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**DIAPHRAGM WALLS AS PERMANENT BASEMENT WALLS
IN REGIONS OF HIGH SEISMICITY**

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Introduction

Reinforced concrete structural slurry walls have been used in the United States since the early 1960s. The typical practice, and one that makes the economics of slurry walls particularly attractive, is to design the walls to act as both temporary excavation support and permanent basement walls. They often serve as multi-story basements and below grade parking for buildings, for tunnels, subway stations, and other buried structures. One of the early applications was for a foundation for a subway station in San Francisco, but for the most part they have been used more extensively in regions of low seismicity. The purpose of this report is to investigate the requirements for extension of this practice to more common use in regions of high seismicity.

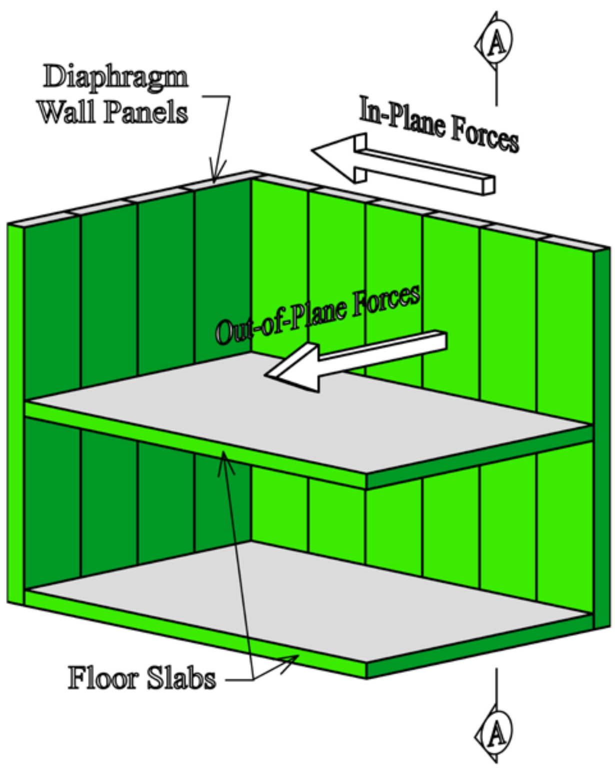

Fig. 1 - Forces Acting on Diaphragm Walls
(see Fig. 2 for Section A-A)

Structural slurry walls are concrete walls constructed below the ground surface. In slurry wall construction, a trench is excavated using a rectangular clamshell bucket or other specialized equipment. During excavation, the trench is held open by introduction of a bentonite or polymer slurry. Steel reinforcement, if required, is lowered into the slurry-filled trench, and concrete is subsequently deposited by tremie, displacing the slurry.

The length of trench open at any one time is limited to a typical maximum of about 20 to 24 feet by excavation stability and concrete placement volume considerations. Each individual concrete placement is referred to as a "panel," and vertical construction joints separate the panels. Temporary "end-stops" are used as formwork to control the geometry of the panel joints, and horizontal reinforcement is discontinuous at the joints.

Structural slurry panels range from 1.5 to 5.0 feet thick, 7 to 24 feet long, and up to 300 feet deep. In the United States, panels that are 2.0 to 3.5 feet thick and depths of 40 to 150 feet are commonplace.

Structural basement walls support earth pressures acting laterally against the wall, dead and live loads acting vertically, and in-plane shear and flexure from wind and earthquake loads. The design of permanent slurry walls in regions of low or moderate seismicity is often limited to providing the strength necessary to resist out-of-plane soil pressures and vertical dead and live loads from the superstructure and basement framing. Although these walls also transfer in-plane lateral forces from the superstructure into the soils, the walls are often not specifically designed for these in-plane forces because their inherent strength is usually much greater than the forces being transferred. If resistance to in-plane forces acting on a wall required an increase in vertical reinforcement at the ends of a wall segment, an increase in the cap beam strength, or an increase in the horizontal reinforcement for shear strength, the overall design and construction approach would not vary significantly from current practice.

Structural slurry walls have been used to a limited extent for buildings designed for high seismic risk, but there is reluctance on the part of design engineers to use them more often because of concern for how to design these walls to resist in-plane lateral forces, lack of code provisions for reinforcement detailing, and damage that may occur at panel joints.

For buildings designed for high seismic risk, such as those assigned to Seismic Design Categories (SDC) D, E, and F as defined in Minimum Design Loads for Buildings and Other Structures (ASCE/SEI 7-10), in-plane shear and flexural actions may likely require modifications of a structural slurry wall only designed for out-of-plane soil pressures and vertical live and dead loads. Design would need to address in-plane lateral forces acting on structural slurry walls and the interaction of the in-plane actions with the out-of-plane and vertical actions.

These issues are discussed in this report, and approaches to design for high seismic risk are presented.

Performance of Basement Walls Subjected To Earthquake Ground Motion

Few structural slurry walls have experienced strong ground motions in the U.S.; however, the performance of other earth retaining structures and in particular basement walls subjected to earthquake ground motions can be used to project how structural slurry walls would likely perform. A summary of damage to earth retaining and buried structures is presented by Ostadan (2005). The paper cites references in which damage to earth retaining structures was observed. It indicates that damage to basement walls of buildings has been reported following more recent earthquakes; however, these walls also supported building inertial forces, so the contribution of the seismic soil pressures to the damage was not quantifiable. The paper did not identify examples of damage to building basement walls due solely to seismic soil pressures.

