilling within the excavation. Where the slurry wall forms part of the final structure, the final structure should be checked for the temporary earth pressures. Temporary earth pressures are generally based on active earth pressures for cantilever and single brace levels, and on empirical (trapezoidal) pressures diagrams for excavations with multiple levels of bracing. When providing temporary earth support criteria, it is suggested a determination regarding the allocation of risk be made. Two approaches may be considered including: 1) risk almost entirely with the contractor, 2) shared risk between the contractor and designer. The determination as to the level of direction the designer will provide to the contractor is project specific and should be determined by the project's management team.

      In the first approach, the contract documents should clearly indicate that the contractor is solely responsible for the design, construction and performance of the temporary earth support system. The designer may modify this slightly by providing minimum design criteria that the project is willing to accept, such as minimum earth and groundwater pressures, maximum spacing of bracing, etc. However, the contractor is solely responsible for determining if more conservative design parameters are appropriate.

The second approach is more common when deformations are a major concern. In this case the contract documents provide strict direction regarding design parameters to be used, such as required earth and groundwater pressures, maximum strut spacing and required strut levels, excavation restrictions, crack control, permissible deformations, etc. The contractor then designs its earth support system to accommodate the specified parameters.

Regardless of the level of direction provided to the contractor, the designer should confirm the 'buildability' of the project by checking the adequacy of the slurry wall to perform as intended under at least one assumed sequence of construction. As part of the temporary condition check, the designer should confirm that additional steel reinforcing required for the assumed construction sequencing can be reasonably added to the slurry wall without impeding the flow of concrete.

b. Earth Pressures on Permanent Structures: For permanent slurry wall structures, long-term loads are commonly based on triangularly distributed at-rest soil pressures, groundwater pressures (normal and flood), seismic and surcharge loads (from traffic and buildings). It is common to assume seismic loads do not act in combination with flood conditions. On occasion, earth pressures other than at-rest may be appropriate; therefore, under difficult soil conditions, such as very soft cohesive deposits, earth pressures should be reviewed by senior staff experienced in the design of underground structures. Consideration should also be given to potential unbalanced lateral loading due to future excavation on one side of the completed structure.

2. Groundwater Modeling: For the most part, groundwater modeling is primarily required for temporary (construction) conditions, with only a few issues associated with permanent slurry wall structures.

   a. Temporary Conditions: For deep excavations, theoretical hydrostatic pressure acting on the toe of the wall may be found to be of such a magnitude as to make stability difficult to achieve. In this case, it may be warranted to perform a groundwater flow analysis to obtain more realistic estimates of groundwater pressures acting on the wall. Reduction in water pressure commonly occurs as a result of flow beneath the wall into the dewatered excavation. Due to the many assumptions required for a groundwater flow analysis, it is recommended that piezometers be installed behind the wall and in front of the wall to confirm the accuracy of the analyses.

A second condition which may warrant a seepage analysis is deep excavations in granular material below groundwater level. In this case, excessive groundwater gradients beneath and in front of the wall could result in a quick condition and instability of the base of the excavation. The groundwater flow beneath the slurry wall should be checked to confirm the bottom of excavation is stable under all stages of construction.

Methods for reducing groundwater gradients include:

- Increasing the depth of slurry wall to increase the flow path.
- Extend the wall to an impermeable stratum to cut off flow; in this case, it is necessary to check uplift pressures acting on the bottom of the impermeable stratum within the limits of the general excavation, to confirm adequate resistance to uplift.
- When the slurry wall is terminated in highly permeable rock, consideration should be given to grouting the rock beneath the slurry wall.
- A temporary pressure relief system may be necessary to relieve uplift pressure beneath the invert slab during the construction period until the final structure and backfill have sufficient weight to resist this uplift load.

b. Permanent Slurry Wall Structure: On occasion, design conditions of a project may justify the use of a permanent pressure relieved base slab. The benefit of this design element is the reduction of invert slab thickness with a corresponding decrease in excavation depth. A pressure relief system can also be used to eliminate permanent tiedown anchors to resist uplift loads. Long term pumping can have significant impacts on existing structures via groundwater drawdown. The use of a permanent pressure relief system also adds long-term operating and maintenance costs. The choice to employ a permanent relief system requires in depth analysis and review by senior staff familiar with groundwater behavior.

3. Global and Basal Stability in Cohesive Soils: Global and basal stability are issues only for the temporary condition. These analyses are essential when planning an excavation in deep soft to medium stiff cohesive soil deposits. Due to the possible catastrophic results of a global or basal failure, design of excavations in such soil deposits should be supervised by a person with extension experience in the behavior of excavations.

   Instability of the excavation base due to excessive seepage gradients in granular soils must be evaluated and addressed as discussed in Section III.A.2.a.

B. Design Considerations

1. Coordination between Disciplines: Proper design of a slurry wall requires close coordination between all design disciplines and an understanding of the characteristics of slurry walls and soil-structure interaction.

a. Temporary Conditions: In addition to coordinating contract requirements regarding responsibility for design of temporary support elements, such as spacing and type of bracing, temporary conditions also require coordination of issues such as construction staging, traffic management, temporary access/egress to businesses, utility relocations, construction ventilation, etc.

b. Permanent Slurry Walls: Slurry walls used for permanent support may not provide the same watertightness as traditional cast-in-place concrete structures with external waterproofing. Finish items, including lighting, electrical, ventilation, fireproofing, tile, drainage etc. need to be selected based on realistic assumptions of the performance of the completed slurry wall. To avoid direct exposure to moisture, finish items should not abut directly against the slurry wall. Where items are attached to the wall, the attachments are suggested to be corrosion resistant, capable of accommodating the irregular finish of slurry walls and adaptable to permit modifications in the event a wall panel is constructed out of specified tolerance.

2. Waterproofing for Permanent Structures: Leaking of slurry walls may occur at four typical locations, including: panel joints, connection to invert/base slab, connection to roof slab, and penetrations. In addition, leaks may occur within the panel due to the presence of inclusions, such as fragments of Styrofoam that were not fully removed during excavation, soil inclusions, and cold joints. Waterproofing details for penetrations, roof connections, and base slab connections are addressed in PB's waterproofing guidelines, 'Guidelines for the Design of Waterproofing Systems for Underground Structures'.

   Waterproofing of slurry walls is considered a means and methods issue, and the responsibility for providing a slurry wall meeting specified watertightness criteria should therefore be left to the contractor. With proper workmanship, forming of panel joints, cleaning of panel joints, slurry properties, and concrete placement, excellent watertightness can be achieved. Although specialty water stops are available, they too are highly dependent on workmanship; therefore, it is suggested that the decision to use these devices to meet contract performance requirements be left to the contractor.

3. Penetrations for both Permanent and Temporary Walls: Utility penetrations are to be coordinated to permit the slurry wall designer to make accommodations in its design, such as adding steel reinforcing around the penetration. Common practice is to install steel sleeves attached to the reinforcing cage; the sleeves are sealed at each end to prevent concrete intrusion. For SPTC walls without reinforcing, utility penetrations are typically cored during general site excavation. Whenever possible, block-outs and/or penetrations in a slurry wall should be rounded to allow the flow of slurry and concrete around the penetration to minimize the risk of trapping soil and/or creating bentonite pockets.

Less common but significantly larger penetrations include break-outs for tunnel boring machines (TBM's). For conditions such as this, constructing the slurry panel with fiber reinforcement at the proposed penetration location is an option to permit passage of the TBM.

4. Construction Tolerances: Tolerances must be compatible with the neat line of the structure. Generally accepted slurry wall tolerances are as follows:

    - For panel excavation, vertical tolerances of 1:80, 1:100 and 1:200 are often specified. 1:100 is the most common and meets the criteria of most projects. 1:80 is typically used for temporary walls and/or for subsurface conditions where significant boulders and/or obstructions are present. A tolerance of 1:200 will likely require the use of a hydromill. A tolerance of 1:200 may be required to maintain slurry wall continuity at panel joints for very deep slurry wall excavations or to provide required finished structure clearances for structures located in urban settings with right of way restrictions.
    - For endstops, a vertical tolerance of 1:200 in a direction parallel to the panel alignment is commonly specified. In the direction normal to the panel alignment, endstops will follow the verticality of the trench excavation.
    - Location of keyways, penetrations, beam pockets etc.: plus or minus 3 inches vertically and horizontally.
    - Vertical tolerance of steel reinforcing cage: plus or minus 2 inches; soldier piles: plus or minus 1 inch.
    - Horizontal tolerance of steel reinforcing cage: plus or minus 2 inches parallel to panel alignment and plus or minus 1 inch normal to the panel.
    - Horizontal tolerance of soldier pile: plus or minus 1 inch in all directions.
    - Twist of soldier piles should not exceed plus or minus 5 degrees.
    - Concrete protrusions are generally limited to 3 to 4 inches.

5. Invert Slab/Floor/Roof Connections: Early in the design process the designer should carefully consider structural requirements for invert, floor, and roof connections. The anticipated structural loads occurring at these connections may dictate the type of slurry wall to be constructed, SPTC or CRC. SPTC walls with welded structural connections may provide additional moment capacity but are more vulnerable to long term corrosion.

6. Top-Down vs. Bottom-Up: Slurry walls provide the flexibility for the designer to have a choice between traditional bottom-up construction and top-down construction. Bottom-up construction is the preferred method as it is less costly. However, certain site constraints may make top-down construction a prudent choice. Top-down construction may be appropriate in constricted

work sites where the area enclosed by the slurry wall is used as the construction lay down area. This method of construction also provides schedule benefit since it allows initiation of above grade construction simultaneously with below grade work.

In top-down construction, slurry walls are installed along with interior columns, if necessary, using load bearing elements and/or drilled shafts. The structure roof is then installed and the soil is mined in vertical lifts as bracing levels or floor slabs are installed. For parking garages, the permanent parking levels, typically at 10 foot vertical spacing, act as both permanent and temporary support. Alternatively, for transportation tunnels or similar structures, tiebacks can be installed beneath the roof as temporary supports. Internal cross lot bracing is not typically used in top-down construction as the installation and removal of struts and wales in the confined mined space is difficult.

Top-down construction requires the slurry wall to be part of the permanent structure. Examples of PB's top-down construction projects include: the Post Office Square Underground Garage, the Beth Israel Clinical Center, the North Station Parking Garage, and the MBTA Harvard Square Station. All four sites were located in urban settings with little or no lay down space and close to or immediately adjacent to existing buildings.

7. Slurry Wall Seepage Criteria: The designer should clearly communicate to the owner that slurry walls seldom provide the same level of watertightness as that achieved in traditional cast-in-place below grade structures which include external waterproofing membranes. Slurry wall seepage criteria should be carefully considered early in the design phase and acceptable criteria agreed upon between the owner and designer. In general, slurry walls constructed in soils with low permeability such as clays, tight tills and dense silts can be expected to meet strict seepage criteria; however, sands and gravels are more problematic.

   a. Permanent Slurry Walls: Following are two samples of watertightness criteria; the first is from a project constructed primarily in outwash deposits and the second from a project primarily in clay. **The ultimate decision on permanent permissible leakage requires agreement between the project owner and senior management, this agreement is to be made in the conceptual stages of the project.**

      Project primarily in permeable ground conditions:

      Leakage rate of 0.15 gpm for 100 lineal feet of wall, 0.01 gpm for a leak in 10 feet of wall, and 0.005 gpm for any single leak.

      Project primarily in clayey soils:

      The term watertight is defined to mean that no running water from the wall nor the formation of droplets on the wall surface is permitted. The *formation of moist patches allowing water to evaporate from the surface is acceptable.*

b. Temporary and Permanent Support Walls: For all slurry walls, watertightness criteria may be based on permissible drawdown outside the excavation to avoid settlement and damage to existing facilities. Standard practice permits a nominal drop in water levels of 2 feet during construction as measured at observation wells. Groundwater levels are generally expected to return to or close to pre-construction levels following completion of the structure. However, this criterion needs to be assessed for each specific project. In some instances, no groundwater drawdown can be permitted beyond historic fluctuations, such as in the case where migration of a contaminated groundwater plume may occur. In this instance, criteria similar to the permanent condition, permitting no droplets, may be appropriate for the temporary condition as well.

8. Water Collection/Disposal: Regardless of the seepage criteria agreed to, long term leakage is a potential issue for all slurry walls used for permanent structures due to the lack of an external waterproofing membrane and the possibility that long term deformations can re-open previously sealed leaks and joints. Water collection and disposal for slurry wall leakage should be designed into the project whenever a slurry wall is used as part of the final structure. This is typically performed by forming collection troughs, typically 2” deep by 4” wide, along the top of slab at the slurry wall face to collect water running down the face of wall. The water trough may have periodic drains to collect the water or, in the case of tunnels with ballasted track, periodic troughs perpendicular to the slurry wall can be provided to divert the water into the ballast/track drainage system. Where drains are used, they should be oversized to minimize clogging, and provisions made for maintenance and cleanout of the drains.

9. Panel Length: Panel lengths are typically on the order of 9 to 25 feet. The primary considerations in choosing panel lengths are soil conditions, and the risk of damage to existing property should panel collapse occur. The longer the panel length, the greater the risk of collapse. Under average subsurface conditions, panel lengths of 15 to 20 feet are typical. In areas immediately adjacent to buildings or in loose sands it may be prudent to limit panel lengths, with 9 foot lengths not uncommon. Panels excavated in medium to stiff clay can typically support panel lengths up to 25 feet. Regardless of the initial panel length assumed in design, flexibility should be built into the design to allow panel length revisions based on field observations and to accommodate the contractor’s selected means and methods. In critical areas, it is acceptable to require the contractor to excavate non-production test panels to better assess the appropriate panel length.

10. Wall Deformations

    a. Permanent Structures: When incorporating the slurry wall into the permanent structure, consideration should be given to slurry wall deformations that will occur during general site excavation. These deformations are in addition to the specified slurry wall construction tolerances noted previously. The designer should be conservative in the assessment of potential slurry wall encroachment to accommodate the realistic possibility that some panels will be constructed out of tolerance and deformations may exceed estimates. Deformations may also alter the distribution of shear and bending moments within the wall, further emphasizing the need to conservatively estimate deformations.

    b. Temporary Conditions: Slurry wall deformations for the construction condition are primarily a concern in regard to damage to existing facilities such as buildings and utilities. Where permanent interior cast-in-place walls are to be cast directly against the interior face of the slurry wall, care must be taken to ensure the slurry wall does not encroach into the design envelope of the permanent cast-in-place wall, similar to the care taken for the permanent wall encroachment concerns.

    c. Estimating Wall Deformation: Wall deformation can be estimated using empirical data or by numerical methods as noted previously in Section III.A.1 of this guide. The magnitude of wall deformation is dependent on many factors, including ground conditions, wall stiffness, spacing of bracing levels, timeliness of installation of the bracing system, and the magnitude of preloading applied to the bracing system. Wall deformation is particularly a concern in soft to medium stiff cohesive soils with low factor of safety against base stability; see FHWA manual on "Earth Retaining Structures" (Munfakh et al, 1999).

11. Buoyancy of Structure

    a. Permanent Structures: Under permanent loading conditions, a minimum factor of safety of buoyancy of 1.1 is recommended for long term normal groundwater elevation, overburden soil and dead weight of structure (including slurry wall). For flood conditions, a minimum factor of safety of 1.05 is recommended. The use of adhesion and friction along the sidewalls is discouraged and should only be considered after review by senior designers with significant experience in the design and behavior of underground structures.

    b. Temporary Conditions: When evaluating buoyancy of the underground structure during construction, the dead weight of slurry wall and the other completed structural items can be assumed to resist buoyancy forces. Generally, soil friction or adhesion on the sides of the slurry wall should be ignored due to the need of vertical deformation to mobilize resistance.

An overall minimum factor of safety against buoyancy of 1.1 for normal groundwater level and 1.05 for flood condition is recommended.

12. Horizontal Loading

    a. Soil: Design earth pressures should generally be determined in accordance with procedures outlined in FHWA manual on 'Earth Retaining Structures' (Munfakh, et al, 1999). In determining design earth pressures, caution should be exercised to avoid over conservatism in selecting design parameters since this approach may add unnecessary cost to the slurry wall.

    b. Groundwater

       Permanent Conditions: Both flood and normal groundwater elevations should be considered in the permanent design. Loadings from flood condition are not typically assumed to occur simultaneously with seismic loads; however, this should be confirmed on a project by project basis. Permanent slurry wall structures are generally designed for the full hydrostatic pressure, even if the final structure is provided with a permanent under drain.

       Temporary Conditions: Since flood conditions are usually assumed to occur on the order of once every 100 years, designing temporary earth support systems to accommodate flood conditions may not always be warranted. In some instances, allowing the excavation to flood will prove to be less costly than designing for maximum flood levels; for this case design of the temporary excavation support walls may be based on the maximum groundwater elevation permitted during construction.

       When appropriate, and when demonstrated by appropriate seepage analysis, design groundwater acting on the lower portion of the slurry wall may be adjusted to reflect anticipated seepage beneath the wall. When a reduction in pressure is assumed, instrumentation monitoring is suggested to confirm the analysis.

    c. Seismic

       Temporary Conditions: Including seismic in the temporary condition is a regional issue and/or a risk decision to be made by the owner and/or contractor or dictated by applicable codes. Combining seismic and flood conditions loads is a decision specific to each project. These issues should be addressed separately for each project.

       The inclusion of seismic lateral loading is almost always included in the permanent wall design. When the permanent wall is used as part of a 'boat section' (i.e. U-section) structure, the dynamic earth pressure method using Mononobe-Okabe theory can be used to account for the seismic effects. The Mononobe-Okabe method assumes that the wall structure moves and/or tilts sufficiently so that a yielding active earth wedge forms behind the wall. For a slurry wall to be incorporated into a more rigid underground box structure with transverse walls (or shear walls), the Mononobe-Okabe method may under estimate the dynamic earth pressure. An example of such a structure is a volume basement structure resting on very stiff/hard medium and rigidly braced across by transverse shear wall diaphragms. In this case another theoretical form of dynamic earth pressure derived by Wood (1973) should be considered.

When a slurry wall is used to form an underground running tunnel structure (such as a cut-and-cover tunnel), seismic design using the displacement-governed method is more appropriate than the force – governed method (such as dynamic earth pressure methods discussed above). The primary and most damaging seismic effect a buried box type tunnel will experience during earthquakes is transverse racking deformations (sidesway motion) due to shear distortions of the ground. Therefore, the design should ensure that the tunnel structure has adequate capacity to accommodate the ground displacement rather than resist it; by taking into consideration the soil-structure interaction effect.

If liquefaction is identified at the site, its effects should be considered in the seismic design. These effects may include increased lateral earth pressures, post-liquefaction settlements, liquefaction-induced lateral spread and uplift pressures. Ground improvement may be warranted in some cases. These issues should be addressed on a project specific basis.

d. Surcharge Loads: Traffic and construction surcharge loads are generally of such a magnitude that they will not have a significant impact on the slurry wall and bracing system except possibly near the top of wall. In urban settings, building surcharge loads can be significant. It is important to gather as much information on building foundations, building loads and building structural design early in the design process as protecting existing structures and satisfying property owners' concerns over potential building damage can have significant scheduling and cost implications to the project, and will likely dictate earth support methods.

e. Unbalanced Loading

Temporary Conditions: In some settings, it is possible to have unbalanced loadings during temporary conditions. Some examples of unbalanced loading include different surcharge loads, sloping ground and sometimes differing groundwater elevations across the site.

