Practical Design of Concrete Diaphragm Walls

Jerome S. B. Iffland, Iffland Kavanagh Waterbury, New York City

Diaphragm walls constructed by the slurry trench method achieve their greatest economy when it is possible to use them as part of the permanent underground structure. To use these support-of-excavation structures as permanent components of a structure, engineers must be assured of their compatibility with structures built in an open excavation. There should be consistent reliability in applied loads, levels of stress, watertightness, durability, and performance. It is suggested that the use of diaphragm walls of precast concrete panels can provide reliable strength and durability and that use of a cement bentonite grout on the backside of the diaphragm wall to displace excess slurry can meet waterproofing requirements. It is recommended that plastic analysis be combined with ultimate strength methods in the design of these walls to resolve the problem presented by the complicated residual stress patterns generated in the diaphragm wall by the construction processes of excavation; installation, prestressing, and removal of braces; and backfilling. In addition, use of a built-in hinge in the diaphragm wall at the lowest brace facilitates control of residual moments. This approach can satisfy the need for reliability in stress levels in the structure. A structure so designed and constructed will be compatible with one built in an open excavation.

A large share of both the theoretical and the experimental research currently available on the subject of diaphragm walls constructed by the slurry trench method is associated with construction methods and problems, trench stability, design of slurry, ground movements and loss of adjacent ground, and the design of these walls as temporary support-of-excavation structures. Little attention has been paid to the problems of the structural engineer when diaphragm walls are incorporated in a permanent underground structure. When these temporary support-of-excavation structures are to be permanent, the engineer is concerned with designing these walls for consistent loads, stress levels, watertightness, and durability and overall structural compatibility with the rest of the permanent structure. Criteria for the performance of temporary structures are generally not satisfactory for the performance of permanent structures.

This paper discusses some of the problems that arise when diaphragm walls are incorporated in permanent underground structures and suggests design approaches and construction details to resolve these problems. Included is a discussion of soil-structure interaction, soil properties, temporary and permanent loading conditions, effects of construction excavation and bracing procedures and techniques, the advantages of precast concrete walls over cast-in-place concrete walls, methods of establishing continuity between the diaphragm wall and the remaining portions of the permanent structure, concrete durability and quality, and watertightness. Based on the discussion and the conclusions drawn, a design synthesis for incorporation of diaphragm walls in permanent underground structures is recommended. The design philosophy is presented from the point of view of the structural engineer rather than from that of the geotechnical engineer.

NOTATION

The following symbols are used in this paper:

- c = cohesion intercept,
- K_o = coefficent of at-rest lateral earth pressure,
- ϕ = internal angle of friction,
- γ = unit weight of soil,
- H = height (depth) of excavation,
- N = standard penetration resistance,
- K_A = coefficient of active earth pressure,
- d = depth to water table,
- S_u = undrained shear strength,
- q = surcharge load, and
- K = modulus of subgrade reaction (spring constant).

ASSESSMENT OF DESIGN PROBLEMS AND ASSUMPTIONS

A number of problems must be resolved by the structural engineer in designing permanent diaphragm walls. Perhaps the fundamental problem is the fact that the stresses within the wall are continually changing during the construction process. These stresses are subject to the vagaries of both the excavation and bracing techniques used and the removal of bracing and the backfilling process. Typical movement of a braced wall installation during excavation and the resulting stresses are shown in Figure 1. Similar movements (and stresses) occur during removal of bracing and backfilling. The problem is further complicated by the fact that the designer has almost no control over these procedures. For consistent performance of structures that do not incorporate temporary components in the permanent structure, the residual stresses that arise from the construction process must be considered in the analysis.

Another major problem is the quality of the construction. Although slurry walls are acceptable in many cases, they have been known to have extremely rough and out-of-alignment surfaces as well as large sand pockets, understrength concrete, or other structural defects. Once they are built, corrective measures are not practical. The structural engineer must consider the real possibility of such defects in a design. Other problems arise—i.e., waterproofing the diaphragm wall and connecting it to the remainder of the structure to be built within the excavation. Assumptions, design procedures, and construction techniques to be used in resolving these problems are considered.

Soil-Structure Interaction

Before an assessment of soil properties or earth pressures can be made, a decision on the use of a mathematical model of soil-structure interaction to implement the basic design approach must be made. Use of such a model will affect the type of soil information needed and assumptions concerning earth pressure loading.

The state of the art of mathematical modeling of the mechanical behavior of soil masses is sufficiently advanced to give serious consideration to the use of such a soil-structure interaction model for solution of the problem of designing diaphragm walls. The complexity of the problem and the availability of finite element techniques and computer technology suggest such an approach. Wong (14) has developed one such solution by using finite element techniques. The capabilities of this solution have been extended by Jaworski (10) and also by Clough and Tsui (2). The solution must incorporate a soil constitutive model. Developing constitutive equations to represent the mechanical properties of the soil mass is the main problem in soil-structure interaction solutions. Considerable attention was devoted to the subject during the Second International Conference on Numerical Methods in Geomechanics held at the Virginia Polytechnic Institute and State University (3). Additional valuable information on the subject has been made available in an American Society for Testing and Materials (ASTM) symposium on concrete pipe and the soil-structure system (1) and by Gudehus (7).