Lew et al. (2010a) discuss damage to building basement walls and other earth-retaining structures. The paper states that the damage reported to earth retaining structures has been almost entirely confined to poorly constructed non-engineered walls, and that many of these failures were in a marine or waterfront environment. It states that no damage to basement walls retaining earth was found following the 1971 San Fernando, 1987 Whittier Narrows, 1989 Loma Prieta, and 1994 Northridge earthquakes. It also addresses damage to basement walls and other earth-retaining structures outside of the U.S. For the few cases in which damage was reported, explanations are provided as to why the damage occurred. One of the structures damaged was a long subway station in Kobe, Japan that only had cross walls at the far ends of the structure. The structure behaved as a flexible wall-slab frame that allowed lateral movement that caused failure of interior reinforced-concrete columns that only had minimal lateral ties. The paper also reports that liquefaction may have occurred at the site, which would have resulted in increased lateral pressures. Lew et al. (2010a) summarizes, “The available literature does not indicate that damage to basement walls is a prevalent or even an occasional concern.” Lew et al. (2010b) indicates that almost all documented failures of earth-retaining structures is due to a soil-related failure in loose or poorly compacted soils at waterfront or marine sites or due to slope instability or liquefaction.

To summarize, a review of the literature indicates that damage due to seismic lateral earth pressures has not been prevalent. Although there is not a compelling reason to design building basement walls that are supported at multiple levels for seismic lateral earth pressures, building codes in the U.S. require that they be designed for those pressures if the building is assigned a higher seismic design category.

Building Code Requirements - General

While there is no language in current building codes that specifically addresses diaphragm walls, the applicable building code governs the design of structural slurry walls used as permanent basement walls. In the United States, an edition of the International Building Code (IBC) is almost always applicable. References to the IBC in this document refer to the 2012 Edition. Chapter 16 of the IBC includes loads for which structures must be designed and adopts ASCE/SEI 7 for determination of forces from earthquake ground motions and other seismic design requirements. ASCE 7 proscribes the methods of structural analysis, typically the equivalent lateral force procedure or a response spectrum analysis for the determination of seismic base shear and overturning moment. Chapter 18 of the IBC includes geotechnical investigation requirements, foundation design requirements, and some requirements for basement walls, which are applicable, but it includes no provisions specifically intended to apply to structural slurry walls. Chapter 19 of the IBC includes requirements for concrete design and construction, which adopts the American Concrete Institute's Building Code Requirements for Structural Concrete (ACI 318-11) for reinforced concrete design. Chapter 19 of the IBC and ACI 318-11 have design provisions that are applicable to structural concrete walls, but no provisions that are specifically intended to apply to structural slurry walls.

Seismic Design Categories

The Seismic Design Category (SDC) is a classification assigned to a structure based on the design earthquake ground motions and the structure's use or occupancy. SDC's may be determined in accordance with Chapter 16 of the IBC or Chapter 11 of ASCE/SEI 7. Each structure designed in accordance with the IBC and ASCE/SEI 7 must be assigned a SDC. SDC assignment depends on the mapped spectral acceleration parameters (S_S and S_1), the 100-foot-deep soil and rock profile, and the risk category, I, which depends on the occupancy. The SDCs range from A to F. SDC A applies to structures with very low risk of being damaged by an earthquake and does not require design for forces that result from earthquake ground motions. SDCs B and C apply to structures with low and moderate risk of being subjected to damaging earthquake ground motions, respectively.

SDCs D to F apply to structures with greater risk of being subjected to high levels of earthquake ground motions. SDC E applies to Risk Category I, II, and III structures for which the 1-second spectral acceleration parameter, S_1, is greater than or equal 0.75, which occurs at sites that are relatively close to an active fault, while SDC D applies if S_1 is less than 0.75. SDC F is only applicable to Risk Category IV structures for which S_1 is greater than or equal to 0.75.

In SDCs D to F, the basement walls must be designed and detailed in accordance with the provisions of ACI 318, Chapter 21 to resist forces from the superstructure's seismic-force-resisting system (SFRS).

Geotechnical Investigation

The requirements for geotechnical investigations are included in Section 1803 of the IBC. A geotechnical investigation is required for all structures assigned to SDCs C through F that addresses the potential for (1) slope instability, (2) liquefaction, (3) total and differential settlement, and (4) surface displacement due to faulting or seismically induced lateral spreading or lateral flow. For SDCs D through F, the dynamic seismic lateral earth pressures on foundation walls must also be determined. Section 1803 further requires that the geotechnical report discuss mitigation measures, such as ground improvement or selection of particular foundation types, that can be taken to address earthquake-induced loads or displacements.

Design Load Combinations

The applicable strength design load combinations that include earthquake forces are Combinations 5 and 7 of ASCE/SEI 7-10 Section 2.3.2 or IBC Equations 16-5 and 16-7. These load combinations are the same but are presented differently. In ASCE/SEI 7-10, load from the lateral static earth and ground water pressures, H, is added to these load combinations with a load factor of 1.6 because these pressures add to the primary variable load effect, which is the earthquake load, E, in the load combinations. Dynamic lateral soil loads are considered an earthquake load, E, in the load combinations [NEHRP 2009 Provisions Commentary 11.8.3; ASCE/SEI 7/10 Commentary 11.8.3]

$$1.2D + 1.0E + L + 0.2S + 1.6H \qquad \text{(Eq. 1)}$$

$$0.9D + 1.0E + 1.6H \qquad \text{(Eq. 2)}$$

Where: D is dead load,
H is soil lateral load,
E is earthquake load,
L is live load, and
S is snow load.

Dead load, live load, and snow load increase the axial load in the wall and can cause a surcharge if applied to the ground surface near the wall.

Building Code Requirements - Lateral Earth Pressures

Section 1610 of the IBC requires that foundation walls be designed to resist lateral soil loads. This section is only referring to the static lateral soil loads. A requirement to design for dynamic lateral soil loads is not clearly stated in the IBC or ASCE/SEI 7; however, the need to design for such loads in SDCs D, E and F is implied by the geotechnical investigation requirements of Section 1803.