Permanent Conditions: In addition to the unbalanced loadings that may occur under temporary conditions, consideration should be given to designing the permanent structure to accommodate adjacent excavations for future development. This issue is a project specific decision that should be made by the owner. Frequently, public owners will want to accommodate future development and will dictate that the design of the permanent structure assume a future excavation to some specified depth, whereas private developers will likely not accommodate future excavation but will assume the future developer will be responsible for protecting the slurry wall structure.

13. Vertical Loading

    a. Soil Loading: Vertical soil loadings for the permanent below grade structure with a roof elevation at depth can be significant. Large soil loads combined with long roof spans create large shear and moment at the roof to slurry wall connection. An early estimation of roof loadings is critical in concept design when structure types and cost estimates are first being prepared.

    b. Uplift Loading: Similar to the vertical soil loading discussed above, for deep inverts, uplift water pressure acting on the permanent invert needs to be assessed early in the project as these loads will likely be transferred to the slurry wall and may dictate the type of slurry wall to be used, the design of the invert slab, the depth of excavation to accommodate the invert slab, and the connection of the invert slab to the slurry wall.

    c. Air-rights Loading: In designing permanent slurry walls for this future loading, it is necessary to consider the verticality of the slurry wall in its capacity to support the axial loads that will be applied. It is suggested that for design purposes, assume that the wall has been constructed to verticality in the range of half its specified criteria, i.e. assume a verticality of approximately 1:100 for a wall specified to be constructed to 1:200. The magnitude of the air-rights loads to be considered in the design is provided by the owner.

    d. Tiebacks

       Temporary Conditions: Tiebacks are installed at a slight angle, typically 10 to 20 degrees from horizontal, and occasionally up to 30 degrees. When tiebacks are anticipated to be used, supervision by an engineer with experience in tieback design is necessary to determine the resulting vertical load on the wall and the potential for slurry wall settlement which would result in relaxation of the tiebacks with corresponding increased lateral deformations.

       Permanent Structures: Tiebacks for permanent lateral support of permanent slurry wall structures should generally be avoided due to concerns of corrosion, permanent right-of-way easements and future disturbance to the tiebacks due to adjacent site development. When used for temporary support during construction staging, these tiebacks are typically de-tensioned as the invert slab, floors, and roof are placed. Should tiebacks be used for permanent support of permanent slurry wall structures, vertical load concerns are similar as the temporary condition.

e. Decking Loads: In urban settings, it is often beneficial to design a temporary decking system, supported on the slurry wall, to maintain vehicle and pedestrian traffic, and to provide construction access. These loads should be considered in the design of the slurry wall.

14. Bracing

a. Cross Lot: Cross lot bracing is the most common and preferred method for temporary support. Cross lot bracing is typically pre-loaded to 50% of the maximum design load anticipated to occur at each strut for the entire construction period. In some instances, where deformations are a critical concern, higher preloads may be considered. Excavations exceeding widths on the order of 65 feet may require intermediate temporary pile support to produce acceptable sizes. For SPTC walls it is typical practice to attach the wales directly to the soldier piles. For conventional reinforced slurry walls, bearing plates are attached to the face of the reinforcing cage, struts can either bear directly on the plates or exterior wales may be attached to the plates. Elimination of exterior wales is possible by including reinforcing beams within the slurry panel cage; however, this method is not generally preferred as the steel congestion may inhibit concrete flow and makes tremie pipe installation difficult. Temporary design of the slurry wall to accommodate bracing is generally the responsibility of the contractor.

b. Top-Down Construction: When considering top-down construction, the slurry wall is designed as part of the permanent structure. The preferred bracing system for top down construction is employment of the permanent structure slabs as excavation proceeds, this works well for parking structures which typically have parking levels on the order of 10 foot spacing which correlates closely with the typical spacing of temporary bracing systems of 12 to 15 feet. However, transit structures frequently have permanent vertical wall spans in excess of what is required for temporary support. When temporary bracing is required for top-down, tiebacks are the most accommodating to the excavation environment, but their use may be precluded by right-of-way constraints and soil and groundwater conditions. The mining procedure with low head room makes the use/installation of cross lot bracing difficult.

c. Tiebacks

Temporary Conditions: As completion of the permanent structure progresses, temporary tiebacks are detensioned and the slurry wall penetrations are sealed. It is suggested that slurry wall penetrations provided for tiebacks use threaded steel sleeves; this permits easy installation of permanent steel caps for sealing. For temporary conditions, the contractor is generally responsible for determining the quantity of additional reinforcing steel to be added to the slurry panel to accommodate the tieback loads.

Permanent Conditions: Tiebacks are not the preferred choice of earth support for permanent slurry walls due to the necessity of penetrating the wall and further compromising the watertightness. In addition to the design considerations given to temporary tiebacks, permanent easements are required as well as long term corrosion protection for the anchors. Since permanent tiebacks extend several inches beyond the interior face of the slurry wall and these heads may be a continued source of leakage, the negative impact permanent anchors may have on the completed structure should be assessed. When permanent tiebacks are to be used, the designer is responsible for determining the additional steel to be added to the slurry panel to accommodate the tieback loads.

General Issues: The following issues should be addressed for use of tiebacks:

- Position and details of block-outs in the slurry wall panels for tieback installation.
- Potential for water inflow and ground loss through the tieback sleeve during tieback installation.
- Temporary and permanent easements for tiebacks.
- Provisions for adding tiebacks if proof tests identify any deficient tiebacks.
- Pre-load and lock-off loads.
- Slurry wall depth of embedment to accommodate the vertical component of tieback loads.

d. Slurry Wall Embedment: Extending the slurry wall into dense soils or rock can provide significant resistance to vertical loads and lateral deformations, and should be considered when the dense soils or rock are at or relatively close to the bottom of excavation. However, where deep deposits of soft soils extend below the proposed excavation, extending the slurry wall is of little benefit in reducing lateral wall deformations.

Extending the wall may be done for reasons other than providing lateral resistance, such as groundwater cutoff and vertical bearing. As one of the main reasons in selecting a slurry wall is control of groundwater, extending the wall into an underlying impermeable stratum is common practice. Common depths of embedment for groundwater cutoff are on the order of 5 feet into clays and the width of panel into rock, i.e. a 3 foot panel would extend a minimum of 3 feet into rock. The same depth of minimum wall embedment into rock applies for the condition where end bearing is required.

C. Design Details: This section provides general guidance for various structural design details associated with slurry walls. Appendix B provides illustrative sketches of details used successfully on previous projects.

1. Keyways: Keyways are typically formed by attaching high density Styrofoam with plywood covering to the outside of reinforcing steel. The keyway should be oversized to accommodate setting tolerances. The depth of keyway is commonly set to a depth of approximately 3 inches. The keyway recess should not be considered to provide any structural capacity in the structural design of the invert slab, beams, roof, and floor to wall connections as the quality and as-built depth of keyways frequently do not meet design criteria.

2. Endstops

   a. Temporary Endstops: Temporary endstops are used with the Conventional Reinforced Concrete slurry wall. Two common types of endstops include circular piles and specialty designed 'V' nosed endstops. The intent of the temporary endstop is to provide a concrete to concrete interlock between panels to assist in groundwater control. No panel to panel structural capacity is assumed to be transferred through the unreinforced joint. Removal of the endstops begins prior to initial concrete set. The unreinforced panel joint eliminates the concern of long term corrosion should leaks occur at the panel joints; this benefit, combined with construction difficulties associated with permanent endstops, makes temporary endstops preferred over permanent endstops for slurry walls that are to be part of the permanent structure. It should be noted that technologies are continually advancing in 'temporary endstops' and there are various endstops that are designed to specifically address watertightness at the panel joints by being capable of leaving a waterstop in place at the panel joints. However, it is suggested that the means and methods of meeting watertightness criteria be the responsibility of the Contractor.

      It is common practice when excavating with a hydromill to eliminate the temporary endstop. This is possible as the hydromill is capable of grinding the edge of the completed panel, providing a roughened surface in place of a formed key.

   b. Permanent Endstops: Permanent endstops are synonymous with SPTC walls. Of primary concern with permanent endstops is removal of overpour concrete from the unexcavated side of the pile. Various contractor methods exist to control this problem, the most common of which is to fill the web area with Styrofoam held in place with plywood and metal banding, similar to a keyway blockout. The banding, plywood and Styrofoam is then removed during the excavation of the adjacent panel. The failure to prevent intrusion of concrete overpour into the web has a significant adverse impact which is a major detriment to permanent endstops. The means and methods of preventing concrete intrusion should be left entirely to the contractor; only review of the submitted means and methods should be performed by the engineer. Any method used, however, must be reliable and suitable for the intended purpose. In instances where the slurry wall design requires the installation of embedded items, these items should be located as far as practical from the panel joint such that panel joint cleaning is not compromised and the flow of concrete at the panel joint is not impaired.

3. Reinforcement

   a. Minimum Cover: For steel reinforcing, minimum concrete cover for each face is 3 inches.

   b. Reinforcing Spacing: Common spacing is a minimum of 12 inches on center for horizontal steel and 6 to 9 inches for vertical (for SPTC walls, where the reinforcing spans horizontally, the typical spacing can be reversed). Control of dimensions, reinforcement placement and concrete placement is more difficult for slurry walls then for conventionally formed concrete. Therefore, although reinforcement requirements should be in general accordance with ACI 318 for reinforced concrete (unless another code governs the project) the minimum spacing between reinforcing should be more generous than what is allowed by ACI 318 to permit flow of the tremie concrete through and around the steel reinforcement. At this time there is not a national code for slurry wall reinforcing spacing. However, both the AASHTO Standard Specifications for Highway Bridges and the AASHTO LRFD Bridge Design Specifications provide reinforcement spacing criteria for drilled shafts constructed by the slurry method. The AASHTO Standard Specifications for Highway Bridges requires the following for drilled shafts: *The minimum clear distance between parallel bars in a layer should be at least 3 times the bar diameter, or 3 times the maximum size of the coarse aggregate, or 1-1/2 inches, whichever is largest. If reinforcing bars are bundled, the spacing limits should be calculated based on an equivalent bar diameter, i.e. the unit of bundled bars are treated as a single bar of a diameter derived from the equivalent total area.* While the AASHTO LRFD Bridge Design currently requires: *a minimum clear space between reinforcing of 5 times the maximum aggregate size or 5 inches whichever is greater*. Recent research is suggesting a minimum reinforcing clear spacing of 10 times the maximum aggregate size may be appropriate for tremie concrete. A pending revision to the AASHTO LRFD specification will increase the minimum space between reinforcing from 5 to 10 times the maximum aggregate size. In their 1999 Edition of the manual on "Drilled Shafts: Construction Procedures and Design Methods", the Federal Highway Administration (FHWA) suggests a minimum clear spacing between reinforcing bars of 5 times the size of the largest coarse aggregate, or 3 inches, whichever is larger. However, the pending update to this FHWA manual will be consistent with the new AASHTO LRFD specification noted above.

   Based on AASHTO requirements and past PB experience it is suggested that for slurry walls, the designer strive for a minimum clearance between reinforcing of 10 times the maximum aggregate size and not less than 5 times the maximum aggregate size or 5 inches, whichever is greatest.

Spacing of stirrups should be planned to accommodate the installation of tremie pipes.

As with typical reinforced concrete, welding of bars is not generally accepted as quality control is difficult and the procedure is expensive. Welding also increases the rigidity of the cage; under most conditions, it is preferred to have a flexible cage for hoisting since a rigid cage is more susceptible to permanent distortion.

c. Epoxy Coated Reinforcement: Epoxy coating has been employed in the construction of slurry walls. However, the usefulness of epoxy is questionable. Epoxy bars are prone to chipping during assembly, hoisting, setting, and concrete placement, especially at dowel bend outs at slab connections. Epoxy coated bars do not bond to concrete and the need to protect against chlorides is typically not needed in slurry walls. Therefore, it is suggested that epoxy coated reinforcement not be used in slurry walls. Should a project owner insist on its use, epoxy coated reinforcing is acceptable but one needs to be aware of its limited effectiveness.

d. Reinforcing Cage Sizes: Reinforcing cages are to be sized to accommodate previously noted setting tolerances plus an additional 3 inches for cover. Reinforcing should be stopped approximately 6 to 12 inches above the bottom of the trench to accommodate any unevenness that may exist along the bottom of trench.

   At panel joints, additional clearance is required to accommodate setting tolerance of the endstops. As noted previously, endstop verticality tolerance is approximately 1: 200; therefore plus or minus 6 inches for a depth of 100 feet. Combining the 6 inch setting tolerance with the required minimum concrete cover of 3 inches requires the reinforcing cage to be terminated 9 inches from the theoretical panel joint resulting in 18 inches of unreinforced concrete between adjacent panels.

e. Reinforcing Bar Sizes: Essentially all bar sizes are acceptable for slurry wall construction. However, Grade 60 #7 bars are typical for horizontal steel and Grade 60, #9 to #11 bars are typical for vertical steel. For reinforcing cages to be incorporated into an SPTC wall, the horizontal and vertical bar sizes are reversed as the cage transfers loads horizontally.

f. General Structural Design: A conventional reinforced wall is reinforced in two directions and spans vertically between supports (temporary bracing members or permanent floors). It is considered good practice to compile moment and shear envelopes along the entire height of the wall using results from an assumed staged excavation analysis and, in the case of a permanent slurry wall, from frame analysis for the final loading conditions.

The structural design involves sizing of the vertical reinforcing for flexure, checking shear, and designing shear reinforcement and stirrups, when needed. In addition, crack control and wall deflection are considered, especially when the slurry wall is part of the permanent structure. Combined axial load and bending require checking if the slurry wall will be supporting vertical loads.

Generally, ACI 318 is applicable for the design of slurry walls; however, project requirements may dictate the use of AASHTO or local building codes. Since quality control is difficult for slurry walls, such as control of dimensions, reinforcement placement, and concrete quality, a more conservative approach to design and detailing is suggested. As an example, when calculating the effective depth of structure, d, in addition to concrete cover and rebar size, slurry wall excavation tolerances should be considered.

g. Permanent Structural Connections: As part of the permanent structure, the slurry wall must support slabs and beams. Depending on requirements for structural behavior, hinged, partially hinged or fixed connections can theoretically be used. However, partially hinged connections are not considered practical for slurry wall design. The designer should carefully consider the use and location of each type of joint. For linear structures, such as cut and cover tunnels, only the roof or invert slab is typically rigidly connected. For box-like structures, such as underground garages, all slab to slurry wall connections may be pinned as the perpendicular slurry walls provide lateral stability.

Fixed connections transmit the moment and shear from the end of the floor into the slurry wall, often resulting in heavy/congested reinforcing.

Hinged connections only transmit shear force from the slab to the slurry wall and are generally simpler to construct than a fixed joint; however, bending moment at midspan of the slab is greatly increased and should be considered in the design development phase of the structure.

CRC slurry wall to cast-in-place slab connections: For pinned connections, bend-out bars are generally used. Since the bend-out bars will be cold bent in the field their size is limited to #4 or #5, Grade 40 rather than the Grade 60 which is used for the main reinforcing. Fixed connections typically require the use of threaded rebar couplers.

CRC slurry wall to steel beam connections: This detail requires the use of embedded steel plates (usually with the use of welded shear studs) in the face of the slurry wall. Following general excavation, the embedded plate is exposed and connection angles are welded to it, the steel beam is then bolted to the angle. If forces permit, single plate shear connections are a simple method of connection, for moment connections, the beam's flanges can be directly welded to the embedded plate or top and bottom connection plates can be used. Appendix B provides connection details successfully used on PB projects.

4. Soldier Piles

   a. Minimum Cover: For SPTC walls, the minimum recommended cover for corrosion protection is 3 inches. For designs where the soldier pile is essentially the same width as the theoretical trench excavation, the exposed interior soldier pile flange should be sealed for protection from corrosion; a design decision regarding the need to provide corrosion protection for the exterior flange should be made following an assessment of subsurface conditions to determine if the soldier pile is subject to long term corrosion. On PB's Baltimore Metro Shot Tower Station, corrosion protection was provided by applying polyamine epoxy to the interior flange of each pile during general excavation. On the Central Artery project, Bridgecoat 8100 (CCS) was applied to the interior flange during excavation. Individual soldier piles should be set on the bottom of excavation, similar to an endstop, to prevent movement during concrete placement. If soldier piles are laced in pairs, preventing horizontal movement, the piles can be terminated 6 to12 inches above the bottom of excavation to accommodate any unevenness that may exist along the trench bottom.

   b. General Structural Design: With SPTC slurry walls, the concrete spans horizontally between the steel piles that provide resistance in the vertical direction. Therefore, the horizontal reinforcing has to be sized to resist moment and shear for lateral pressures. Usually it is assumed the wall is a series of simple spans between the soldier piles. Reinforcing may be omitted if the flexural, shear, compression and bending stresses are less than the concrete cracking strength and the permissible stresses allowed by ACI for plain concrete. The design of the steel piles is in accordance with the AISC Manual for Steel Construction.

   c. Permanent Structural Connections: Connections, fixed, hinged or partially hinged, are similar as those provided for the conventional reinforced slurry wall.

   SPTC slurry wall to steel beam connection: Typical structural steel beam to steel column connections can be used in this case. Simple shear connections or high capacity moment connections can both be achieved. The steel beam is connected to the pile with field welded angles and top and bottom plates, or the beam can be directly welded to the soldier pile.

   SPTC slurry wall to cast-in-place slab connections: These connections are usually used for moment transferring joints between unreinforced SPTC walls and reinforced concrete slabs. Short segments of structural steel shapes are welded to the steel soldier pile and embedded in the reinforced slab.

When required, splicing of soldier piles is commonly performed by bolting as field conditions and time constraints are not typically conducive to welding.

Appendix B provides illustrations of connection details successfully used on PB projects.

5. Concrete: To accommodate tremie placement and removal of endstops, concrete mix designs have a high slump, typically 7 to 9 inches at the time of placement, and may include retarders and plasticizers. Aggregate size is typically ¾”; however, in panels where steel congestion is relatively high, 3/8” aggregate is commonly used. To accommodate endstop removal prior to concrete set, pour size/panel sizes are often determined to allow completion of concrete placement in 4 hours. Concrete placement commonly occurs at about 40 cubic yards per hour per tremie pipe. Common concrete strengths are 4,000 and 5,000 psi. It is common practice to provide a concrete mix in the specifications; however, similar to bentonite slurries, contractors will have their preference for concrete mixes to accommodate their chosen means and methods of construction to meet required performance criteria. Modifications to the design mix should be permitted provided there is no compromise in the final structural performance requirements of the concrete. All concrete mixes should be evaluated at the start of slurry wall construction for compliance with project performance requirements.

IV. SLURRY WALL CONSTRUCTION

This section provides guidance on various topics related to the construction of slurry walls.

A. Slurry Selection

1. Bentonite: Bentonite slurry is the preferred type of slurry for providing trench stability and should be used in all cases unless there are site restraints that dictate otherwise. In addition to better trench stability, bentonite is believed to provide some level of increased watertightness in comparison to polymer slurry. Although bentonite is not considered as a waterproofing membrane, it does provide a watertightness barrier on the external surface of the slurry wall, after the tremie concrete is placed. The slurry wall utilizes whatever filter cake is formed on the side walls of the excavated trench which provides some ability in sealing minor seepage. When clean gravels are expected to be encountered, trench instability should be anticipated as the relatively large voids prevent the formation of an effective filter cake.

   As noted previously, the behavior of bentonite slurries can be affected by contaminants. Of particular concern is brackish or salt water. When salt water is encountered, the contractor will likely be required to mix additives in with the slurry to maintain the require slurry parameters. Attapulgite clay has been found to be more effective in this environment than bentonite, but is not as readily available.

2. Polymer: Polymer slurries provide economical benefits in comparison to bentonite, primarily savings in desanding, disposal, and decreased staging area. However, polymer slurries are not considered an equal replacement to bentonite in regard to trench stability and water sealing capability. Polymer slurries are not recommended for slurry walls unless specific site constraints require their use. Such site constraints might include lack of an on site or off site staging area of sufficient size to accommodate a slurry plant. Subsurface materials most acceptable for polymer use are medium to stiff clays, very dense impermeable tills and rock. The likelihood of collapsing trenches is substantial when polymers are used in soft organic silts and loose cohesionless soils. Based on PB experience, polymer slurries are not currently suggested for granular soils.

B. Slurry Properties

1. Bentonite: The bentonite slurry is primarily a contractor's means and methods for constructing the slurry wall, provided the slurry conforms to specified performance requirements. As such, latitude needs to be provided to allow revisions to specified bentonite properties based on actual field observations. Properties that may require revisions in the field typically include density and viscosity. In general, just prior to steel placement, a viscosity on the order of 45 seconds and density less than 72 pcf are preferred,

and a sand content of less than 5% and a pH between 7 and 11 are required. Schedule conflicts, risk of damage to adjacent structures, or sloughing of the trench may require judgment modifications to the slurry properties and, in some instances concrete placement under less than ideal conditions is warranted in the interest of minimizing risk to adjacent facilities. Testing of the bentonite is performed frequently with the results reported to the engineer. The most important test is prior to the placement of steel into the trench; this test should be witnessed by the engineer's on site representative, and consists of testing a slurry sample obtained within 12 inches of the bottom of trench.

Below is a suggested general guideline. Slurry properties and testing procedures are per American Petroleum Industry Standards, API - 13Aand 13B-1.

- Density:
  Fresh: 65 to 68 pcf,
  During excavation: less than 78 pcf (Although a minimum of 64 pcf is commonly specified, the actual minimum value is that which is required to maintain trench stability)
  Prior to steel placement: less than 72 pcf (72 pcf is preferred; however, if necessary, a maximum value of 80 pcf is within the limits of practice)

- Viscosity:
  Fresh: 30 to 45 sec,
  During excavation: 30 to 70 sec,
  Prior to concreting: 30 to 45 sec. (45 seconds is reasonable for most soils; however, values as high as 70 seconds may be required for some soil types, such as gravels)

- Sand content:
  Prior to concreting: less than 5%,
  Where end bearing is critical: less than 3%

- pH: 7 to 11

- Fluid loss: less than 25cc

Slurry is continuously pumped into the panel trench as excavation proceeds, and the slurry is maintained at a level not less than 4 feet above groundwater level. In instances where the groundwater level is at, near, or above ground surface, the ground surface can be raised to permit constructing the guidewalls at a higher elevation to maintain the required bentonite level above groundwater. Following excavation, the slurry is continuously pumped from the bottom of trench, processed/cleaned by passing through a desanding unit and returned to the top of trench. This process continues until the slurry properties are in accordance with the specifications noted for "prior to steel placement".

During concrete placement, the slurry is pumped from the top of trench to storage tanks as the concrete is placed. Cleaning of the slurry becomes more difficult and time consuming with each use; the contractor will determine the appropriate time to dispose and replace slurry, provided the slurry continues to meet specification requirements and provides the necessary trench stability. Bentonite slurries are not to be disposed of in drains or other public utilities/waterways; they are required to be transported to approved handling facilities.

2. Polymer: Use of polymer slurries is site specific. Generally, the use of polymer slurry should be precluded in the project specifications unless the engineer is satisfied that it is appropriate for the anticipated ground conditions, currently polymer is not suggested for granular soils. If polymer slurries are being considered for a project, an in depth review of polymer slurry should be performed. The contractor should be required to submit case histories of successful performance of the proposed polymer slurry. The polymer slurry should be prepared and used in accordance with the manufacturer of the polymer. The contractor should excavate a test panel (non-production) to assess the performance of the polymer. The contractor must also adjust the polymer slurry, as necessary, to maintain trench stability and comply with all other specified performance requirements.

C. Pretrenching/Guidewalls: Pretrenching allows for the removal of shallow obstructions and soils unsuitable for guidewall bearing. In urban areas, pretrenching typically extends at least to the bottom of miscellaneous fill and is intended to remove possible obstructions in the fill. Pretrenching is backfilled with either compacted structural fill or flowable lean mix, the strength to be determined by the contractor. Guidewalls are typically 3 to 4 feet deep, the inside face of the guidewall is set along the theoretical inside face of the slurry wall, and the distance between inside and outside face of guidewall is typically 2 inches wider than the slurry wall design width. It is considered good practice for the guidewalls to be reinforced, with the reinforcing continuous through guidewall joints. Guidewall design is a means and methods item that should be the responsibility of the contractor. (See Section VIII, Photos 1 and 2.)

D. Panel Excavation

1. Equipment Type: The contractor is responsible for selecting the method of excavation. All methods of excavation are capable of excavating panels to depths in excess of 300 feet. However, typical panel depths range from 50 to 130 feet. For excavations greater than 130 feet, in-depth research and review by senior staff is suggested. The three types of excavation equipment that are commonly used are discussed below.

   Cable suspended clam bucket: This is the most common and versatile method of excavation. The primary concern with the use of cable suspended clam buckets is control of verticality. Clam buckets, in combination with chiseling, can excavate soft to moderate rock and can accommodate excavation of the full range of soil types, and obstructions. Hard rock excavation is difficult and usually limited to a nominal penetration, a few feet, to achieve end bearing or groundwater cutoff. The rig can be modified for low headroom of less than 20 feet. (See Section VIII, Photos 3 and 4.)

Rigid Kelly Bar Rig: The rigid Kelly bar is generally slower than the cable suspended method, but verticality is generally considered to be better for shallow walls, less than about 50 feet. They come equipped with either cable or hydraulically actuated buckets. A separate crane for rock chiseling is often required; rock excavation is similar to a cable suspended rig. (See Section VIII, Photo 5.)

Hydromill: Hydromills are primarily used for excavation in sands and rock. They are not typically preferred for clays as the cuttings tend to clog the spoil return lines, and the mixing of the clay particles and bentonite slurry requires frequent slurry replacement. Excavation of rock with compressive strengths in the range of 15,000 psi is reported; however, if significant excavation of hard rock is anticipated, the designer should consult with specialty contractors to confirm the reasonableness of the planned construction. The equipment can be modified for low headroom, less than 20 feet, making it suitable for urban conditions. (See Section VIII, Photo 6.)

The hydromill has several major advantages over the cable suspended clam bucket and the rigid Kelly bar rig, including:

- Efficient removal of spoil since spoil is discharged simultaneously with trench excavation.
- Provides the best verticality for deep walls as the cutter head is equipped with instrumentation to continuously monitor verticality and permits adjustments to be made by the operator.
- Contains spoil and can pump spoil to remote locations making it very suitable for urban settings.

2. Panel Sequencing: A typical slurry wall would include primary, secondary and follow-up panels (sometimes referred to as sequential panels). Primary panels are the first panels excavated and include the use of two endstops. Primary panels are installed in an alternating sequence, usually leaving at least two unexcavated panel widths between open trench excavations. Once the primary panels achieve adequate concrete strength, the secondary or follow-up panels are excavated. Secondary panels are excavated between two completed panels and have no endstops. Follow-up panels are excavated adjacent to one completed panel and require one endstop.

   To avoid undermining of constructed panels, particularly in granular soils, slurry panel design and construction sequencing should be such that secondary and follow up panels do not require excavating below the bottom of the primary panels. In some instances where subsurface profiles vary, unforeseen conditions may result in a violation of this criterion; however, this is most likely to occur where the panels are to be founded in rock which is a condition that should not result in undermining.

3. Panel Verticality: Slurry wall verticality is generally accepted to range from 1:80 to 1:200. 1:100 is considered achievable with all methods of excavation in typical soil conditions. For verticality between 1:100 and 1:200, a hydromill should be considered.

   As noted previously, hydromills are typically equipped with automated monitoring devices located in the cutter head assembly. These devices provide continuous verticality data back to the cab where the operator can make the necessary adjustments. The cutter wheels for the hydromill can be titled or operated at different speeds and the boom adjusted to maintain alignment of the excavation.

   Verticality measurements with cable suspended clam buckets are typically made manually at a specified interval by: 1) attaching plumb lines to the center of each side of the bucket, 2) lowering the open bucket to the bottom of excavation, 3) plumbing the lines, and 4) measuring the distance from inside face of guidewall to plumb line. A testing interval of 20 feet is considered reasonable.

   With rigid Kelly bars, the verticality of the bar is checked with the use of levels.

E. Joint Cleaning: Following excavation of secondary or follow-up panels, the existing concrete joint or permanent endstop of the adjacent panel must be cleaned. Cleaning of the joint is critical for minimizing water intrusion through the completed wall. The contractor submits its proposed means and methods for joint cleaning for review and acceptance by the engineer. It is critical that this procedure be observed by the engineer’s on site representative and documentation provided by the contractor’s quality control inspector that each joint is clear of all material. A typical cleaning tool may consist of a weighted W section with an attachment fitting the shape of the panel joint. The tool is raised and lowered by a service crane and any change of alignment or slack in the crane cable indicates the joint is not clean. Lowering of the excavation bucket with a specially designed attachment conforming to the shape of the panel joint is also a method commonly used for joint cleaning.

F. Endstop Placement/Removal: During installation, endstops frequently scrape the sides of the excavation and cause vibrations, both of which can result in significant amounts of soil to accumulate on the trench bottom. Therefore, it is preferred that endstops be installed following completion of excavation but prior to final cleaning of the trench bottom. Endstops should be firmly seated in the bottom of excavation; this is generally accomplished by simply allowing the endstop to free fall for the last few feet. The verticality is checked with the use of levels. Once verticality is confirmed, the top of endstop is firmly attached to the guidewall to prevent movement during concrete placement. For low headroom conditions, endstops can be assembled in sections.

Depending on the size of pour and properties of the concrete mix, removal of temporary endstops may commence prior to completion of the tremie concrete operation, generally about two hours after the start of pour. Removal needs to begin prior to the initial setting of the concrete but after the concrete has adequate stiffness so as not to deform upon endstop removal. The decision to start endstop removal is at the discretion of the contractor. A typical method a contractor may use to confirm proper concrete stiffness for endstop removal is to set aside a sample of concrete at the start of concrete placement; the stiffness of the sample is periodically observed by the contractor throughout the pour. The engineer's site representative should document the start of pour, start of endstop removal, end of pour and completion of endstop removal. Should any difficulties be noted, they should be recorded and the contractor's procedures adjusted accordingly. (See Section VIII, Photos 7 and 8.)

G. Desanding: Desanding is a process that can be ongoing from the time excavation is complete up to the time the reinforcing is ready for lowering. Desanders may be large stationary plants or small portable systems for sites with limited space. Once the contractor has determined that desanding is complete, he will obtain a sample of slurry from approximately the bottom 12 inches of the excavation. The sample should be obtained and tested in the presence of the engineer's representative. Following acceptance of the test but prior to removing the desanding equipment, the contractor together with the engineer's site representative should sound the bottom of excavation for cleanliness. Sounding should be performed at a minimum of three locations; near each end of the trench and at the center of trench. Soundings are typically performed with a weighted tape; when end bearing resistance is of particular importance, buoyancy neutral rods can be used. (See Section VIII, Photos 9 and 10.)

H. Steel Placement: Prior to setting the steel reinforcing cage or soldier piles, the engineer's representative shall have finished inspection of the completed steel assembly to confirm it is consistent with approved shop drawings. The steel should be marked clearly indicating inside face to ensure proper orientation in the trench. To minimize the risk of caking of bentonite to the steel, concrete placement commonly commences within 2 hours after placement of the steel is completed. If this criterion is violated, the steel is often removed and cleaned. Cleaning is typically performed by simply spraying with a hose; power washing is not normally required. After cleaning the steel and trench bottom, the steel is reinserted. On occasion, project requirements may dictate the need to significantly exceed the 2 hour guide, in such cases it is suggested that mitigative measures be specified and senior construction staff be involved to develop the appropriate time restraints. To help locate the reinforcing cage in the center of the excavation, concrete spacers are attached to both faces of the steel; typically 4 inch wide concrete blocks or 4 inch wide concrete rollers are tied to the steel. Concrete block spacers should have tapered or rounded ends to minimize the scrapping of soil from the sides of the excavation which may cause some minor amount of spoil to accumulate on the trench bottom. Spacers are generally located at about 10 feet on center horizontally, with a minimum of two, and about

20 feet on center vertically. Spacers are usually attached as the cage is lowered into the trench. Spacers are not typically used when setting soldier piles. Plumbness of soldier piles is confirmed by checking verticality above grade with the use of levels and assuming the pile stiffness is sufficient to maintain verticality with depth.

Once the steel is in place; it is hung from the top of the guidewall, often with the use of steel angles attached to extended vertical bars for reinforcing cages and rigid steel frames for soldier piles. The angles/frames are anchored to the guidewall to prevent horizontal movement during concrete placement.

Blockouts for keyways, instrumentation items and all embedments are built into the cage prior to hoisting. Their inclusion and proper location should be confirmed during the general inspection of the reinforcing cage.

Welding of cages is generally not accepted as it increases the rigidity of the cage and can cause permanent deformation of the cage during hoisting. Hoisting of the cage is a dangerous procedure and inspectors should keep a safe distance during this process. On occasion, due to the flexing of the cage, some reinforcing loosens and falls; the inspector should note this and the reinforcing bars re-installed during the lowering of the cage. (See Section VIII, Photos 11 through 17.)

I. Concrete Placement

1. Slump: Concrete commonly has a slump between 7 to 9 inches at the time of placement. The frequency of samples may vary from project to project, but a frequency of one set of cylinders per 50 cubic yards of concrete is common. Slump tests are typically performed for each set of cylinders. Concrete placement is typically planned to be completed within 4 hours to maintain concrete fluidity throughout the pour.

2. Tremie Requirements: The tremie pipes shall have a suitable plug for the initial pour to prevent mixing of the concrete and bentonite slurry. Tremie pipes range in size from 6 to 10 inches in diameter, but 10 inches is the recommended minimum diameter. Flows from tremie pipes are assumed to travel horizontally up to 8 feet; therefore, one tremie may be used for panels up to 15 feet wide. For ‘T’ panels and corner panels, one pipe is to be used for each leg. For SPTC walls, one tremie pipe is to be used between each pair of soldier piles. When multiple tremie pipes are used, the concrete placement should be coordinated to maintain a uniform level of concrete within the panel at all times.

   Concrete placement is typically required to commence within 4 hours of completion of slurry and bottom cleaning and 2 hours after steel placement. However, in constricted sites, such as low headroom conditions where splicing of the steel is required, significant relaxation to these time constraints is necessary. On occasion, placement of concrete may take place as late as 24 hours after final cleaning. Under such circumstances, it is suggested that mitigative measures be specified and senior construction staff be involved in developing appropriate time constraints.

If a trench is located in a critical area where trench collapse would likely result in damage to an adjacent structure, the trench should not be permitted to remain open for an extended period of time. When excavating adjacent to an existing structure, it is a common practice that once the slurry trench excavation is deeper than an existing structure's foundation, the panel construction continues uninterrupted until concrete placement is complete. If the panel construction must be ceased, the trench should be backfilled with crushed stone or lean concrete mix and re-excavated when conditions permit.

During placement of the concrete the engineer's representative should verify the contractor is taking measurements to confirm the concrete rise is approximately level as each truck or pair of trucks have completed concrete placement.

On occasion, delays in concrete placement will occur, such as from plant breakdown or truck delays. Should this occur the contractor should provide a remedy. Options may include completing the panel with a cold joint and repairing the panel during general excavation or excavating the concrete prior to cure and removing the steel.

Should the contractor lose the concrete seal of the tremie while placing the the concrete and it is determined that stopping the pour and excavating the concrete and steel is not an option, there are alternatives to permit the pour to continue. One method is for the contractor to re-insert a new tremie with a closed valve at the end with charged concrete in the tremie pipe. A second alternative is for the contractor to re-install the tremie pipe and then bail the slurry from the tremie pipe until only concrete remains. Should either of these options be employed, the panel should be noted in the field records and the condition of the panel monitored closely during general excavation.

On occasion, site constraints require the use of concrete pumps. In such cases the diameter of the pump line should not be less than 5 inches. When site conditions necessitate the use of concrete pumps, it is suggested that the assumed typical 8 foot horizontal flow of concrete be decreased to maintain a level concrete rise and flushing of the panel joints. On past projects, PB has successfully used a 4 foot horizontal flow with 5 inch pump lines. Pump lines should be added if measurements suggest concrete rise is not uniform.

Tremie pipes are to be water tight and remain a minimum of 10 feet into the concrete. The exception to this is pouring the top 10 feet or so of panel at which time the head differential makes concrete flow difficult, requiring a reduced embedment to about 5 feet. (See Section VIII, Photo 18.)

3. Laitance Removal at Top of Wall: It is common for the top portion of concrete to have had some mixing with the bentonite slurry. Generally, the mixing is assumed to be within the top 6 to 12 inches, but may extend to greater depth. If the top of wall requires full structural integrity, it is common practice to chip the top 12 inches of concrete after the concrete has fully cured, or to over pour the panel approximately 12 inches beyond the required height. The depth of laitance and magnitude of concrete overpour should be evaluated at the start of each slurry wall project, and should be adjusted as necessary to obtain sound concrete up to the design top of wall elevation. Removal of laitance is commonly performed with the use of high impact hammers, hydraulic concrete crushers or chipping hammers. However, high impact hammers have been reported to have loosened the concrete to soldier pile bond in SPTC walls, resulting in some water seepage.

J. Corrective Measures

1. General Comments: Due to the nature of slurry walls, essentially all projects should be expected to include panels not constructed in accordance with the specifications or design, and some corrective measures should be anticipated. Cleaning of the slurry wall is required and is suggested to be done as general site excavation progresses. All soil and bentonite laitance should be removed by power washing, sand blasting, or other methods accepted by the engineer. All bentonite and soil inclusions should be removed. The wall cleaning is an essential step in determining if corrective measures are necessary.