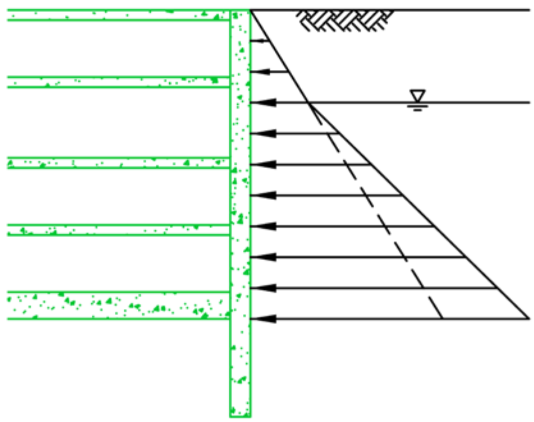

Fig. 2 - Earth Pressures (Section A-A from Fig. 1)

Static Earth Pressures

The minimum static lateral soil loads are determined in accordance with Table 1610.1 unless otherwise determined by a geotechnical investigation in accordance with Section 1803. Slurry walls are generally relatively deep so a geotechnical investigation is almost always required to establish the soil and groundwater profile at the site, classify the site for seismic design, establish the required depth of the slurry wall, and determine the soil strength parameters. Section 1803.5.5 of the IBC requires that a geotechnical investigation be conducted unless there is sufficient existing information on which to base the design. Therefore, static lateral (i.e., out-of-plane) soil loads for structural slurry walls are almost always obtained from a geotechnical investigation in accordance with Section 1803. Lateral movement of the top of structural slurry walls is almost always restrained by horizontal diaphragms (floor framing) supported by the opposing walls, so at-rest pressures are used for the permanent condition.

Procedures for a geotechnical engineer to determine at-rest and active pressures are well established (e.g., see NAVFAC Design Manual 7.02). The static earth pressures are usually defined as an equivalent fluid pressure or pressure distribution. An example is shown in Fig. 2. Alternatively, more sophisticated numerical methods such as soil-structure interaction finite element analyses can be used to estimate lateral earth pressure and wall movements. Such analyses can yield more reasonable agreement with observed wall performance, particularly in the case of deep basements and staged excavations.

Seismic Increment of Earth Pressure

For structures assigned to SDCs D, E, and F, dynamic lateral soil loads from earthquake ground motions are required to be included in the design of the basement walls, including structural slurry walls. Basement walls of structures assigned to SDCs B and C are sometimes designed for dynamic lateral soil loads as well. For example, the Massachusetts State Building Code (2008) requires design for the seismic increment of soil pressure even though SDCs B and C are generally applicable. The IBC and ASCE/SEI 7 do not define how these dynamic lateral soil loads should

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be computed. Therefore, structural engineers generally rely on a project's geotechnical engineer to provide seismic lateral soil pressures for commercial buildings. For non-commercial buildings, some design codes, standards, and guidelines provide procedures for computing seismic lateral soil pressures. Procedures for computing seismic earth pressures for nuclear safety-related structures are provided in ASCE 4 (ASCE, 1998), which refers to the Mononobe-Okabe method for flexible walls and Wood's method for walls that are restrained against displacement, commonly referred to as rigid walls. The NEHRP Recommendations (BSSC, 2003) , which is a Federal design guidance document for buildings that serves as a resource document for the seismic provisions in ASCE/SEI 7, recommends the Ostadan method for computing basement wall seismic earth pressures.

The geotechnical engineering profession has not reached a consensus on how to compute the seismic increment of lateral soil pressures on basement walls. For buildings designed in accordance with the IBC, the seismic increment of earth pressure should be established by the project geotechnical engineer. For safety critical structures of a nuclear power plant, seismic lateral soil pressures should be computed in accordance with ASCE 4.

Current Slurry Wall Design Practice

The Deep Foundations Institute (DFI) has published *Industry Practice Standards and DFI Practice Guidelines for Structural Slurry Walls*, which provides standards and guidelines for the design and construction of structural slurry walls. This publication covers practical aspects of slurry wall construction such as slurry wall panel configurations, panel dimensions, forming ends of panels, equipment used for construction, slurry properties and mixing, cleaning of slurry, use of precast panels, reinforcement placement, use of post-tensioning, use of bracing, phases of panel construction, and construction inspections and observations.

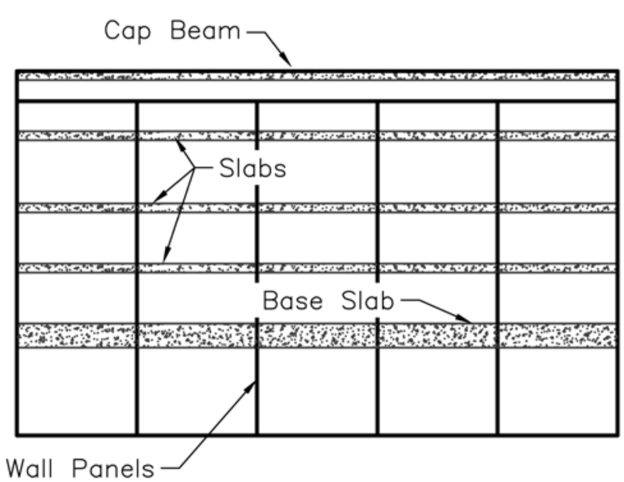

Fig. 3 - Wall Elevation

An example of a structural slurry wall elevation is shown in Fig. 3. In addition to the slurry wall panels, a reinforced concrete cap beam generally connects the top of the panels to one another.