   Defects should be identified as general site excavation progresses. An implementation schedule indicating at what stage of construction slurry wall repairs are to be made should be kept by the on site representative, the contractor and the engineer. As each slurry wall defect is identified by either the contractor or the engineer’s representative, the defect should be added to the implementation schedule. The repair procedure should be prepared by the contractor and submitted for approval by the engineer. The engineer is to determine at what stage of construction the repair is to be completed and this information added to the implementation schedule along with the date of repair completion. All observed defects should be documented and evaluated by the engineer as they are exposed. The contractor is ultimately responsible for ensuring all defects are noted, developing corrective measures, and implementing corrective measures to the satisfaction of the engineer. Appropriate corrective measures should be implemented in a timely fashion as warranted by the nature and extent of the defect and its impact on the performance of the slurry wall during and following construction activities.

2. Work Plan: For typical defects, the contractor should include anticipated corrective measures as part of its work plan submitted prior to the commencement of slurry wall work. As defects are exposed during excavation, the contractor should propose an appropriate repair based on the typical corrective measures identified in the work plan, or other measures as

appropriate. The contractor should submit the proposed corrective measures to the engineer for review and approval.

3. Definition of Defects: Defects are considered to be any item that could potentially have an adverse impact on the intended performance of the slurry wall. Protrusions are not considered defects but rather a natural occurrence in the construction of slurry walls, the removal of which are required for aesthetic reasons or to accommodate interior works. Typical defects and corrective measures are discussed below.

   a. Leakage: Leakage primarily occurs at panel joints, roof and invert slab connections, penetrations, and at items embedded in the slurry wall. The sealing of leaks that exceed contract permitted quantities is generally performed by standard drilling and injection methods, from the inside face of the slurry wall. Occasionally leaks may be of such a magnitude that exterior waterproofing methods may be required, possibly accomplished by drilling and grouting immediately adjacent to the slurry wall. The type of grout to be used is usually at the discretion of the contractor subject to approval by the engineer. (See Section VIII, Photo 19.)

   b. Out of Tolerance: Occasionally, out of tolerance panels may be accommodated by chipping the exposed face of wall or modifying the architectural finish to provide the required clearances. If this is not possible, removal of portions of the wall, including misaligned soldier piles, and replacement with cast-in-place concrete with added reinforcement may be required. Additional temporary internal bracing may be required for the repair, or, in the extreme case, installation of a temporary support system and excavation of the exterior soil may be necessary. (See Section VIII, Photos 20 and 21.)

   c. Structural Integrity: In the majority of cases, structural integrity is compromised by the inclusion of bentonite pockets, soil and/or miscellaneous debris such as Styrofoam or plywood from endstop removal; damaged keyways; cold joints; contaminated concrete; or excessive depth of laitance at the top of wall. These defects tend to be localized and structural repairs are usually performed by removal of the foreign material or poor quality concrete and replacement with cast-in-place concrete and/or cement grout. In unreinforced SPTC walls, the replacement concrete/grout may require the drilling and grouting of dowels and/or the use of exposed structural steel anchored to the interior face of wall to restore structural stability. For large repairs, additional bracing and/or the excavation of the exterior soil may be required as described in item (b) above. (See Section VII, Photos 22 and 23.)

K. Inspection

1. Responsibilities: Slurry walls are considered foundation elements, similar to drilled shafts, piles, and spread footings, and require a similar level of

inspection. For design-bid-build contracts, it is suggested that the engineer have field inspectors or an on site representative dedicated solely to the oversight of slurry wall construction. One inspector should be capable of overseeing two excavation rigs, excluding concrete testing. The inspector should be responsible for logging soil, verifying steel inspection, observing verticality measurements, confirming slurry properties, sounding and accepting bottom of excavation, observing joint cleaning, observing steel placement, observing concrete placement, noting any deviation from accepted means, methods and design, and reporting these deviations to the supervising engineer followed with written notice to the contractor. The supervising engineer is responsible for determining what, if any, follow up action is to be recommended, and should communicate the recommendations to the owner or, if applicable, directly to the contractor, in writing with copies to the design engineer's inspector or on site representative.

2. Supervising Engineer Qualifications: Preferably, the designer's supervising engineer should be familiar with slurry wall construction, having worked on at least two previous slurry wall projects. The designer should have a geotechnical engineer and structural engineer available for timely responses/direction to field issues during slurry wall construction. Either the geotechnical engineer or structural engineer may also act as the supervising engineer.

3. Field Staff Qualifications: The engineer's on site staff should include at least one lead inspector for every six rigs. The lead inspector should have experience on at least two drilled shaft or slurry wall projects. The support inspectors may be trained on the job.

4. Record Keeping: A complete slurry panel inspection log should be kept for each panel. The individual log should document all construction operations for the panel such as, rate of excavation, soil stratification, verticality measurements, steel placement, endstop placement/removal, rate of concrete placement, verification of concrete testing, verification of steel inspection, bottom cleaning and sounding, and slurry properties before concrete placement. The log should document the type of excavation equipment used, including the dates, times and depths of special equipment used such as chiseling for breaking obstructions or rock. The name of each inspector, and the date/time of changes in inspector, should be noted on the log. A sample log is included in Appendix C; however, each project will likely require its own log format to address the specifics of the project. The sample log provided is for excavation with a cable suspended bucket where verticality measurements are made at regular intervals of excavation depth. In the event the inspector is not able to observe a specific item of work this should be noted on the log. Deviations from specifications, design, or approved work plan, and any unanticipated field events should be noted on the log and immediately reported to the supervising engineer followed with written notice to the contractor. Items known to require corrective action are to be added to

the implementation schedule described in Section IV.J.1. Logs are to be kept in the field during construction for reference, with copies sent to the supervising engineer. Copies are not provided to the contractor except by request. Concrete test inspections reports and steel inspection reports are not part of the slurry panel inspection log other than reporting when and by whom the inspections were performed.

During general excavation, it is suggested that inspection of the slurry wall be conducted on a daily basis as the slurry wall is exposed and cleaned. Any defects requiring repair should be noted by the inspector, reported to the supervising engineer and followed up in writing to the contractor, and added to the implementation schedule.

V. MEASUREMENT AND PAYMENT

The primary methods of payment for slurry wall construction are either unit price, (per square foot of wall) or lump sum, and includes all work associated with slurry wall construction: mobilization, pre-trenching, guidewall construction and removal, trench excavation, steel, concrete, disposal of slurry, etc. When subsurface conditions are extremely uniform and the bottom of wall is well defined with little or no variation in depth anticipated, the lump sum method is suggested with a nominal unit price quantity to permit payment for minor unforeseen alterations in depth. Where subsurface conditions are variable and the bottom of wall is likely to be adjusted based on field conditions encountered, the unit price method is suggested. When using the unit price method, it is common to provide separate payment items for soil excavation and rock excavation.

Obstructions require special consideration. Obstructions are considered manmade objects; items such as boulders and cobbles are commonly not considered as obstructions. Known obstructions which can be identified on the plans may be included in the slurry wall payment item. However, for unknown obstructions below allowable pre-trench depths, it is suggested there be a separate pay item for obstruction removal based on unit price or time and material for changed conditions.

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VIII. PHOTOS

Following are photos 1 through 23 showing typical slurry wall construction procedures.

Photo 1: Formwork for guidewalls.

Photo 2: Failure of guidewall due to discontinuation of steel reinforcement at joint.

Photo 3: Typical cable suspended clam bucket.

Photo 4: Typical chisel for rock and obstruction excavation
(note 'V' nose end-stop, bottom left corner).

Photo 5: Rigid Kelly bar rig.

Photo 6: Hydromill.

Photo 7: Temporary pipe endstops.

Photo 8: Temporary 'V' nose endstops.

Photo 9: De-sanding Unit.

Photo 10: Airlift pipe for de-sanding and bottom cleaning.

Photo 11: Instrumented reinforcing cage. Vertical sleeves for inclinometer and vertical extensometer, cable is for strain gages, horizontal sleeves are for tieback and horizontal extensometer.

Photo 12: Hoisting cage, approx. 25’ x 100’ (note flexing at far right).

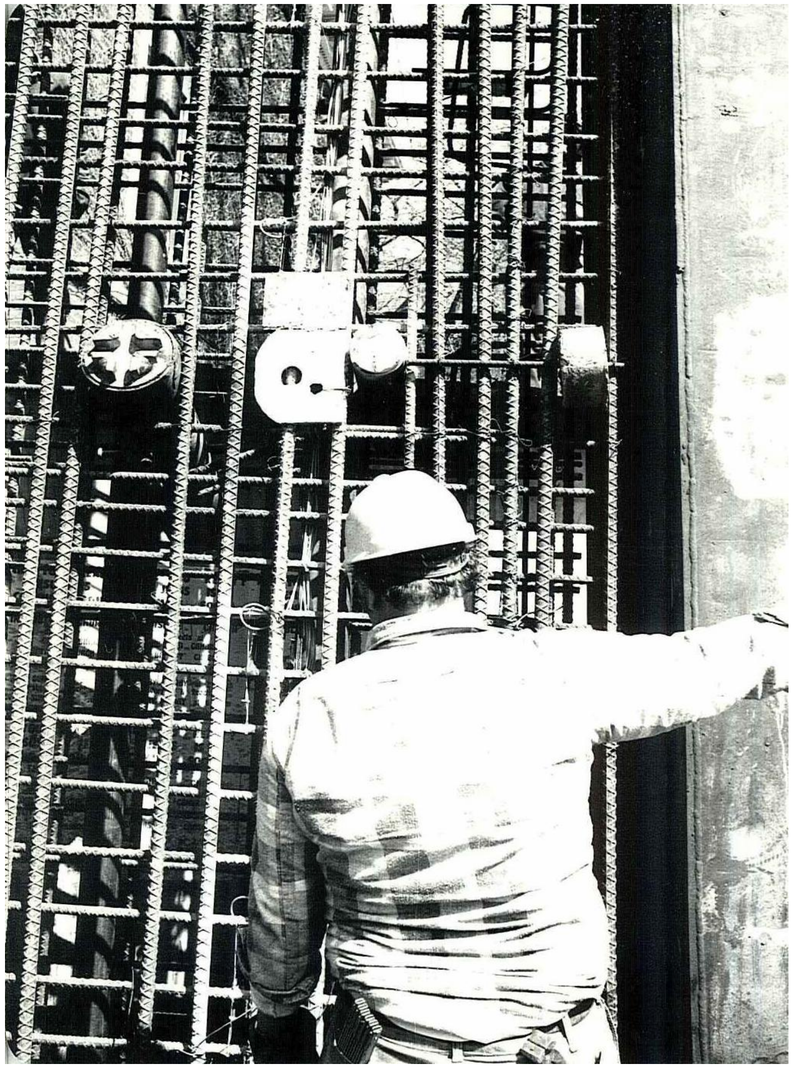


Photo 13: Lowering cage (note steel screw cap on tieback sleeve and 4” wide spacer roller).

Photo 14: Lowering cage (note angles attached to vertical steel at top of cage, angles set on guidewall to support cage at design elevation).

Photo 15: Setting soldier piles.

Photo 16: Soldier pile template to secure soldier piles.

Photo 17: Soldier pile secured for splicing.

Photo 18: Concrete placement, sequential panel (one end-stop).

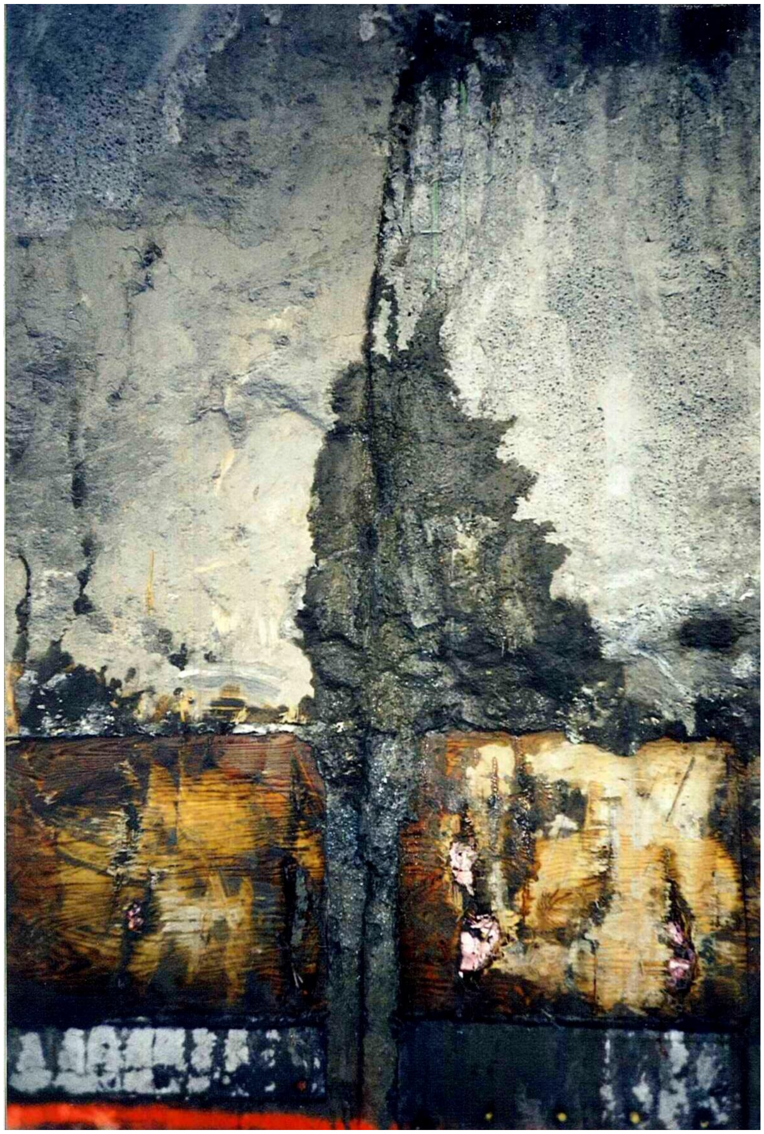


Photo 19: Typical slurry wall leak at panel joint.

Photo 20: Chipping overpour concrete.

Photo 21: Exposed plywood and Styrofoam ready for removal from keyway. Significant overpour above keyway.

Photo 22: Void in slurry wall at keyway location.

Photo 23: Repairing structural defect, debris removed,
relieving water pressure to facilitate repair.

IX. APPENDICES

Attached are the following Appendices:

Appendix A Comparison Table for Various Wall Types

Appendix B Sample Design Details

Appendix C Sample Slurry Panel Inspection Log

Appendix D Sample Standard Specification

Appendix E Lisitng of PB Slurry Wall Projects

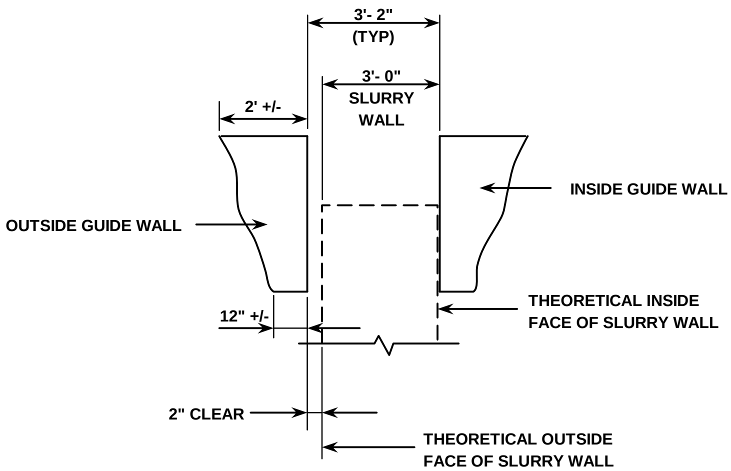
Appendix A - Comparison Table for Various Wall Types

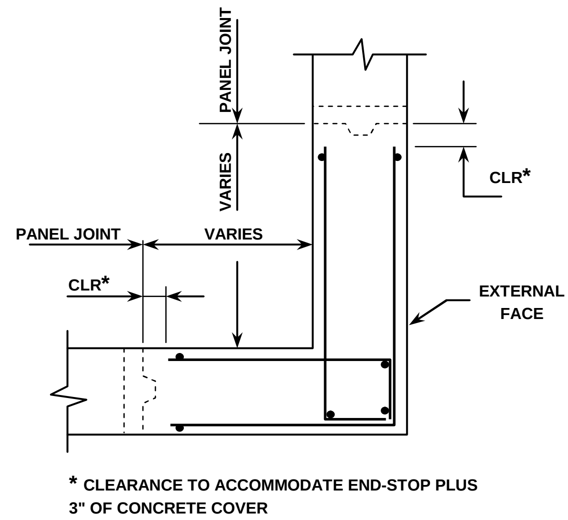
Comparison Table of Various Wall Types

Wall Type	Perm.	Temp	Common Height Range (ft)	Cost in $ per ft^2 of wall face(1)	Lateral Movements	Temp. Water Tightness	Perm. Water Tightness	Advantages	Disadvantages
Sheet-pile wall	No	Yes	20 to 50	15 to 40	large	fair to good	N/A	▪ rapid construction ▪ readily available	▪ difficult to construct in hard ground or through obstructions
Soldier pile/lagging wall	No	Yes	20 to 75	10 to 35	medium to large	poor	N/A	▪ rapid construction ▪ soldier beams can be drilled or driven ▪ readily available	▪ difficult to maintain vertical tolerances in hard ground ▪ potential for ground loss at excavated face ▪ groundwater lowered outside of excavation
Slurry (diaphragm) wall	Yes	Yes	50 to 100	60 to 85	small	excellent	fair to good	▪ can be constructed in all soil types or weathered rock ▪ wide range of wall stiffness	▪ requires specialty contractor ▪ significant spoil for disposal ▪ requires specialized equipment ▪ requires large lay down area
Tangent pile wall	No	Yes	50 to 100	40 to 75	small	good	N/A	▪ adaptable to irregular layout ▪ can control wall stiffness ▪ smaller equipment than slurry wall ▪ lay down area smaller than slurry wall ▪ reinforcement can be fabricated off site	▪ difficult to maintain vertical tolerance in hard ground ▪ requires specialized equipment ▪ significant spoil for disposal
Secant pile wall	Yes	Yes	50 to 100	40 to 75	small	good to excellent	fair	▪ adaptable to irregular layout ▪ can control wall stiffness ▪ smaller equipment than slurry wall ▪ lay down area smaller than slurry wall ▪ reinforcement can be fabricated off site	▪ difficult to maintain vertical tolerance in hard ground ▪ requires specialized equipment ▪ significant spoil for disposal

Notes: (1) Total installed costs in 1995 U.S. Dollars. Costs are dated but provide relative comparison of different wall systems.