Vertical reinforcement from the wall panels extends into this beam. A representative cap beam with reinforcement is shown in Fig. 4. For buildings, a thick base slab is usually present and structurally connected to the walls as shown in Fig. 5.

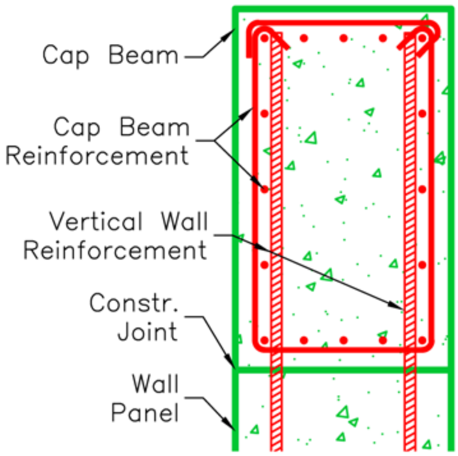

Fig. 4 - Cap Beam

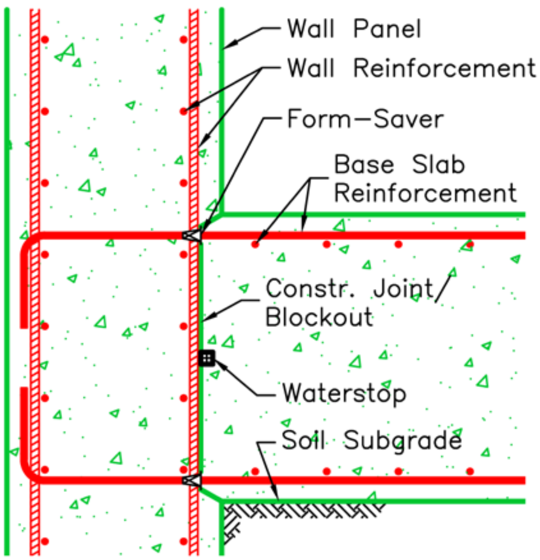

Fig. 5 - Base Slab Connection

Vertical construction joints are formed between adjacent panels by means of temporary end-stops installed prior to placement of the concrete in the first panel. The end-stop is removed after excavation of the second panel. Joints are typically constructed with a keyed profile to provide out-of-plane engagement between the panels. Horizontal reinforcement is discontinued several inches from of the joint. Joint profiles are typically proprietary, and may include a waterstop to improve joint watertightness. An example joint is shown in Fig. 6.

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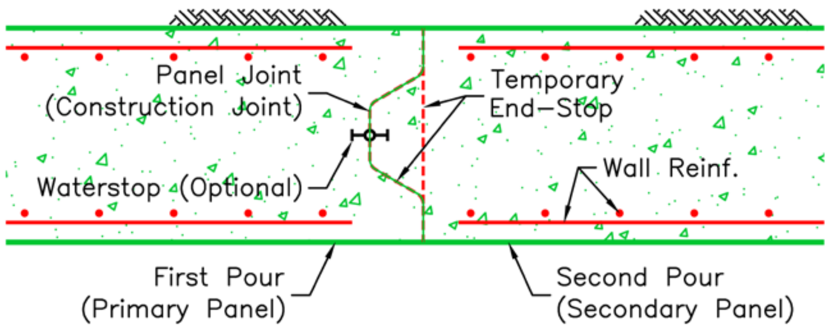

Fig. 6 - Panel Joint

Structural Slurry Walls Designed for Low and Moderate Seismic Risk

Structural slurry walls for the basements of buildings that are designed for low or moderate seismic risk (SDCs) are usually designed in the same manner as conventional reinforced-concrete basement walls. Out-of-plane earth pressures are included in the design of the slurry walls, including the seismic increment when required by the applicable building code or recommended by the geotechnical engineer. The slurry walls are designed to resist in-plane seismic forces and overturning moments computed from a structural analysis of the building superstructure. Note that for SDCs A, B, and C, the IBC does not require the geotechnical investigation to include determination of the seismic increment of soil pressure, nor does it specifically require that seismic soil pressures be included in the design.

Like conventional reinforced concrete basement walls for buildings in these SDCs, the structural slurry walls are usually not assigned a seismic-force-resisting system (SFRS) designation. Also, the transition from the vertical SFRS of the building to the foundation slurry walls is not considered a change in the seismic system. However, ordinary reinforced concrete shear walls is the appropriate SFRS to consider for the design of the slurry walls of a building assigned SDC B or C. Ordinary reinforced concrete shear walls are designed in accordance with Chapters 1 through 18 of ACI 318-11, which means there are no detailing requirements that specifically address earthquake effects. Therefore, structural slurry walls for a building assigned SDC B or C have the same detailing requirements as walls for buildings assigned to SDC A, which are designed for wind forces but not seismic forces.

Out-of-Plane Seismic Forces

The controlling load combination for out-of-plane flexural design is usually the one that includes static earth pressures plus the dynamic soil pressures from design earthquake ground motion. The vertical dead and live loads in this combination may be ignored if the level of axial compression they cause is significantly less than the compression for the balanced point on an axial force-moment (P-M) interaction diagram. Ignoring the vertical compression is a safe assumption due to the fact that tension-controlled sections with axial compressive forces have a weaker computed flexural strength if compression is ignored. The balance point on a P-M interaction diagram is the point at which the concrete reaches a strain of 0.003 as the reinforcing steel yields. The axial compressive force is normally shown on the vertical axis and the moment is shown on the horizontal axis. For axial compressive forces well below the balanced point, an increase in compressive force results in an increase in design flexural strength (for instance, Points A and B in Fig. 7).

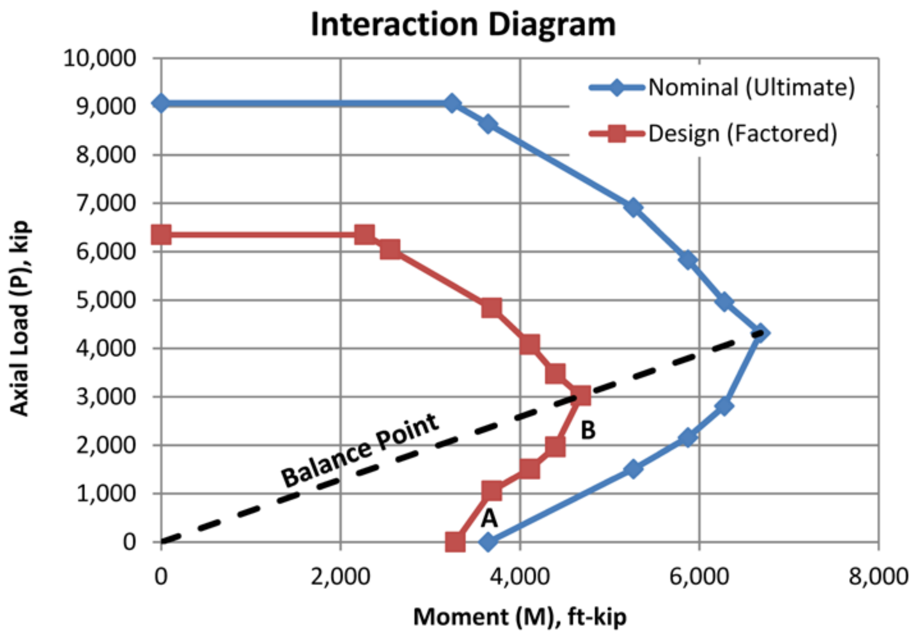

Fig. 7 - Interaction Diagram

The structural slurry wall panel design for out-of-plane wall forces and vertical bending is similar to one-way slab design. Panels are designed in accordance with standard flexural design assumptions and the general principle requirements of Chapter 10 of ACI 318-11. Some engineers apply the minimum flexural reinforcement requirements of 10.5 while others design the minimum vertical reinforcement as for slabs in accordance with Section 7.12. For a 24-inch-thick wall, No. 5 bars at 12 inches on center on both faces provides the minimum allowed reinforcing ratio of 0.002 in accordance with Section 7.12.2.1(a) (although heavier reinforcement might be required for constructability).

Out-of-plane shear design is also controlled by load combinations that include static and dynamic earth pressures. The structural slurry walls are typically thick enough so that shear reinforcement is not required. If reinforcement for out-of-plane shear is required, single-leg stirrups or u-shaped stirrups are provided at specific elevations within the wall.

In-Plane Seismic Forces

Design of structural slurry walls for in-plane seismic shear and overturning varies somewhat among engineers. The assumptions made with respect to the continuity of panels in a wall are critical to the distribution of in-plane forces. For cases of relatively low demand, it can conservatively be assumed that the panels are discontinuous at the joints; i.e., that no vertical shear is transferred between panels. Given this assumption, as illustrated in Fig. 8a, below, forces causing in-plane shear are distributed to the panels based on their relative in-plane stiffness, which is a function of the individual panel length if all slurry wall panels in a line are the same depth.

Alternatively, it may be possible to consider partial or full continuity of the panels, as illustrated in Figs. 8b, and 8c, respectively. This continuity is based on the vertical shear strength provided by the cap beam, base slab, and intermediate floor slabs. Greater continuity provides greater strength and stiffness in the wall, but these less-conservative assumptions require an analysis of the shear strength available in the connecting elements.

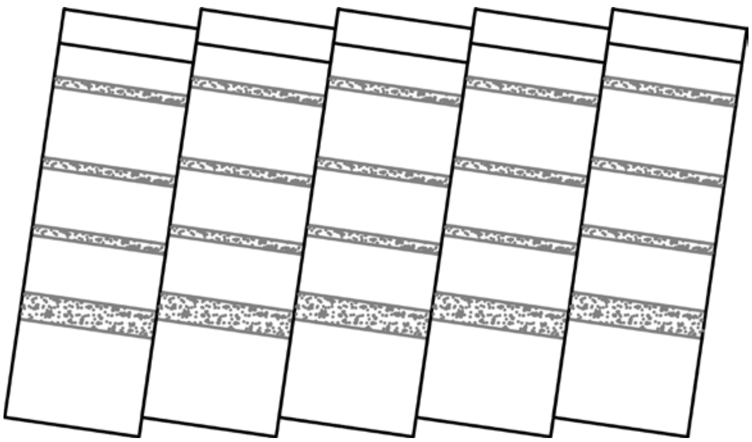

Fig. 8a - In-Plane Deformation (no restraint)

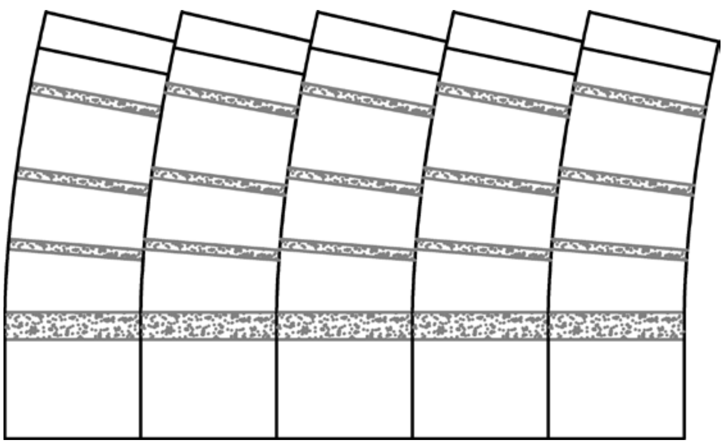

Fig. 8b - In-Plane Deformation (partial restraint)