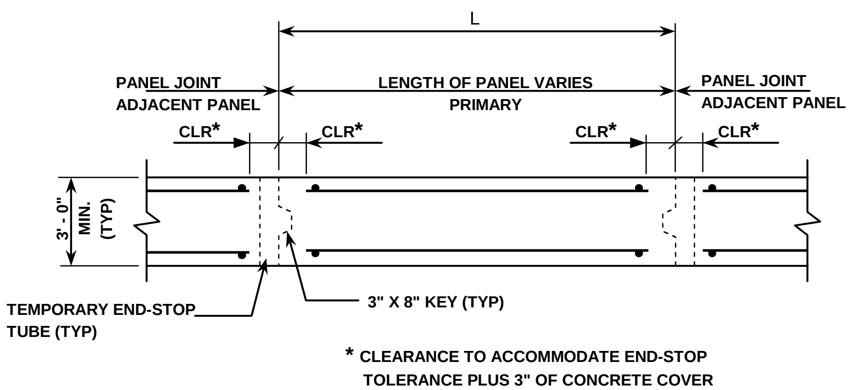
Appendix B - Sample Design Details



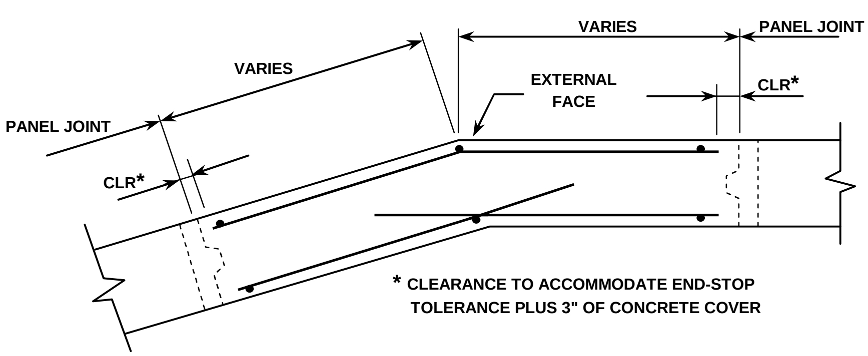


GUIDE WALL DETAIL

CORNER PANEL DETAIL



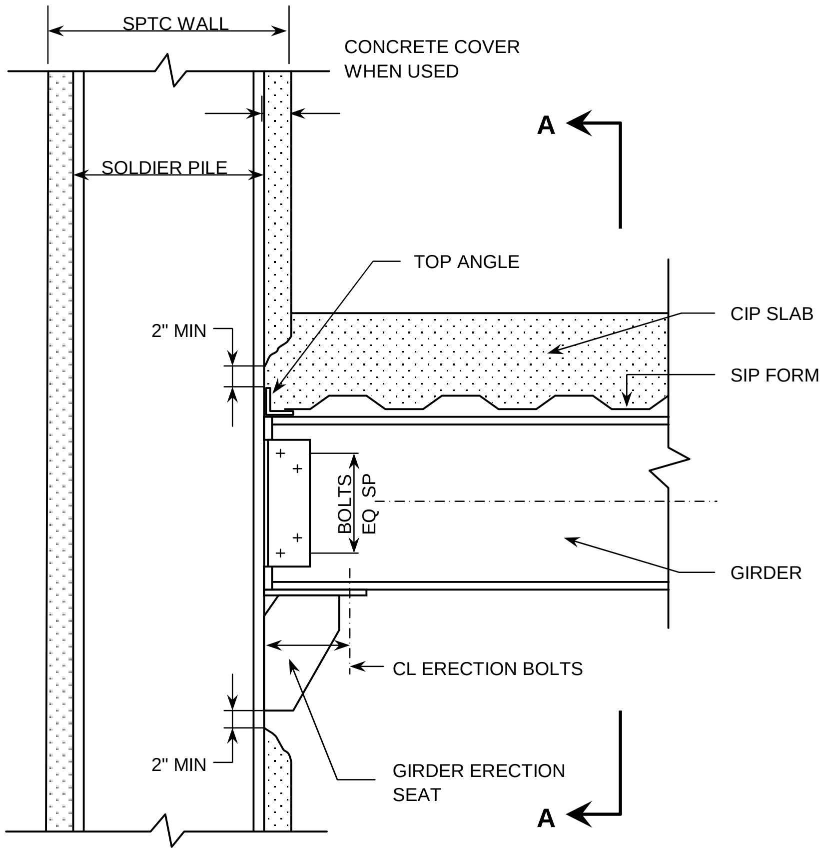
PANEL DETAIL



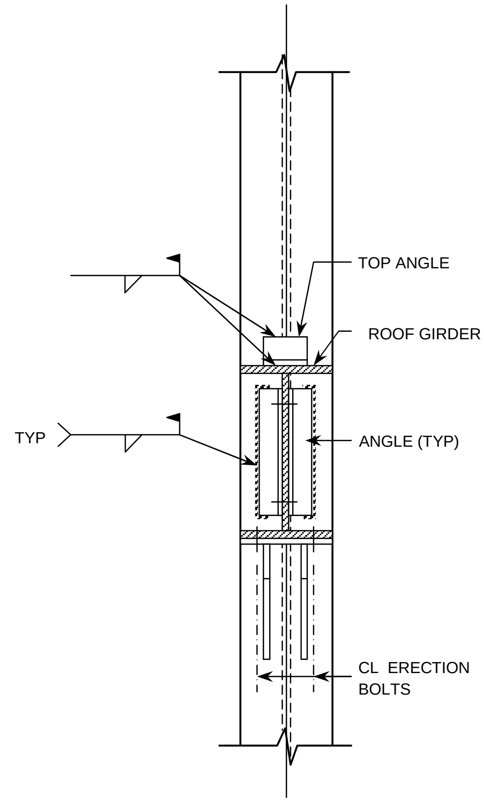
SKEWED PANEL DETAIL

NOTES:

1. Vertical bars can be placed inside or outside of horizontal bars. If cracking is a concern, placing horizontal bars outside may be beneficial
2. These details are illustrative, site specific details shall be developed for each project

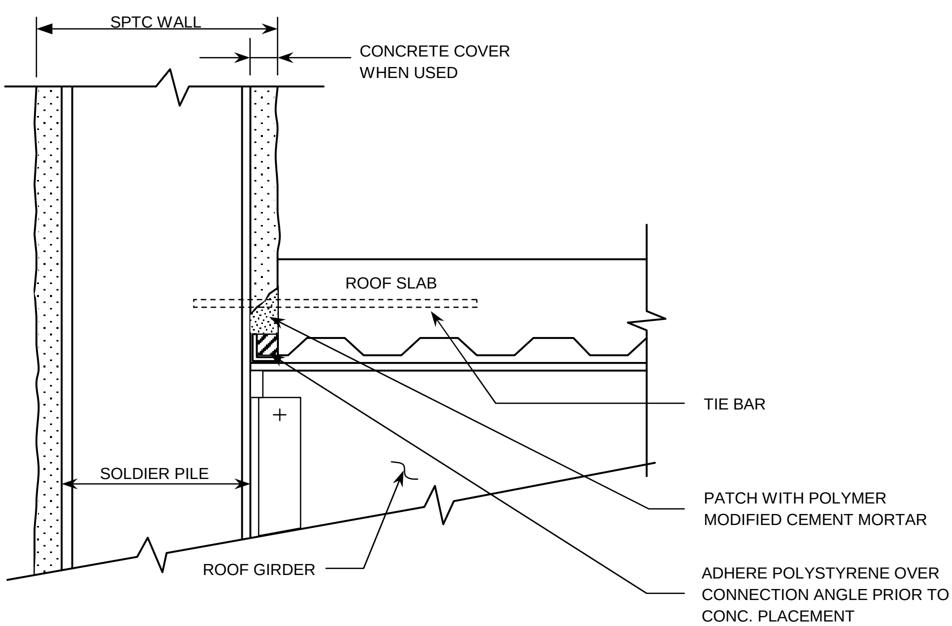


ELEVATION



SECTION A
(SLAB NOT SHOWN)

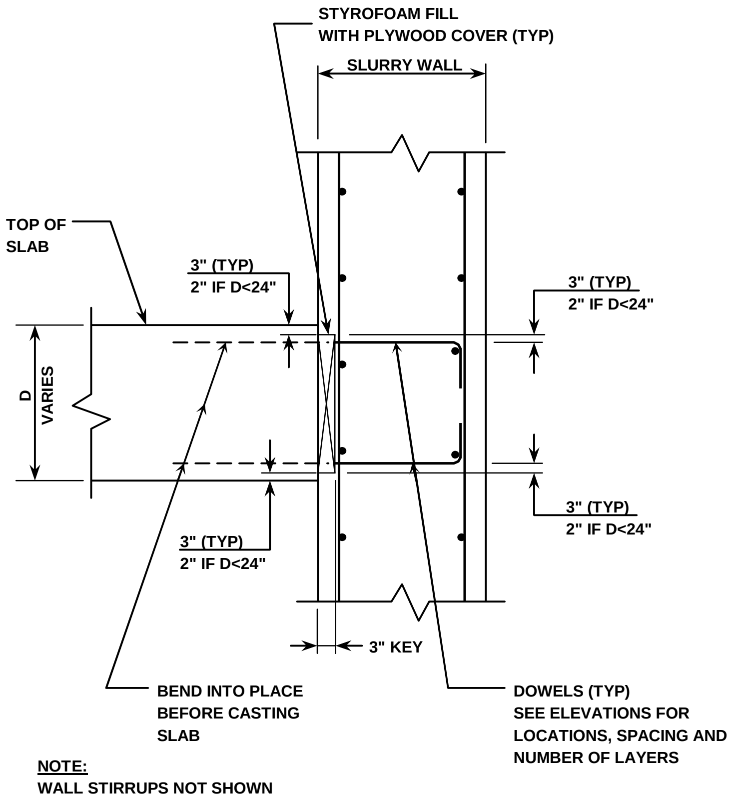
SPTC WALL TO STEEL BEAM CONNECTION AT ROOF SLAB



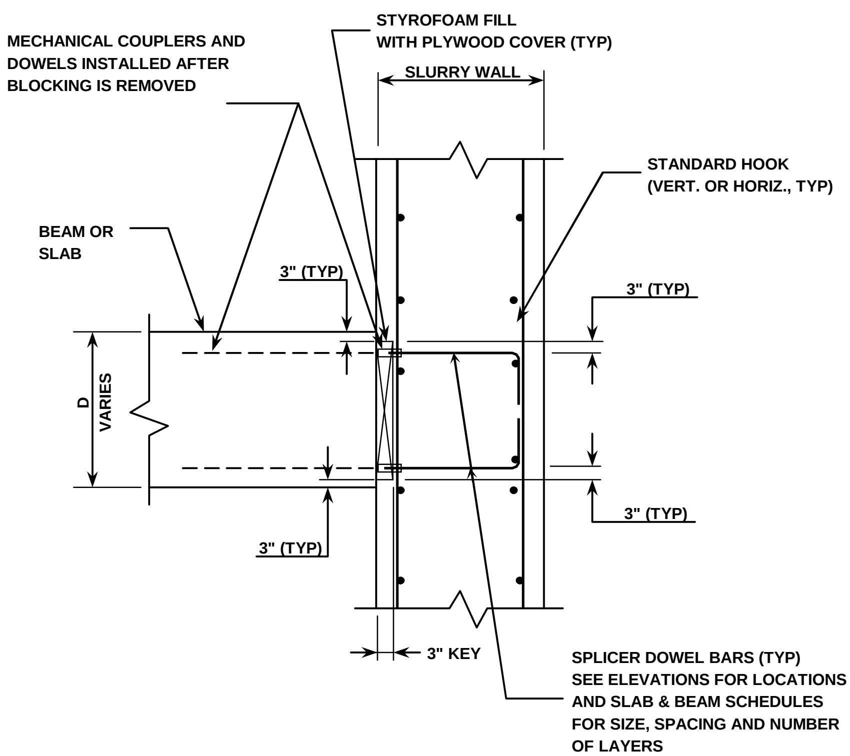
CIP SLAB TO SPTC WALL JOINT AT ROOF SLAB

NOTES:

1. **For waterproofing details see Parsons Brinckerhoff's 'Guidelines for the Design of Waterproofing Systems for Underground Structures'**
2. **These details are illustrative, site specific details shall be developed for each project**



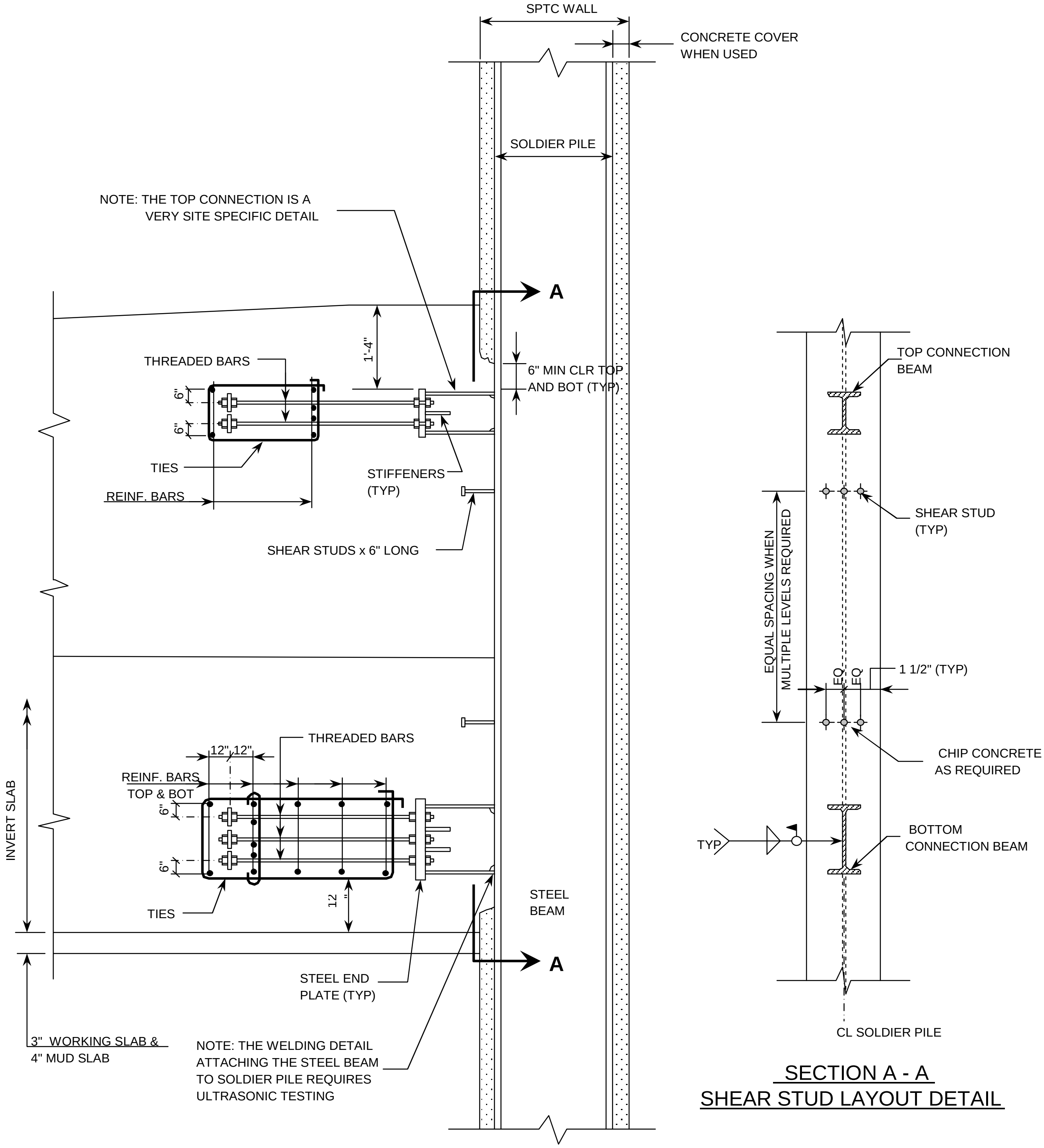
SLAB KEY AT BEND-OUT DOWELS



SLAB/BEAM KEY SPLICER DOWEL BARS

NOTES:

1. Wall stirups not shown
2. For waterproofing details see Parsons Brinckerhoff's 'Guidelines for the Design of Waterproofing Systems for Underground Structures'
3. Vertical bars can be placed inside or outside horizontal bars. If cracking is a concern, placing horizontal bars outside may be beneficial
4. These details are illustrative, site specific details shall be developed for each project

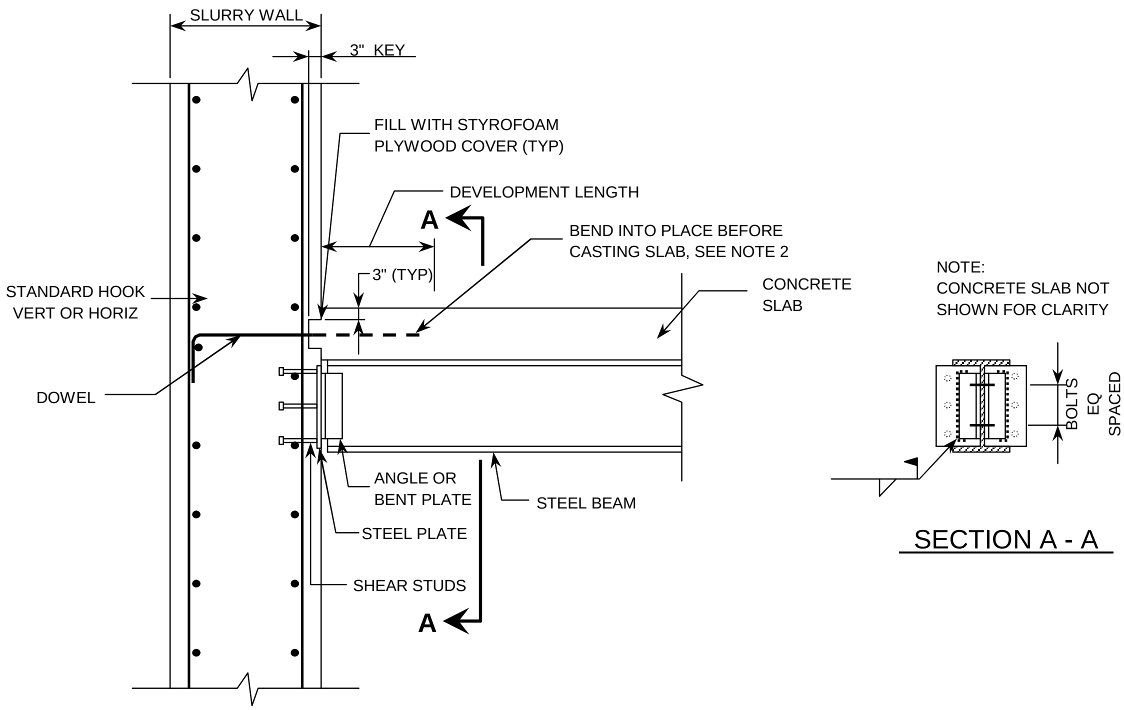


SECTION A - A
SHEAR STUD LAYOUT DETAIL

CONCRETE INVERT SLAB TO SPTC WALL CONNECTION DETAIL

NOTES:

1. **For waterproofing details see Parsons Brinckerhoff's 'Guidelines for the Design of Waterproofing Systems for Underground Structures'**
2. **These details are illustrative, site specific details shall be developed for each project**



REINFORCED CONCRETE
SLURRY WALL TO STEEL BEAM CONNECTION

NOTES:

1. **For waterproofing details see Parsons Brinckerhoff's 'Guidelines for the Design of Waterproofing Systems for Underground Structures'**
2. **Bendout dowels are common for pinned connections with reinforcing bar size upto #5 Grade 40, for fixed connections and larger reinforcing threaded couplers are used**
3. **Vertical bars can be placed inside or outside horizontal bars. If cracking is a concern, placing horizontal bars outside may be beneficial**
4. **These details are illustrative, site specific details shall be developed for each project**