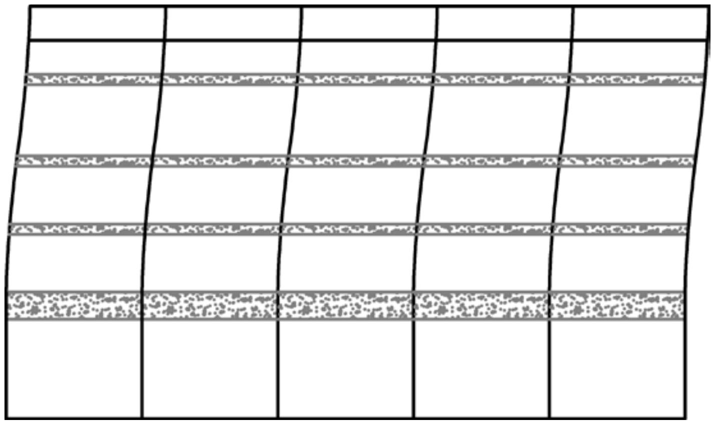

Fig. 8c - In-Plane Deformation (full restraint)

Finally, overturning moments from vertical elements of the SFRS must be resolved locally at the ends of the vertical elements. For example, vertical reinforcement of a shear wall is made continuous by splicing to vertical reinforcement from the slurry wall panels and cap beam directly below as shown in Fig. 9. Cap beams may be designed and constructed with the ability to spread the vertical force couples from overturning moments, or the force couples can be resolved by transferring the force to the panels immediately below a vertical element.

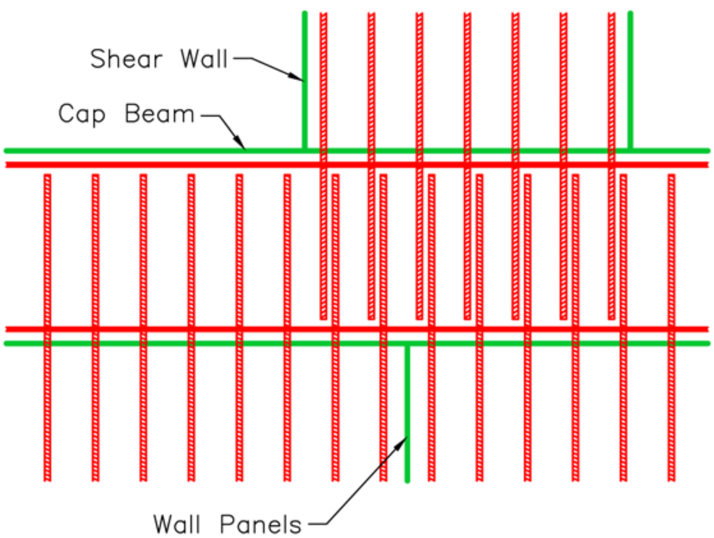

Fig. 9 - Shear Wall Connection (Elevation View)

Horizontal bars parallel to the length of the wall segment resist in-plane shear forces. The concrete contribution to the in-plane shear strength of these walls almost always exceeds shear demand, so the horizontal bars are usually provided for crack control as required in ACI 318-11 Chapter 14 rather than for structural strength. These horizontal bars are generally No. 6 or larger thus requiring a minimum reinforcement ratio of 0.0025 in accordance with Section 14.3.3. Horizontal bars comply with the 18-inch maximum spacing of Section 14.3.5. Typically, the thinnest wall used is

24 inches thick, which would require No. 7 bars at 18 inches on center for a horizontal reinforcing ratio of 0.0028.

The vertical reinforcement required is usually controlled by out-of-plane forces as discussed above, but additional vertical reinforcement needed to resolve force couples from overturning moments may be required for the slurry wall panels directly below vertical seismic-force-resisting elements. This additional reinforcement will be controlled by the load combinations that include seismic and wind forces.

Exactly how in-plane vertical and horizontal forces distribute within slurry wall panels and transfer to soil is left to the design engineer to consider in his or her design. Mechanisms for transfer of in-plane forces between slurry wall panels and soil or rock include the following:

- Soil friction on the outside face of the wall panel.
- Friction on the base of panel or embedment into rock.
- Bearing against adjacent panels, resolved by soil side friction and passive soil resistance at the end of the line of panels.
- Shear force transfer into the slabs, resolved by passive soil pressure on the perpendicular wall.

Slurry wall panels should be reinforced to resist in-plane forces consistent with an appropriate load path. If using side friction to resolve in-plane slurry panel forces, consideration should be given to the possibility that the wall panels will separate from the soils at shallow depths. In regions of low and moderate seismicity the slurry wall panels usually have substantial in-plane shear strength, so minimum reinforcement requirements usually control the amount of required horizontal reinforcement rather than force demands from load combinations that include seismic and wind forces.

Recommendations for Design in Regions of High Seismicity

Design of diaphragm walls for high seismicity requires the designer to provide a complete load path to transfer forces between the building and soils. The load transfer must address the soil loads acting on the basement walls and transfer of lateral forces and moments from a building's seismic-force-resisting system to the soils.

Design for Earth Pressures

Lateral seismic forces from the soils will combine with static soil pressures resulting in pressures acting on the diaphragm walls that are higher than pressures from static forces alone. Applicable load combinations from ASCE/SEI 7-10 are load combinations 5 and 7 with a term added for the static earth pressures. These equations are presented Eq. 1 and Eq. 2, above.

For diaphragm wall design, axial compressive stress on the wall is generally low, such that sectional analyses of the wall will be below the balance point on an axial load-moment interaction diagram (Fig. 7). Therefore, Eq. 2 will control over Eq. 1 for most cases. In these load combinations, the seismic soil pressure is considered an earthquake load with a load factor of 1.0.

The load path for the seismic earth pressures is similar to the load path used to design for the static earth pressures. For out-of-plane pressures acting on the wall, the wall spans vertically between floor framing, and the floor slab acts as a horizontal diaphragm to transfer the forces to supporting walls.

Design for Forces from Superstructure SFRS

In cases where the building code requirements stipulate that the basement walls be designed and detailed as special reinforced concrete structural walls to resist forces from the superstructure's seismic-force-resisting system (SFRS), the provisions of ACI 318, Chapter 21 apply. It is these provisions that are not harmonized with typical slurry wall design practice and can lead to constructability problems. Addressing this conflict to facilitate use of slurry walls in regions of high seismicity requires consideration of two general issues:

1. Review of the assumptions made in the structural analysis, specifically with regard to the relationship between the forces calculated from an elastic analysis, the design forces computed assuming inelastic behavior, and the expected strength of the structural members supported on the basement walls.
2. Investigation of the strength of diaphragm walls relative to loads transferred from the superstructure, and the adjustment of typical details to provide the required resistance.

These issues are reviewed in more detail below.

Analysis Considerations

The analysis of building structures for seismic loads is performed based on the assumption that it is acceptable for large earthquakes to cause inelastic behavior of the structural members. This inelastic behavior dissipates the energy imparted by the earthquake ground motions and generated by the structural response. Relying on inelastic behavior results in smaller design forces than required for elastic behavior. Forces are typically reduced by a factor of 3 to 8, depending on the type of SFRS. It is critical that members designed to undergo inelastic deformations be detailed to prevent significant loss of strength that could lead to structural collapse; it is this consideration that drives the detailing requirements of ACI 318, Chapter 21.

Frequently, the substructure components, such as the basement walls, will have significantly greater strength and stiffness than the supported members of the SFRS. (This is more likely to be the case for a building frame system than for a shear wall system.) In these cases, it is reasonable to investigate the strength of the substructure components relative to the maximum forces that might be exerted by the superstructure members, based on the strength of the latter with due consideration of possible overstrength. If the substructure components can be designed to resist the applied forces elastically, it theoretically would not be required to detail those components for significant inelastic behavior. It would be necessary, however, regardless of any requirements for resistance to forces transferred from the superstructure, to examine ductility requirements that might be associated with the earth pressures acting directly on the substructure.

Current building code provisions are not written in such a way as to facilitate this approach of designing for higher forces such that the substructure remains elastic, and use of this approach for typical design situations is not common. The theoretical issues require further investigation and thorough vetting, but the concept offers a means of alleviating some of the problematic detailing requirements. In the meantime, slurry walls should be designed in accordance with current code requirements (i.e., design forces based on inelastic response and detailing per ACI 318, Chapter 21).

Connection of the superstructure members to the basement walls is required to conform to the detailing requirements associated with the superstructure design assumptions. This typically means that the Chapter 21 provisions will apply in the upper portions of the basement walls, at a minimum to such a point as is required to fully develop the reinforcement and distribute forces into the supporting substructure components. As slurry wall systems almost always include a conventionally cast-in-place cap beam, it may be possible to confine the stringent detailing requirements to the cap beam and any portion of the basement wall not placed under slurry.

Detailing Approaches

Regardless of the methods of analysis or assumptions used in determining the design forces, the structural components must be designed to resist those forces. Diaphragm walls are typically quite massive, but the loads generated by large earthquakes are also very significant, even after accounting for inelastic building response. Conventional diaphragm wall design may not be able to adequately resist these loads, primarily because the separately-cast panels do not form a continuous shear wall to resist in-plane forces.

It is generally considered impractical to make horizontal reinforcement continuous across panel joints, and very difficult to splice reinforcement cages within multiple-cage panels. Shear transfer may occur across the joints; however, this transfer cannot be guaranteed or quantified and is typically ignored. This consideration indicates that panels should be designed as independent shear walls, instead of considering an entire wall of multiple panels to act as a single unit. Each panel provides shear resistance based on its dimensions. If the panels acting individually do not provide the required strength, three methods, presented in order of increasing difficulty, may be considered to adjust the typical slurry wall detailing to resist the design forces.

1. In cases in which the in-plane shear forces are relatively small, a cap beam made more robust than typical may sufficiently increase the overall wall stiffness and strength to meet the design requirements. The objective in providing a stiffer cap beam is to prevent rotation and relative vertical displacement of the tops of the panels. In order for this method to be

effective, the cap beam depth would need to be some significant fraction of the panel length, perhaps as much as one-third to one-half.

2. As the design forces become larger, increasing the size of the cap beam alone may not provide the required resistance. In such cases, additional inter-panel restraint may be provided by enlarged perimeter beams on the floor slabs framing into the slurry walls, as shown in Fig. 10. These edge beams would prevent relative vertical shear of adjacent panels at the floor slab elevations, increasing the stiffness and strength of the wall.