Appendix C - Sample Slurry Panel Inspection Log

Parsons Brinckerhoff

PANEL NO. ________

PROJECT:

CLIENT:

JOB NO.:

PRIME CONTRACTOR:

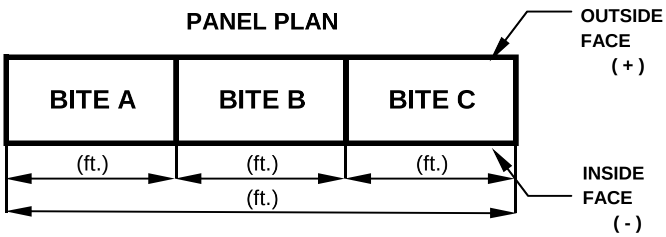
SUBCONTRACTOR:

INSPECTOR:

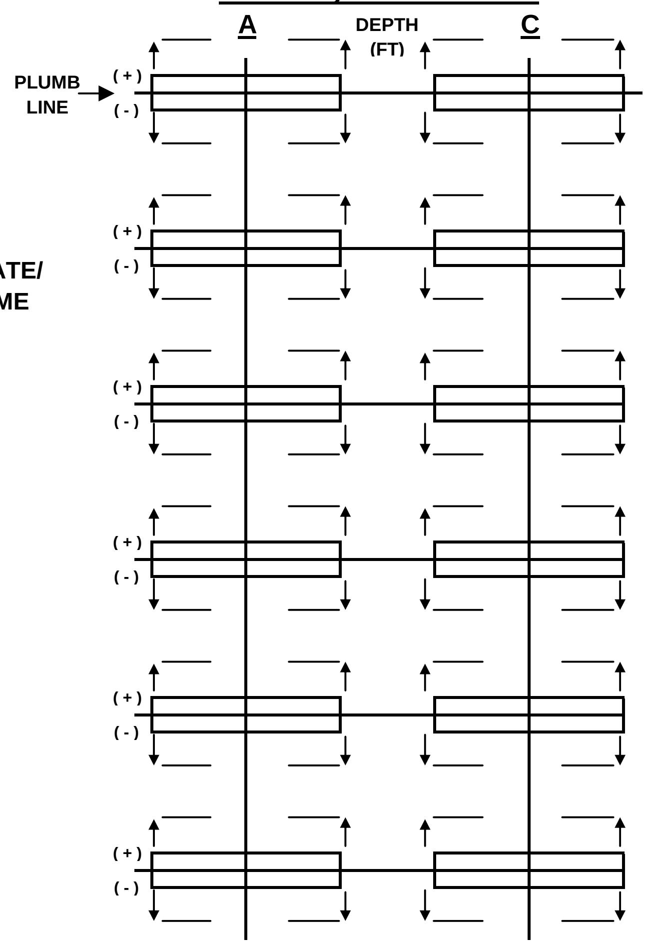
SLURRY PANEL INSPECTION LOG

EXCAVATION RECORD

PANEL PLAN



Verticality Measurements



DATE/ TIME				DEPTH/ FT.	DATE/ TIME
				(0)	
				(10)	
				(20)	
				(30)	
				(40)	
				(50)	
				(60)	
				(70)	
				(80)	
				(90)	
				(100)	
				(110)	
				(120)	

STRATIGRAPHY

PANEL TYPE ________

GUIDEWALL ELEV. ________

DESIGN BOTTOM OF PANEL ELEV. ________

ACTUAL BOTTOM OF PANEL ELEV. ________

END STOPS PLACED ________

EXCAVATION STARTED ________

EXCAVATION COMPLETED ________

BOTTOM OF PANEL CLEANED ________

TOTAL HOURS ________

Parsons Brinckerhoff

PANEL NO. ____________

PROJECT:

PRIME CONTRACTOR:

CLIENT:

SUBCONTRACTOR:

SLURRY PANEL INSPECTION LOG

QUALITY ASSURANCE
SLURRY TESTS

DATE	TIME	TEST	BY	RESULTS	
				ACTUAL	DESIGN

PANEL DESANDED START ____________ END ____________

BOTTOM CHECKED ____________ SLURRY MIX ____________

STEEL REINFORCING CHECKED BY ____________ DATE/TIME ____________

CONCRETE TESTED BY ____________ DATE/TIME ____________ NO. SLUMP TESTS ____________

REINFORCING AND CONCRETE PLACEMENT

REINFORCING SET ____________ NUMBER OF TREMIE PIPES ____________ SIZE ____________

PANEL CONCRETED START ____________ END ____________

END-STOPS REMOVED START ____________ END ____________

CONCRETE QUANTITY

NO. OF TRUCKS	CONC. PER TRUCK C.Y.	VOLUME PLACED C.Y.	ACTUAL CONC. RISE		THEORETICAL CONC. RISE		VARIATION
			FROM	TO	FROM	TO	

TOTAL CONCRETE QUANTITY: ACTUAL: ____________ C.Y.

THEORETICAL: ____________ C.Y.

REMARKS: ____________

Appendix D - Sample Standard Specification

CONCRETE DIAPHRAGM (SLURRY) WALLS

PART 1 - GENERAL

****

Note to Specifier: Articles 1.01 through 1.07 are required to appear in each technical specification. If they are not used, they remain and are labeled as 'not used'. For example, if a project has no CITED STANDARDS, the article would consist of '1.03 CITED STANDARDS- not used'. Any additional articles to be included in Part 1 follow Article 1.07.

****

1.01 SECTION INCLUDES

A. Requirements for furnishing all labor, materials, tools, and equipment, and performing all operations necessary for the construction of concrete diaphragm (slurry) walls by the bentonite slurry trench method, indicated on the Contract Drawings and specified herein.

B. Where the design of the walls, or any details thereof, is not indicated, Contractor shall be responsible for such design, in accordance with design criteria and loads specified herein or shown on the Contract Drawings.

******OR******

B. Where methods of construction, or any details thereof, are not indicated, they will be at Contractor's option, subject to applicable codes, Contract requirements, and acceptance by the Engineer.

C. Concrete work, steel reinforcement, and soldier piles (structural steel) shall conform to Sections- xxxx- Concrete Reinforcement, Section xxxx,-Cast-In-Place Concrete, Section xxxx-Portland Cement, and Section xxxx-Structural Steel of these Specifications, as modified herein.

D. The estimated bottom of slurry wall elevation is indicated on the Contract Drawings. The depth of slurry wall has been estimated from soil borings, and some variations in depth are to be anticipated to accommodate site specific conditions.

E. During excavation and below grade construction period, the slurry wall is intended as a cut-off wall for groundwater and as a construction bulkhead to retain the surrounding ground, streets, pavements, utilities, buildings, and other structures and facilities from damage due to ground deformations; as such, all precautions shall be taken against such damage. The wall reinforcement and strengths, as shown on the Contract Drawings, are designed for conditions imposed after completion of the slurry wall and all connecting structural framing and slabs of the completed structure.

1. All temporary loading conditions that may be produced by Contractor's excavation and/or construction procedures shall be analyzed and compensated for by Contractor with increased wall reinforcing and/or temporary bracing, and/or other means acceptable to the Engineer, as necessary.

2. Review of Contractor's working drawings, design calculations, and methods of construction by the Engineer does not relieve Contractor of responsibility for the adequacy of the support system or the slurry wall during temporary support conditions.

3. Temporary earth support design criteria provided on the Contract Drawings, such as soil pressures, groundwater pressures, seismic earth pressures, and surcharge loads, will be considered as the minimum acceptable. Contractor is responsible to determine if more stringent criteria are warranted

F. Definitions:

****

Note to Specifier: Options A and B are given as examples for watertightness criteria. Achievable/reasonable criteria for each project are dependent on a variety of factors such as: intended use of permanent structure, soil conditions, and the permanent or temporary use of slurry wall. Reference is made to PB's slurry wall guide for further information.

****

1. (**Option A**) Watertight: The term 'watertight' is defined to mean that no running water from the wall nor the formation of droplets on the wall surface is permitted. The formation of moist patches allowing water to evaporate from the surface is acceptable.

******OR******

1. (**Option B**) Leakage rate of 0.15 gpm for 100 lineal-feet of wall, 0.01 gpm for a leak in 10-feet of wall, and 0.005 gpm for any single leak.

2. Concrete Diaphragm (Slurry) Wall: A reinforced concrete wall constructed by the slurry trench method. Reinforcing shall be provided with a steel reinforcing cage, soldier piles, or a combination of both.

******OR******

2. Soldier Pile Tremie Concrete (SPTC) Wall: A slurry wall that uses steel soldier piles as the principal vertical bending element.

******OR******

2. Conventional Reinforced Concrete (CRC) Wall: A slurry wall that uses a steel reinforcing cage as the principal vertical bending element.

1.02 REFERENCED SECTIONS

****

Note to Specifier: List other sections of the Contract Specifications only if they are referenced elsewhere in text of this Section. Following is sampling of other specification sections that are often referenced within slurry wall specifications.

When referencing other spec sections, the full title of the referenced section gets included in Article 1.02; anywhere else within the section only "Section XXXXX" is used.

****

A. Section xxxx - Submittals

B. Section xxxx - Geotechnical Instrumentation

C. Section xxxx- Concrete Reinforcement

D. Section xxxx - Cast-In-Place Concrete

E. Section xxxx - Portland Cement

F. Section xxxx - Structural Steel

G. Section xxxx – Painting

H. Section xxxx - Support of Excavation

I. Section xxxx – Dewatering

J. Section xxxx – Earthwork

K. Section xxxx – Existing Utilities

L. Section xxxx - Utilities

1.03 CITED STANDARDS

****

Note to Specifier: List only industry standards that are cited elsewhere in text, such as ASTM, etc.

Do not include any dates or editions in the citation. In the titles such as ASTM, it is not necessary to use the words "Standard Specification for" for each title.

****

A. ASTM International (ASTM)

1. C33 - Concrete Aggregate
2. C88 - Soundness of Aggregates by Use of Sodium Sulfate or Magnesium Sulfate
4. C150 – Portland Cement
4. C494 - Chemical Admixtures for Concrete
5. C595 – Blended Hydraulic Cement
6. C618 - Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Concrete
7. D1785 - Poly (Vinyl Chloride) Plastic Pipe, Schedules 40, 80 and 120.

B. American Petroleum Institute (API)

1. RP 13A - Drilling Fluid Materials
2. RP 13B-1 - Field Testing Water-Based Drilling Fluids

******OR******

None Cited

1.04 NOTED RESTRICTIONS

****

Note to Specifier: This article presents a listing of exceptional, extraordinary, or unusual requirements and restrictions pertaining to the Work.

****

A. Protection: Protect surfaces of adjacent structures, pavements, sidewalks, and other facilities to prevent contamination of these surfaces by excavated material, slurry, and concrete. At the completion of slurry wall construction, restore adjacent exterior surfaces to their original conditions, as acceptable to the Engineer.

B. Vibration Control: Vibration due to the removal of boulders, obstructions, rock excavations or other operations in connection with slurry wall construction shall be limited to prevent damage to adjacent buildings, structures, utilities, and all other facilities. The Engineer may monitor such vibrations by means of seismographs. Limiting vibrations criteria shall be as specified in Section xxxx.

C. The slurry wall will be constructed in an urban area with active vehicular and pedestrian traffic. Interruption of vehicular and pedestrian traffic will not be permitted, except as specified herein and/or as shown on the Contract Drawings.

******OR******

None Noted

****

1.05 QUALITY CONTROL

****

Note to Specifier: List Federal, State, and Local agencies whose regulations govern this Section as follows, as applicable.

****

A. Regulatory Requirements: Comply with applicable requirements of the laws, codes, ordinances, and regulations of Federal, State, and local authorities having jurisdiction. Obtain necessary approvals and permits from all such authorities.

****

Note to Specifier: Additional quality control will follow the Regulatory Requirements, as applicable. If there are no Regulatory Requirements, begin with Paragraph B.

****

B. Slurry Wall Contractor: Experienced firm that has successfully installed in urban areas a minimum of five slurry wall systems of a similar type required for this project. Employ only skilled tradesmen who are thoroughly experienced with the materials, equipment and construction methods to be used in this work, and provide a fulltime project superintendent who has worked on at least three slurry wall contracts in similar ground conditions, depths, and using similar equipment as required for this project

C. Contractor’s Responsibilities for Quality Control Testing and Inspection:

1. Cooperate with the Engineer and Engineer’s representative who will be responsible for overseeing control testing and inspection.

2. Furnish notification, with at least one business day’s notice, for all slurry wall fabrication and installation operations.

3. Furnish material samples as required for testing.

4. Furnish access and proper facilities, including but not limited to scaffolding, temporary work platforms, and hoisting facilities, as required for inspection and testing.

5. Furnish labor as required to facilitate testing and inspection of all slurry wall work.

6. Provide heated and/or cooled storage facilities for concrete cylinders, as appropriate.

7. Contractor shall be responsible for all additional slurry wall inspection and testing resulting as a consequence of slurry wall work not evidencing compliance with this specification, performed without prior notice, or performed contrary to previously submitted procedures.

8. Raise and lower excavating equipment, bucket or hydromil, through the slurry to confirm that the trench has been excavated to the required dimensions.

9. Raise and lower joint cleaning device along the cleaned joint to confirm joint has been cleaned and cleared of all materials.

D. Testing of bentonite slurry shall be performed by Contractor as required hereinafter with the results of every test submitted to the Engineer within the time limit specified herein. At a minimum, the final testing prior to steel placement shall be performed in the presence of the Engineer. Testing methods and equipment shall be per API RP 13B-1.

1. Required Tests

   a. Viscosity (Marsh Cone)

   b. Specific gravity

   c. pH

   d. Fluid Loss Test

   e. Sand Content

2. Testing Sequence (for Each Panel)

   a. Viscosity, specific gravity, and sand content:

      1) During panel excavation (at least three times per shift)

      2) Completion of panel excavation

      3) Immediately prior to installation of steel

      4) After every rainfall or snow fall

      5) As directed by the Engineer

   b. pH

      1) Immediately prior to installation of steel

      2) At completion of panel concreting but prior to re-use for future excavation

      3) When viscosity is above specified limits

      4) As directed by the Engineer

   c. Filter Press Test

      1) At least once every 2 days

      2) As directed by the Engineer

3. Calibrate density measuring devices monthly, or more often if necessary to ensure correct calibration to an accuracy of plus or minus 0.05 pcf.

4. Perform API fluid loss test, at least once every two days as directed by the Engineer, in accordance with API-RP-13A. Fluid loss is not to exceed 25-cc in 30 minutes.

E. Contractor's Engineer: Contractor's engineer responsible for preparing and stamping all Contractor designs shall be a Professional Engineer licensed in the State of *_____* and shall have designed a minimum of three similar slurry walls and slurry wall support systems in conditions similar to this project.

F. Survey Control

1. If guidewalls are used as reference points, as reference lines, or as benchmarks for routine control of slurry wall construction, verify elevation and location of guidewall on a daily basis during panel excavation.

2. Use benchmarks outside zone of influence of construction activities and control slurry wall construction by survey methods. Use benchmarks accepted by the Engineer.

1.06 SUBMITTALS

****

Note to Specifier: Submittals are items that require review by the Engineer. General information on submittal procedures is covered in Section xxxx and should not be repeated in this Article.

****

A. Qualifications: Submit qualifications of firm and assigned key staff for slurry wall construction not less than 15 calendar days following Notice to Proceed. Work shall not be initiated until the firm and work force has been accepted by the Engineer.

B. Mill Certificates: Submit copies of certified mill reports covering the chemical and physical properties of reinforcing and structural steel elements.

C. Product Data: Submit copies of manufacturer's specifications for the following products including copies of laboratory test reports and other data as may be required to show compliance with these specifications.

1. Fly Ash
2. Water reducing admixtures
3. High range water reducing admixtures
4. Aggregate sieve analysis for stone and sand for concrete
5. ASTM C88 aggregate sodium sulfate soundness test
6. Portland cement including certified source test reports
7. Bentonite

D. Working Drawings: Submit Working Drawings showing proposed equipment and methods of construction including the following:

1. Sequence and schedule of constructing guidewalls and the various panels of the slurry walls. Include layout drawings showing proposed location, panel identification number, lengths, soldier piles and the planned sequence of installation.
2. Guidewall drawings showing dimensions, reinforcement, plan location, and all other details and calculations.

3. Description of excavating equipment to be used including space requirements for operations and for the storage of excavated materials.

4. Methods of excavation, procedures for vibration control, and estimated rates of excavation for each material type expected to be excavated.

5. Method of slurry preparation, storage, site distribution, reclamation, and disposal.

6. Slurry mix composition and methods of monitoring and testing.

7. Method of monitoring and maintaining slurry level in excavations left open overnight or over an extended period of time.

8. Measures for preventing slurry from entering into utility facilities.

9. Method of maintaining stability of excavated trenches in case of sudden loss of slurry.

10. Method of monitoring plumbness and deviation of wall panels during excavation, and details of proposed corrective measures to be implemented if necessary.

11. Equipment and method of checking and proving the cleanliness of the trench bottoms prior to concrete placement.

12. Method of forming and cleaning joints between adjacent wall panels, method for verifying joints are clean, method of checking plumbness, and details of corrective measures to be implemented, if needed.

13. Method of installing and securing reinforcing steel cages and/or soldier piles.

14. Method of concrete placement.

15. Methods for preventing concrete overpour from entering the web area on the unexcavated side of soldier piles.

16. Methods to protect the public and the surrounding property from hazards inherent in the operations, including leakage and spillage of slurry, falls into open guide trenches or excavated wall panels, and methods of lifting and setting soldier piles, reinforcing cages, tremie pipes, and desanding pipes.

17. Method for cleaning bottom of trench prior to placing reinforcing steel cage and/or soldier piles.

18. Methods and details of forming keyway recesses and blockouts.

19. Drawings showing templates or other devices for installing steel reinforcing cage and/or soldier piles to specified tolerances.

20. Methods for repairing slurry wall leaks.

E. Shop Drawings: Submit Shop Drawings for the following:

1. Reinforcing steel including permanent and temporary reinforcing details, and provisions for lifting, stiffening, and splicing.
2. Soldier piles including structural steel sizes, lengths, and splice details.
3. Panel layouts and end form details.
4. Details of beam and slab anchorages, keyways, and pockets.
5. Details of plates, sleeves, pipes, and other embedded items and the requirements for instruments and utilities to be installed in or through the wall.
6. Lacing details for tying soldier piles together.
7. Guidewall details showing reinforcing, width, and height.
8. Spacers for providing required concrete cover.

F. Mix Designs: Submit mix designs for the following:

1. Concrete: Mix design requirements shall be as specified or as submitted and approved.
2. Slurry: Submit slurry mix composition.

G. Record Documents: Submit the following:

1. During slurry wall construction, any unusual conditions encountered shall be noted by the Contractor, and the Engineer shall be informed immediately.
2. Results of quality control tests performed on slurry shall be made available to the Engineer within 24 hours after test completion.