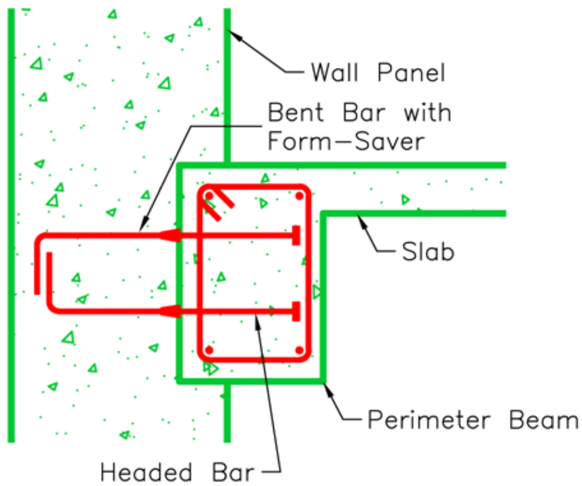

Fig. 10 - Perimeter Beam (cross-section)

3. In the few cases involving very large in-plane forces, it may be necessary to restrain relative vertical shear over the entire exposed height of the panel joints. Pilasters built at blockouts on the exposed panel edges can provide this type of restraint, as illustrated in Fig. 11.

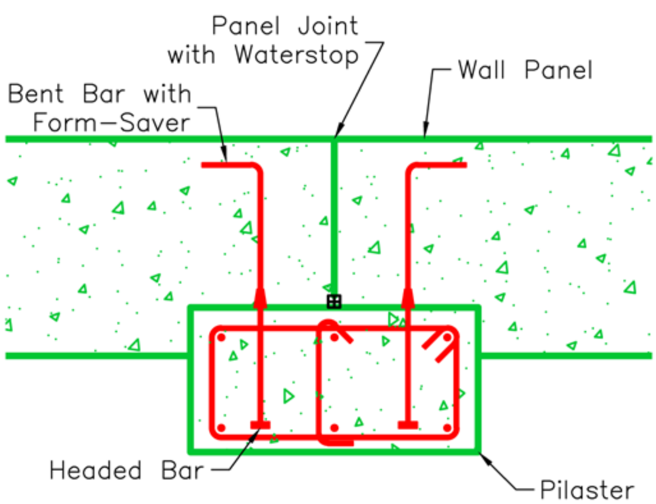

Fig. 11 - Pilaster (plan view)

4. Another alternative for resisting large in-plane forces is to splice the diaphragm wall horizontal bars between panels. This is usually accomplished by means of a box or blockout at the end of the first panel poured that prevents concrete from flowing into the last few feet of the excavated trench; the reinforcing cage of the adjacent panel then overlaps the bars of the first panel, effecting a splice. Several such details are described by Xanthakos (1994) and a recent application is presented by Fantaye, et al. (2014). These types of splices have been used successfully in construction, but are dependent on rigorous quality control.

Additional detailing considerations include boundary elements and panels with multiple reinforcement cages.

Boundary elements are regions of enhanced reinforcement provided at the edges of shear walls (see Fig. 12). These elements must be designed and detailed in the slurry wall panels, and the reinforcement will likely be heavier than typical, particularly with respect to transverse reinforcement (i.e., hoops).

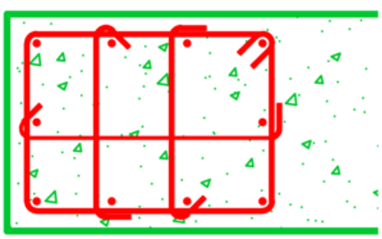

Fig. 12 - Boundary Element (plan view)

The use of multiple reinforcement cages in slurry wall panels does not allow for continuous horizontal reinforcement as required for shear walls in regions of high seismicity. (Continuous horizontal and vertical reinforcement are required; increasing vertical reinforcement alone does not increase resistance to in-plane forces.) It will generally be necessary to build such panels with single cages, requiring heavier cranes and larger laydown areas, and precluding off-site tying of the cages. Alternatively, project-specific investigation of the in-plane flexural and shear stresses may indicate that the demands are relatively low, in which case multiple-cage panels may be acceptable. These constraints and considerations must be understood at an early stage in a project.

Summary & Conclusions

Structural slurry walls have a proven track record of good performance in regions of low to moderate seismicity, and there is little evidence that basement walls in general have experienced significant damage even in large earthquakes. Current building code provisions are somewhat vague with respect to seismic earth pressures and design requirements for below-grade structures, and practice varies widely.

No special concrete detailing is required for SDCs A through C in the current building code. It is therefore recommended that structural slurry walls in SDCs A through C be designed and detailed according to conventional practice for both in-plane and out-of-plane design forces.

In SDC's D through F, structural slurry walls resist large in-plane and out-of-plane forces, include reactions from the superstructure's seismic-force-resisting system. Special concrete detailing requirements apply. However, these requirements can lead to problems with slurry wall constructability. The detailing requirements are driven by the assumption that the elements of the seismic-force-resisting system will yield during large earthquakes. Although it is theoretically possible to design slurry walls to remain elastic while resisting earthquake effects, such an approach is not considered in current building codes.

Resistance to large seismic forces may require providing continuity between slurry wall panels. Several methods consistent with current slurry wall construction practice may provide the required strength and stiffness, including an enlarged cap beam, perimeter beams at the slab edges, and pilasters at the panel joints. Very large seismic forces may require special detailing within the slurry wall panels, including boundary elements and single-cage panels.

From the discussion presented in this report, it is possible to draw several conclusions:

- Current diaphragm wall detailing and construction practice is generally suitable for structures in regions of low to moderate seismicity.
- Understanding of the actual behavior of basements and below-grade structures during earthquakes is somewhat limited, and building code design provisions are non-specific.
- Further development of design procedures to allow for design based on elastic response of substructure elements may present a better way to harmonize diaphragm wall construction practices with design and detailing in regions of high seismicity.
- Relatively minor adjustments to conventional structural slurry wall detailing can be made to create panel continuity, provide strength and stiffness to better resist large seismic forces, and potentially alleviate impractical detailing and reinforcement requirements.

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