H. Calculations: Submit engineering design calculations for slurry wall for conditions during construction, prepared and sealed by a Professional Engineer licensed in the State of *_____*

I. Corrective Action:

1. Repair all defective concrete. Submit repair procedures for the acceptance of the Engineer.

2. Should the Engineer determine that a defective panel requires structural design calculations, submit, for approval by the Engineer, the required calculations and the proposed design repairs signed and sealed by a Professional Engineer licensed in the State of *_____*.

3. Prepare and submit for review and approval corrective measures to restore or replace nonconforming panels to specified requirements at no additional cost.

1.07 DELIVERABLES

****

Note to Specifier: Deliverables are items that do not require review/approval by the Resident Engineer

****

A. As-built drawings shall be provided in accordance with Section xxxx, except as modified herein.

B. During slurry wall construction, maintain and submit to the Engineer within 24 hours of panel concrete placement as-built records of the work including:

1. Panel identification.
2. Plan location, dimensions of excavation, and elevations of guide walls and top and bottom of panels.
3. Dates and times of panel excavation, reinforcing/soldier pile placement, tremie concrete placement, and endstop removal.
4. The volume of concrete placed and the actual level of the top of concrete in the trench shall be recorded and compared to the theoretical panel volume at not greater than ten-foot vertical intervals during the concrete placement operation.
5. Description of soil, rock, and obstructions, and excavation problems, if any.
6. Description of any variations from the Shop Drawings regarding steel reinforcing/soldier piles, cut-outs, threaded inserts, sleeves, or other embedded items. Variations from accepted shop drawings require acceptance of the Engineer prior to proceeding with the work.
7. Details of casing for geotechnical instrumentation or grout tubes installed in panel, if any.
8. Plumbness and deviation from plan location.

PART 2 - PRODUCTS

****

Note to Specifier: These articles need to be reviewed and modified, as appropriate, for each specific project.

****

2.01 MATERIALS

A. Tremie Placed Concrete

1. Class: 4,000-psi

****

Note to Specifier: Concrete strength may vary from project to project; occasionally 5,000-psi concrete is specified.

****

2. Aggregate: ASTM C33, Size No.7.

****

Note to Specifier: Aggregate size may vary based on reinforcing spacing, 3/4-inch, maximum size, is typical, but for panels with congested reinforcing steel and/or significant blockouts, 3/8-inch, maximum size, aggregate is sometimes specified to minimize resistance to concrete flow. Concrete mixes vary from project to project, similar to slurry mix design, each contractor will likely have a preferred mix which may differ from the specified mix, the contractor's mix should be submitted for approval. The mix below is a standard mix used on some of PB's projects and is provided for information, it is suggested that a performance mix specification be used. in lieu of a detailed concrete mix.

****

3. Water cement ratio: 0.60 maximum.

4. Cement content: 7.5 sacks per cubic yard minimum.

5. Slump range: 7- to 9-inches at time of placement.

6. Air content: 4-percent plus or minus 1.5-percent.

7. Provide mixtures containing a minimum of 10 per cent fly ash conforming to ASTM C618 and a plasticizing admixture conforming to ASTM C494.

8. The concrete mix at the time of design shall be checked for setting time, and retarders added, if required, to delay setting time. Coordinate mix design with the endstop removal requirements. The concrete shall have proper retarders to maintain a minimum 4-inch slump for the full length of time required for tremie placement.

9. Type II cement shall be used.

B. Steel Reinforcement: Steel reinforcing bars and soldier piles shall be as indicated on the Contract Drawings for permanent design and as indicated on the accepted Shop Drawings for Contractor designed work.

C. Lean Concrete Backfill: 1,000-psi minimum compressive strength at 28 days, two sacks of cement minimum per cubic yard.

D. Bentonite: API-RP- 13A.

E. Bentonite Slurry shall consist of a stable solution of powdered or granular bentonite and water. Initial bentonite solution shall meet the following criteria. Modifications may be permitted with the acceptance of the Engineer based on observed field conditions. Polymer slurries will not be permitted.

****

Note to Specifier: In general, polymer slurries are not recommended for slurry wall construction. On occasion, there may be an occurrence where the use of polymer is warranted. Please see PB's slurry wall guides for further information if polymer is being considered. Also see PB's slurry wall guide for additional information regarding slurry properties.

****

1. pH of bentonite slurry shall be controlled within the range of 7 to 11.

2. Bentonite slurry shall not be used before 8 hours after it is mixed, except where specifically permitted by the Engineer.

3. The slurry shall be as required to provide stable trench conditions.

4. The slurry shall conform to the following requirements unless field conditions dictate otherwise, or alternative requirements are submitted by the Contractor and accepted by the Engineer. All revisions require the acceptance of the Engineer.

    a. Viscosity of bentonite shall not exceed 45 seconds (Marsh Cone) prior to placement of steel reinforcement and/or soldier piles.

b. Specific gravity of bentonite slurry shall be a maximum value of fresh fluid of 1.08 and a maximum value of 1.15 at the bottom of trench prior to steel placement.

c. The density of slurry shall be controlled to prevent the formation of excessive caking.

d. The sand content of the slurry shall be less than 5% prior to placement of steel.

5. Any admixtures proposed for use in the bentonite slurry must be reviewed by the Engineer.

6. The slurry shall not have adverse effects on the concrete including but not limited to, setting time, density, and strength.

7. Bentonite slurry properties may be adjusted to suit field conditions, with the acceptance of the Engineer.

8. Water shall be potable.

F. Concrete for plugging open ends of existing utilities and structures to be abandoned in place shall be Class 3000-psi concrete conforming to Section xxxx.

G. Centering devices for steel reinforcing cages and/or soldier piles shall be made of concrete, 4-inches wide minimum. Plastic rollers will not be permitted.

H. Inclinometer outer casings and grout sleeves installed in panels shall be 6-inch and 4-inch, respectively, PVC pipe, Schedule 80, conforming to ASTM D1785.

I. Polyamide Epoxy Coating for Soldier Pile Corrosion Protection: Section xxxx.

****

Note to the Specifier: Due to the continued modifications to waterproofing materials, the use of coating should be reviewed for each project to verify the most appropriate material is being used.

****

PART 3 - EXECUTION

****

Note to Specifier: These Articles may not be applicable to all projects. The Specifier needs to review carefully and modify as necessary for each project.

****

3.01 GENERAL REQUIREMENTS

A. Place the slurry wall along the lines shown on the Contract Drawings. Excavate the wall within the specified tolerances to the depths shown on the Contract Drawings. The Engineer reserves the right to adjust at any time the bottom elevation to which the wall is to be excavated. Excavate the slurry filled panels through whatever material is encountered to the depths indicated on the Contract Drawings, unless otherwise directed by the Engineer.

B. Stockpile materials and install plant only in staging areas within the property limits or designated work areas. Keep public ways and areas clear of all spillages from construction operations and from trucks hauling materials to or from the project site. Employ construction methods, including protective coverings when necessary, to prevent excavated material and/or slurry from entering utilities, and to prevent all spillage onto streets, sidewalks or other facilities.

C. Protect all exterior surfaces of adjacent structures from damage and disturbance. At the completion of the concrete slurry wall construction, all exterior surfaces of adjacent structures shall be restored to their original condition, as acceptable to the Engineer.

D. Take all necessary measures to prevent collapse of the excavated slurry trench prior to concrete placement. In the event collapse occurs, backfill with lean concrete and re-excavate as accepted or as directed by the Engineer.

E. Confirm that the trench has been cleaned of all loose soil, rock fragments, and other foreign material. Sample and test bentonite from top and bottom of panel prior to tremie concrete placement.

F. Check the verticality of the panel during panel excavation at a minimum of 20-foot intervals (continuously when using a hydromil) and make modifications to the excavation procedures as required to maintain verticality within the specified tolerances.

G. Provide a ‘watertight’ wall system. Repair or otherwise render ‘watertight’ all joints between panels and other penetrations or points of leakage through the wall.

H. Do not excavate two adjacent panels at the same time. Sequence the work so that at least one concreted panel is left between two open panels. At least two panels of unexcavated ground must remain between open panels.

I. Do not excavate next to an existing panel until the concrete in the existing panel has been in place at least 72 hours and has strength of at least 1,800-psi.

J. Excavate and cast together the two sides of each corner panel. No corner joints will be allowed. The length of the sides of the corner panels shall be as indicated on the Contract Drawings.

K. Lay out and measure panels taking as reference the inner face of the wall as shown on the Contract Drawings.

L. Provide inclinometer outer casings and grout pipes embedded within the indicated wall panels for the full height of the panel.

M. Below ground obstructions will be encountered. Such obstructions include but are not limited to boulders, concrete slabs, walls, footings, timber, piles, railroad track, railroad ties, abandoned and active utilities, pavement, miscellaneous steel members, and miscellaneous rubble. Remove obstructions by pre-trenching to the extent practicable and backfilling with suitable material. Construction methods and equipment shall be selected with consideration of the possibility that obstructions may be encountered within the slurry wall excavation. Piles located within the slurry trench may be pulled during pre-trenching; piles outside the theoretical slurry trench shall not be pulled.

N. The slurry level shall be maintained a minimum of 4 feet above the groundwater level and within 2 feet of the top of guidewall, whichever is higher, at all times.

O. Remove and legally dispose of the guidewalls and any portions of slurry wall that require removal.

P. Cut openings for drainage and utilities as necessary or as indicated on the Contract Drawings.

Q. Haul and legally dispose of excavated material and slurry.

R. Provide all keyways, dowels, mechanical connections for splicing reinforcing and/or soldier piles, outer casing for instrumentation, grout tubes and any other embedded items as indicated on the Contract Drawings or accepted Shop Drawings.

S. Provide concrete, reinforcing and soldier piles for all additional depth of slurry wall panels as shown on the Contract Drawings or as directed by the Engineer.

T. Use endstops that are clean and have a surface that conforms to the excavation tool. For SPTC walls, soldier piles may be used as endstops. Use excavation methods to ensure a clean contact between the soldier pile and tremie concrete. Tools used to clean permanent endstops shall not cause damage to soldier pile splices or the soldier pile.

3.02 PROTECTION OF EXISITNG UTILITES

A. Before excavating over or adjacent to existing utilities, notify the utility owner to ensure that protective work will be coordinated and performed by Contractor in accordance with the requirements of the owner of the utility involved. If existing service lines, utilities, and utility structures to remain in service are uncovered or encountered during these operations, protect from damage and provide support as necessary.

B. Remove existing work, including but not limited to, piping, conduit, and manholes to be abandoned as necessary to accommodate the new work. Plug open ends of existing piping and conduits, to be abandoned, with 3000-psi concrete.

C. Should uncharted or incorrectly charted piping or other utilities be encountered during excavation, immediately notify the Engineer and the utility owner. Cooperate with the utility owner in keeping their respective service, utility and facilities in operation. Repair damaged utilities to the satisfaction of the Engineer and utility owner.

3.03 PRE-EXCAVATION AND GUIDEWALL CONSTRUCTION

A. Pre-excavation (Pretrenching): Prior to commencing guidewall and slurry wall construction, the lines of the slurry walls shall be pre-excavated to the depth required to remove obstructions, rubble, loose fill and unsuitable materials. However, pretrenching depth shall not exceed *___* -feet without the acceptance of the Engineer. The excavation shall be backfilled with sand, bentonite and cement mixture proportioned as required by the Contractor to conform to its construction and excavation methods and to create a finished wall with a uniform appearance without cavities and bulges.

B. Bracing and Shoring: Take every precaution and guard against movement or settlement of the work and adjacent property, existing and new construction, utilities, paving, walks, light standards, piping, conduit, etc. Design and provide bracing, sheet piling, lagging, sheeting, and shoring as necessary to guard against movement or settlement. Contractor is responsible for the strength and adequacy of all bracing and shoring and for the support of construction, utilities, and other existing facilities, and for any movement, settlement, damage, or injury thereto.

C. Protection: If at any time the safety of any existing or new construction, utilities, roadways, walkways, or other facilities, shall appear to be endangered, take all necessary means to support such structures, utilities, etc.

D. Guidewalls shall be constructed at an elevation that will allow Contractor to maintain the slurry level as specified herein.

3.04 EXCAVATION

A. Excavating equipment shall be capable of excavating trench sections to the required widths, depths and lengths. Equipment shall be capable of excavating a trench not less than 20 feet deeper than the deepest panel shown on the Contract Drawings or accepted Shop Drawings. Excavation shall include excavation of all materials encountered. Arrange equipment to permit free vertical passage of slurry within the trench and to prevent development of suction or pressure.

B. Contractor's attention is directed to the possibility that vibrations resulting from slurry trench excavation operations may cause damage to adjacent buildings or utilities. Vibrations shall be controlled to avoid such damage. The dropping of the trench excavating tools, chisels, or chopping bits and other operations, shall be controlled in such a way as not to cause damaging vibrations. The Engineer may elect to monitor vibrations. Work shall be controlled to limit the peak vibration velocity to a maximum of 0.5-inches per second as measured at the ground surface immediately adjacent to the structure of concern.

C. Excavation shall proceed continuously from the ground surface to the required depth. All loose debris from the bottom shall be removed by a large capacity air lift and suction system. The trench bottom shall be free of all loose soil, rock fragments, and debris using methods acceptable to the Engineer.

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Note to Specifier: When terminating a panel in cohesive soil, cleaning of the trench bottom should include the use of a smooth edge bucket.

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D. Slurry panels shall be concreted within 24 hours of completing excavation.

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Note to Specifier: In low headroom, restricted work areas, it may be necessary to increase the 24 hour criteria substantially to accommodate splicing of steel reinforcement. Please see PB's slurry wall guides for further information.

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E. Slurry panels shall not exceed *___*feet in length without acceptance of the Engineer.

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Note to Specifier- Maximum panel length is a project specific item. Please see PB's slurry wall guides for further information on selecting panel lengths.

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F. Maintain a reserve supply of mixed bentonite equal in volume to 50 per cent of the volume of one fully excavated panel. If panel sizes vary, the size of the bentonite reserve shall be based on the largest panel.

3.05 PLACING REINFORCING STEEL/SOLDIER PILES

A. Before placing reinforcing steel and/or soldier piles in the slurry filled trench, the joints of any adjacent panels shall be cleaned in the presence of the Engineer and to the satisfaction of the Engineer. If temporary endstops or permanent soldier pile endstops are required, the endstops shall be installed and secured prior to placing reinforcing steel or interior soldier piles in the slurry filled trench. Reinforcing steel cage and/or soldier piles shall not be placed until the bottom of excavation has been sounded and accepted by the Engineer, the Contractor has demonstrated to the Engineer that the panel joint is clear, and the final slurry test has been performed in the presence of the Engineer and found acceptable for concrete placement. Bottom sounding shall be performed at not less than 3 locations; at each end of the panel and at the center of panel. Endstops are to be adequately restrained at the bottom and top to prevent movement in any direction during concrete placement. Steel soldier piles may be used as permanent endstops provided a submitted and accepted filler material is used between the pile and end of excavation. The filler material shall prevent the migration of tremie concrete around the pile, and shall be easily and completely removable during excavation of the adjacent panel. Both temporary and permanent endstops shall be seated at the bottom of excavation. Twisting of endstops will not be permitted.

B. Secure the reinforcing bars together in a manner that will provide a reinforcing cage of sufficient rigidity to resist distortion during lifting and placement into the trench. Welding of the steel reinforcing will not be permitted.

C. Mark the steel reinforcing cage and/or soldier piles to indicate its correct orientation for proper insertion into the trench.

D. Fit the steel reinforcing cage with approved centering devices on both the exterior and interior faces. Centering devices shall be located at a minimum of 10-feet on-center horizontally, minimum two per level, and 20 feet on center vertically. When using soldier piles, in lieu of concrete spacers, extending the soldier piles above grade and confirming pile verticality with a 4-foot level or other approved method is acceptable.

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Note to Specifier: Centering spaces on soldier piles are not normally used.

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E. Lift and suspend the steel reinforcing cage and/or soldier piles in the trench. Lower the steel reinforcement cage and/or soldier piles into the excavated panel immediately after cleaning and sounding the panel bottom. Dropping or forcing the reinforcing cages and/or soldier piles into the excavation will not be permitted. If the steel reinforcing cage and/or soldier pile does not properly and smoothly enter the excavation, the steel reinforcing cage and/or soldier pile shall be retrieved, and the excavation adjusted and recleaned until proper insertion of the steel reinforcing cage and/or soldier pile is achieved. If removal of the steel reinforcing cage and/or soldier pile is required, the reinforcing/soldier pile shall be washed clean of bentonite and/or soil and any damage to the reinforcing that may have occurred shall be repaired to the satisfaction of the Engineer.

F. All embedded items, forming items, keyways and other embedded items shall be securely fastened to the reinforcing to prevent their displacement during hoisting, setting of the steel and concrete placement. Recesses and blockouts as detailed on the working drawings shall be formed using high-density Styrofoam, plywood and necessary steel fasteners, or other methods accepted by the Engineer.

G. Steel reinforcing cages and soldier piles, when tied together in pairs, shall not be permitted to rest on the bottom of excavation. Soldier piles set singularly shall extend to the bottom of trench to prevent movement during concrete placement.

3.06 CONCRETE PLACEMENT

A. Immediately prior to concrete placement, verify the depth and levelness of the excavation in the presence of and to the satisfaction of the Engineer. Measurement of the excavation depth shall be within plus or minus 0.1 foot of the depth measured immediately prior to setting the steel reinforcing cage and/or soldier pile. If sediment deposits on the bottom of trench exceed 0.1 foot, the reinforcing shall be removed and the bottom recleaned and the bottom resounded as previously specified. The reinforcing steel shall be cleaned of all bentonite and debris and repaired of all damage before re-inserting into the trench.

B. Commence placement of concrete in the panels as soon as possible but not more than four hours after completion of slurry and panel bottom cleaning, and no more than two hours after reinforcing cage and/or soldier pile placement. Proceed continuously until completion of concrete placement. If the time limitations specified above are exceeded, remove the steel from the excavation and re-clean the slurry and the bottom of excavation. The steel shall be cleaned of all bentonite and debris and repaired of all damage before re-inserting back into trench.

C. Place concrete in the slurry filled trench by the tremie method in such a manner that the concrete displaces the slurry from the bottom up and rises like a liquid, and mixing of the concrete and slurry will not occur. The concrete shall be placed through a metal hopper and into a rigid watertight elephant trunk tremie, sufficiently large enough to permit free flow of concrete, but not less than 10 inches in diameter. The tremie pipe shall have sufficient length and weight to discharge concrete at the base of the panel excavation. The tremie shall not contain aluminum parts that will have contact with the concrete. The inside and outside surfaces of the tremie pipe shall be clean and smooth to permit both flow of concrete and unimpeded withdrawal during concrete placement operations.

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Note to Specifier: On occasion, site conditions may require pumping from a remote location. Concrete pumps with minimum 5-inch diameter rigid pump lines have been used for this purpose; however, this is not considered typical practice and should be avoided if possible.

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1. Initially there shall be a suitable plug at the bottom of the tremie pipe, which will not discharge until the concrete head has at least reached the top level of the slurry. Thereafter, a positive concrete head shall be maintained throughout.

2. The tremie discharge end shall be immersed at least 10 feet in concrete at all times after starting the flow of concrete. The flow of concrete shall be continuous, suspended only as necessary to accommodate the staging of concrete delivery. The concrete in the tremie shall be maintained at a positive pressure differential at all times to prevent slurry intrusion into the concrete. The tremie shall be marked in 5 foot intervals starting at the discharge end to allow ready determination of the tremie pipe depth.

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Note to Specifier: Some standard specifications permit a minimum 5 foot of tremie in the concrete at all times. Therefore, there is some room for judgment in the field. Additionally, since many slurry walls extend to the ground surface, the minimal head differential makes concrete flow difficult to achieve and the last few-feet of the pour may require the embedment to be reduced to 5-feet.

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3. The number and spacing of tremie pipes used for each panel shall be determined from the requirement that the concrete level shall be kept approximately horizontal during the placement operations. The horizontal flow of concrete from one tremie shall not exceed 8-feet; therefore, tremie pipes shall be located less than 8 feet from panel joints, and the maximum panel length permitted to be poured with one tremie pipe is 15 feet. For SPTC walls, there shall be at least one tremie pipe between each pair of soldier piles. For the placement of concrete for corner panels and ‘T’ panels, in addition to the above criteria for tremie pipe spacing, there shall be at least one tremie in each leg of the panel.

4. The rise of the concrete shall be measured at not less than 10-foot vertical intervals at each joint and middle of panel in the presence of the Engineer to confirm the concrete rise is level.

5. The concreting of the panels shall proceed continuously until concrete of the required strength and quality reaches the top of slurry wall elevation as shown on the Contract Drawings, but in no case shall concrete placement be less than 6 inches above top of slurry wall as shown on the Contract Drawings.

6. The tremie pipe shall not be moved horizontally.

7. Cold joints within the slurry wall panel will not be permitted. Any slurry wall panel that has a cold joint will be considered defective and all the design, implementation, and costs for repair shall be the responsibility of Contractor and shall be subject to the acceptance of the Engineer.

D. If at anytime during the concrete placement the tremie line orifice is removed from the fluid concrete and discharges concrete above the rising concrete level, the panel will be considered defective. In such cases, remove the reinforcing cage and/or soldier piles and concrete, complete any necessary panel excavation cleaning as determined by the Engineer, and repour the panel concrete. Alternative correction measures may be used, if accepted by the Engineer. All costs for replacement or repair of defective panels shall be the responsibility of Contractor.

E. The withdrawal of the temporary endstops shall be accomplished before the initial set of the concrete and before any damage to the concrete is likely to occur.

3.07 TOLERANCES

A. Slurry Wall

1. The slurry wall face to be exposed shall be vertical within the tolerance of 1:100 perpendicular to the panel alignment and the wall ends and/or permanent endstops shall be vertical within the tolerance of 1:200 in a direction parallel to the panel alignment.

2. A tolerance of 3 inches will be allowed for protrusions from the exposed face of the wall resulting from irregularities in the ground as excavated. Any bulges, protrusions, or cavities exceeding specified tolerances in the wall shall be repaired in a manner acceptable to the Engineer.

3. Notwithstanding the above tolerances, the finished inside wall surface including slurry wall deformations from excavation shall not encroach on the minimum clearances shown on the Contract Drawings.

4. The depth of excavation shall not be less than that shown on the Contract Drawings or as directed by the Engineer.

B. Formed Recesses and Embedded Items

.Anchorage plates, formed recesses for slab and beam keyways, pipe sleeves and other embedded items shall be within plus or minus 3 inches horizontally and vertically.

C. Reinforcing Steel Cage and/or Soldier Pile Placement

1. Normal to wall alignment: Plus or minus 1 inch for reinforcing cage and soldier pile.

2. Parallel to the wall alignment: Plus or minus 2 inches for reinforcing cage, plus or minus 1 inch for soldier pile..

3. Vertical: Plus or minus 2 inches for reinforcing cage, plus or minus 1 inch for soldier pile.

4. Maximum tolerance for rotation of soldier piles shall be plus or minus 5 degrees.

5. Minimum concrete cover on reinforcing bars shall be 3 inches. Minimum cover for soldier piles shall be as indicated on the Contract Drawings.

D. Dowels: Plus or minus 3 inches in vertical direction and plus or minus 3 inches in horizontal direction.

E. Guidewalls: The finished face of the guidewalls towards the trench, and on the side of trench nearest the main excavation shall be vertical and shall represent the theoretical inside face of the slurry wall. There shall be no ridges or abrupt changes on the face and its variation from straight line shall not exceed ½ inch in 10 feet. The clear distance between faces of the guidewall shall be the theoretical thickness of the diaphragm wall plus not less than 1 inch but not more than 2 inches

3.08 SLURRY WALL CLEANING

A. During earthwork excavation, after the placement of the slurry wall, clean the interior wall face as it is exposed utilizing rakes, brushes, sand blasting, power washing or other methods acceptable to the Engineer, to remove bentonite caking, soils, and film materials and expose a clean surface.

B. Chip bulges on the interior face of the wall to within specified tolerances as excavation proceeds.

C. Clean all keyways and bring wall dowels to their final bend out conditions

D. Provide internal and external methods of sealing sources of seepage, including pressure grouting of the wall to the 'watertight' condition as previously specified for all areas of wall leakage including panel joints, wall penetrations, voids, cold joints, cracks, and other sources of leakage. Sealing of leaks shall be performed as general site excavation proceeds. Additionally, sealing shall be performed as required or directed by the Engineer as construction proceeds.

E. Apply waterproofing coating to all exposed interior soldier pile flanges. Where its use is indicated on the Contract Drawings, waterproofing coating on exterior flanges shall be shop applied. Coating on interior flange facing shall be applied in the field after completion of excavation and removal of earth support system, defect repair and sealing of any leaks. Coatings shall be in accordance with Section xxxx.

3.09 DEFECTIVE CONCRETE

A. Slurry wall panels exhibiting the following deficiencies will be considered defective:

1. Cold joints in panel.
2. Areas of voids, honeycombs, aggregate runs, or pockets of segregated aggregate.
3. Panels out of tolerances specified herein.
4. Leakage rates in excess of those specified herein.
5. Areas of concrete contaminated with bentonite slurry, bentonite pockets/inclusions, or dried bentonite.
6. Under strength concrete.
7. Any specification violations.

3.10 CORRECTIVE ACTION

A. Submit corrective action as specified in Article 1.06 of this Section.

3.11 NON-CONFORMING PANELS

A. Submit corrective action as specified in Article 1.06 of this Section. Non-conforming panels are panels not meeting the design requirements indicated on the Contract Drawings or specified herein.

PART 4 - MEASUREMENT AND PAYMENT

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Note to Specifier: Method of payment can be either lump sum or unit price. When subsurface conditions are uniform and the bottom of wall is well defined with little or no variation in depth anticipated, it may be preferable to use the lump sum payment method with nominal unit price quantities to accommodate minor alterations in depth, 'ADDITIONAL DEPTH SLURRY WALL'. The description of rock is project specific and should be provided by the designer for each project.

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4.01 MEASUREMENT

A. SLURRY WALL for indicated thickness, installed by the slurry trench process through overburden will be measured by the (*square foot or lump sum)*. For purposes of this measurement, overburden shall include all materials encountered including fill, organics, sand, gravel, clay, till, boulders, cobbles decomposed rock, and any other material encountered except rock and obstructions as defined herein. The length of wall installed will be measured on the inside face, within the limits indicated on the Contract Drawings *(or as directed by the Engineer for unit price*). The height of wall will be measured from the top of design strength concrete indicated on the Contract Drawings to the elevation where rock, as defined below, is encountered, or to the bottom of wall shown on the Contract Drawings *(or otherwise directed by the Engineer where the wall is founded on material other than rock. for unit price*).

Slurry wall work shall include but not be limited to, furnishing all labor, materials, tools, equipment, and incidentals and for all work necessary to complete the slurry wall as indicated and directed. The *(unit price or lump sum)* shall include verification of utility locations; protection of utilities; coordination with utility owners; pre-trenching and backfilling; removal of obstructions with an in-situ volume of less than one cubic yard; construction, demolition, removal and legal disposal of guidewalls; excavation through overburden, rock and all other materials encountered whether natural or man-made; watertight joint forming; reinforcing steel; soldier piles; the supply of recess forming devices, inserts, dowels, and tremie concrete; chipping top of wall for drainage; the supply, handling, and legal disposal of slurry; the hauling and disposal of excavation materials; the trimming of the top of slurry wall to expose sound concrete; the removal of bulges or projections; cleaning of slurry wall; sealing the slurry wall where necessary for watertightness, including joints between the slurry wall and existing structures; the cost of obtaining any patent rights and royalties; the cost of all repairs required to the slurry wall to meet contract requirements.

B. SLURRY WALL IN ROCK for the indicated thickness, installed by the slurry trench process through rock, will be measured by the square foot. The wall will be measured on the inside face only within the limits indicated on the Contract Drawings from the bottom of wall through overburden, as specified above, to the final foundation level indicated on the Contract Drawings or as directed by the Engineer. For Purposes of this measurement, rock is defined as material that satisfies the following:

1. It cannot be excavated nor removed by specifically designed bentonite slurry wall excavating tools, by grabbing, scraping or rotary-scrapping action only.

2. Rock fragments only are consistently recovered by the above tools when used alone or after chiseling operations.

Payment at the contract unit price per square foot shall constitute full compensation for furnishing all labor, materials, tools, equipment, and incidentals and for work necessary to complete the slurry wall as indicated and directed. The unit price shall include but not be limited to all excavation; watertight joint forming; reinforcing steel; soldier piles; the supply, handling, and legal disposal of slurry; the excavation, hauling and legal disposal of all excavation materials; tremie concrete; sealing the slurry wall where necessary for watertightness.

C. Removal of obstructions with a volume greater than one cubic yard, encountered within *__* feet of the ground surface, will be measured and paid under Payment Item xxx, REMOVAL OF OBSTRUCTIONS as described in Section xxxx, Earthwork. Obstructions encountered below *__* feet will be addressed as changed conditions. Obstructions are considered manmade items such as granite blocks, piles, steel sheeting, etc. Encountering boulders and/or cobbles should be anticipated; these items shall not be considered as obstructions and therefore no separate payment will be made for their removal. Payment for obstruction removal shall include materials, equipment, and labor required for their removal and legal disposal as well as any costs including but not limited to costs from schedule delay and standby time of all labor, equipment and material.

D. ADDITIONAL DEPTH OF SLURRY WALL *(lump sum only)* for the indicated thickness will be measured by the square foot. The wall will be measured on the inside face only from the bottom of wall indicated on the drawings to the depth as directed by the Engineer.

Payment at the contract unit price per square foot shall constitute full compensation for furnishing all labor, materials, tools, equipment, and incidentals and for work necessary to complete the slurry wall as indicated and directed. The unit price shall include but not be limited to all excavation; watertight joint forming; reinforcing steel; soldier piles; the supply, handling, and legal disposal of slurry; the excavation, hauling, and legal disposal of all excavation materials; tremie concrete; sealing the slurry wall where necessary for watertightness.

4.02 PAYMENT

Slurry walls shall be paid at the unit prices described above

4.03 PAYMENT ITEMS

Item No.	Description	Unit
xxxx.xxx	SLURRY WALL	SQ. FT or LS
xxxx.xxx	SLURRY WALL IN ROCK	SQUARE FOOT
xxxx.xxx	ADDITIONAL DEPTH OF SLURRY WALL	SQUARE FOOT

END OF SECTION

Appendix E - Listing of PB Slurry Wall Projects

Listing of PB Slurry Wall Projects

PROJECT	LOCATION	OWNER/CLIENT	ROLE	DATE	DESCRIPTION
Baltimore Metro – Section C	Baltimore, Maryland	Maryland Mass Transit Administration	PB was retained, in joint venture, to provide final design and construction related services during the Baltimore Metro – Section C project.	1996	SPTC walls with reinforcing between soldier piles were selected for the permanent walls of the 610 ft long Shot Tower Station. A portion of the station was constructed below Jones Falls conduit. An approximately 40 ft section of the main station was constructed using a jet-grouted cutoff wall in order to accommodate and not disturb existing electrical lines.
Panchiao Extension Project	Taipei, Taiwan	Taipei Railway Underground Project Office	PB was involved in all phases of the Panchiao Extension Project, served as general consultant and provided detailed design review and construction advisory services for a segment of the railway underground program.	1996	Project site is characterized by a high groundwater table and relatively poor soil; some adjacent building foundations are less than 3 ft from the excavation. Braced slurry walls were used for most of the temporary support where deep excavations were required. Slurry walls with eight levels of bracing were required near the Hsitien River, where the excavation depth exceeds 78 ft.
63rd Street Tunnel Connection	New York, New York	MTA NYC Transit	PB, in joint venture, provided final design services including design support during construction and contract close-out.	2001	More than 3000 ft of slurry walls were used for a portion of the project where new track sections will cross under the existing Queens Boulevard Line tracks prior to merging with them. The temporary support walls controlled groundwater, providing a relatively watertight enclosure in an area where external dewatering could not be used because of the potential impact or drawdowns on nearby contaminant plumes and consolidation of peat deposits below nearby structures.
Beth Israel Hospital Clinical Center	Boston, Massachusetts	Beth Israel Hospital	PB, as a subconsultant to an architectural firm, provided design management and construction services for the underground portions of the clinical center.	1996	Project included the construction of a five-level underground garage that provided foundation support for a 20-story medical facility. Construction included slurry walls to reduce impacts to adjacent buildings and to provide the permanent structural walls of the below grade garage. The slurry wall was designed for two future openings – a service tunnel and a connection to a future adjacent garage.

Listing of PB Slurry Wall Projects

PROJECT	LOCATION	OWNER/CLIENT	ROLE	DATE	DESCRIPTION
Rio Salado Town Lake Project	Tempe, Arizona	Engineering Division, City of Tempe	PB provided full construction administration services.	1998	Plans called for converting a section of the Salt River Channel into a recreational lake. Approximately 1-mile long slurry bentonite cut-off walls were constructed in the channel invert paralleling the lake boundary. The walls are up to 50 ft deep and will minimize seepage from the downstream half of the lake area.
North-South Toll Road Construction Inspection	Chicago, Illinois	Illinois State Toll Highway Authority	PB provided construction inspection services.	1989	Project included 2000 ft of slurry wall construction.
Harvard Square Station	Cambridge, Massachusetts	Massachusetts Bay Transportation Authority (MBTA)	PB provided full design and construction phase services.	1980s	First slurry wall to be used for both permanent and temporary conditions for rapid transit tunnel in the U.S. Project included approximately 1000 ft of tied back slurry wall for excavation depths of 55 ft. Excavation was as close as 7 ft to historic Harvard University structures founded on shallow spread footings. Deformations were typically maintained at less than 1/4 inch horizontal and vertical.
Post Office Square Park and Garage	Boston, Massachusetts	Friends of Post Office Square, Inc.	PB was retained as the lead firm to provide design and construction phase services for a seven-level parking garage in the middle of Boston's financial district.	1990	Project included excavating the deepest excavation to date in the Boston area, approximately 80 ft, with adjacent buildings typically located on shallow foundations. Most adjacent structures were within 50 ft of the excavation. Construction used the top down method with permanent slurry walls. Approximately 1100 ft of slurry wall and a permanent groundwater relief system were installed with no reported damage to adjacent structures. The soil profile included a deep soft clay deposit. Complex numerical analyses were performed to model the top down construction and to predict long term seepage quantities and drawdown.

Listing of PB Slurry Wall Projects

PROJECT	LOCATION	OWNER/CLIENT	ROLE	DATE	DESCRIPTION
Central Artery/Tunnel	Boston, Massachusetts	Massachusetts Highway Department (MHD)	PB, as part of the Bechtel/PB joint venture, served as management consultant.	2006	Downtown portion of the project includes approximately 23,000 ft of SPTC slurry wall. The slurry walls form the permanent walls of the highway tunnels, being excavated beneath the 6-lane I-93 viaduct as it remains in use. About a third of the length of slurry walls were constructed under low head room.
MBTA Tunnel Ventilation Shafts	Boston, Massachusetts	Massachusetts Bay Transportation Authority (MBTA)	PB provided planning, design, architectural/engineering, and construction-phase services.	1996	Thirty ventilation shafts and/or emergency exits at 30 locations along three existing transit lines. Slurry walls, for temporary and permanent support, were designed at some sites to minimize ground movement and avoid potential damage to the subway tunnel and nearby historic structures.
Long Wharf Vent Shaft	Boston, Massachusetts	Massachusetts Bay Transportation Authority (MBTA)	Geotechnical study as part of investigation of condition of wharf and condition of granite sea walls for eventual rehabilitation of pier end into a public park.	1980s	Project included slurry wall construction on the Boston water front for an approximately 75 ft deep excavation immediately adjacent to the existing MBTA Blue Line Tunnel. Construction included use of permanent soldier piles to accommodate cross-lot bracing that served as both temporary bracing and the permanent floor levels for the vent structure. It was necessary to buttress the Blue Line Tunnel with the slurry wall to maintain water control and the structural stability of the tunnel. This necessitated excavating and casting the slurry wall in contact with the existing unreinforced concrete tunnel.
North Station Parking Garage	Boston, Massachusetts	Massachusetts Bay Transportation Authority (MBTA)	As part of a joint venture, PB provided structural and geotechnical design services and construction phase services.	1993	Approximately 1700 ft of permanent slurry wall construction, employing top down scheme and permanent underdrain/pressure relief system. General site excavation was approximately 60 ft deep through primarily fill and organic soils. The slurry wall was within 4 ft off the existing Boston Garden Arena. Slurry wall excavation extended 30 ft below the foundation of the existing Garden which maintained operations throughout the construction.

Listing of PB Slurry Wall Projects

PROJECT	LOCATION	OWNER/CLIENT	ROLE	DATE	DESCRIPTION
South Boston Piers Transitway Project	Boston, Massachusetts	Massachusetts Bay Transportation Authority (MBTA)	As subconsultant, PB provided structural and geotechnical design services and construction phase services.	2004	Approximately 800 ft of 3ft thick and 1000 ft of 4 ft thick internally braced permanent slurry walls were constructed. Excavation depth of 60 ft and widths of 110 ft were performed in deep deposits of very soft dredge materials and very soft Boston Blue Clay, requiring state of the art numerical analyses to confirm base and global stability and provide deformation predictions.
Section F.4 Washington D.C. Metro	Washington D.C.	Washington Metropolitan Area Transit Authority (WMATA)	PB, in joint venture, provided structural, geotechnical and tunneling design services	1985	Permanent slurry walls were used for the fan shaft and tunnel drainage pumping station. The shaft is 38 ft by 81 ft in plan, and extends to a depth of 113 ft.
BART Embarcadero Station	San Francisco, California	Bay Area Rapid Transit (BART)	PB, in joint venture, was general engineering consultant for the BART system; for the Embarcadero Station, PB was the designer.	1970s	SPTC walls were used for excavation support. The walls had a total depth of approximately 120 ft and penetrated up to 55 ft of soft clay ("recent bay mud") Ref. "Cofferdam for BART D, Embarcadero Subway Station" by William J. Armento, ASCE Journal of Soil Mechanics and Foundation Engineering, SM10, Oct. 1973, pp 727-744.