Currently, the following deficiencies can exist in such solutions:

1. Our ability to furnish appropriate material properties and boundary conditions of the soil mass is limited compared with our ability to formulate mathematical models and solve theoretical problems.
2. Existing solutions can be unrealistically sensitive to changes in the physical parameters that define the problem.
3. Existing solutions can be plagued by gross inaccuracies because of the truncation of matrixes and round-off errors.
4. Existing solutions have given reasonable results for the distribution of earth pressure behind diaphragm walls but poor results for displacements and the corresponding stresses they produce.

It is concluded, therefore, that, although they are a powerful tool, finite element solutions are not yet practical for solving design problems of this type. Soils are extremely complicated materials, and their mechanical behavior is governed by very complex factors. Sophisticated solutions that incorporate finite element methods may not be more realistic than solutions obtained by using good engineering judgment. The results could also be grossly in error and misleading.

Soil Properties

Soil mechanics has been aptly described as an art rather than a science. This definition is inherent in the nature of soil. It is usually a heterogeneous material, sometimes artificially deposited, subjected to varying degrees of consolidation, surcharge loads, and pore-water pressure, and all of these conditions are subject to considerable variation from one point in the ground to another. Even the best available methods for determining the parameters that define soil properties give results that might vary 100 percent from actual conditions. When the variations of properties from point to point are considered, assessment of average soil properties for design purposes becomes an art and not a science. The soil mechanics engineer rightfully uses science and all the modern means of testing and analysis in evaluation. However, these results must be judiciously applied in view of the overall nature of the complex heterogeneous soil mass. The nature of the problem suggests avoiding complexity and using simple assumptions.

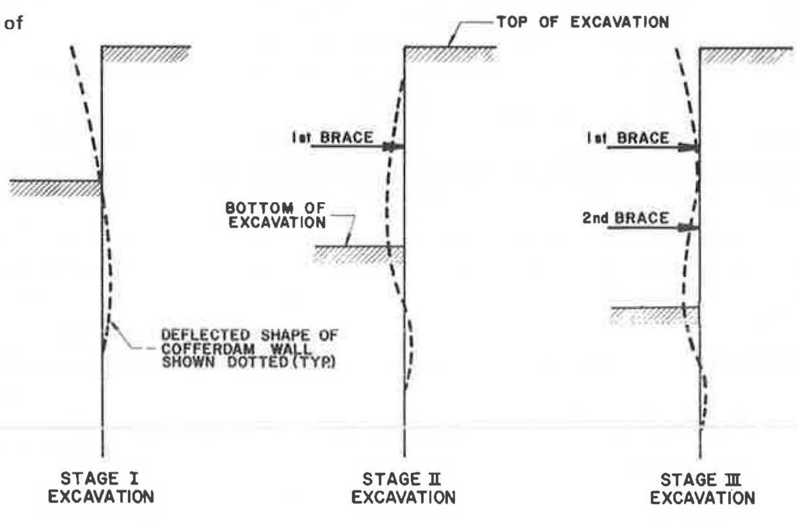
It is suggested that the assumptions used for soil properties by Wickham and Tiedemann (13) generally be used in designing diaphragm walls. They used an average angle of internal friction ϕ and zero for the soil cohesion c. Most soils encountered will have some cohesion, but use of an equivalent ϕ—even if $c = 0$ for clays—is proposed as a conservative assumption in many cases. Soil loading conditions as well as the unit soil weight γ, undrained shear strength S_u, standard penetration resistance N, and the knowledge of surcharges and the existence and levels of groundwater are to be determined from these parameters. Even if a value of c is used, the number of parameters that define the soil properties is relatively small and can be obtained from reasonably reliable and simple testing procedures.

Loading Conditions

Assumptions for earth pressure and its distribution should be consistent with those used for the parameters that define the soil properties. Field measurements of earth pressure behind braced retaining structures show considerable variation. Actual performance cannot be correlated with sophisticated assumptions, and there is little justification for their use. Earth pressure and its variation are materially affected by the method of excavation, the sequence of construction, and the installation and the possible prestressing of bracing. The engineer does not have control over or even postdesign knowledge of many of these factors.

Therefore, as in the case of soil parameters that define the properties of the soil, simplifying assumptions are warranted in establishing design earth pressures on diaphragm walls. Goldberg, Jaworski, and Gordon (5) have made a comprehensive study of earth

Figure 1. Typical movement of braced walls during stages of excavation.



pressures on lateral support systems. Their recommendations are shown in Figure 2, where they have taken the first three cases from Terzaghi and Peck (12). These pressure diagrams were developed from empirical data for flexible walls. Goldberg, Jaworski, and Gordon (5) have shown that higher pressures develop behind stiffer diaphragm walls. However, this was a theoretical study and, at the present time, some (6), but not sufficient, empirical data are available for pressures behind braced diaphragm walls to justify any significant change from the pressure diagrams shown in Figure 2. For practical purposes, the temporary earth pressure to be used in design can be taken as a constant uniform load, as shown in Figure 3. The hydrostatic water pressure and any surcharge loads must be added to this. Prestressing of the braces is recommended as a mandatory requirement for stability considerations.

Figure 2. Design diagrams of earth pressure for internally braced, flexible walls (hydrostatic pressure not shown).

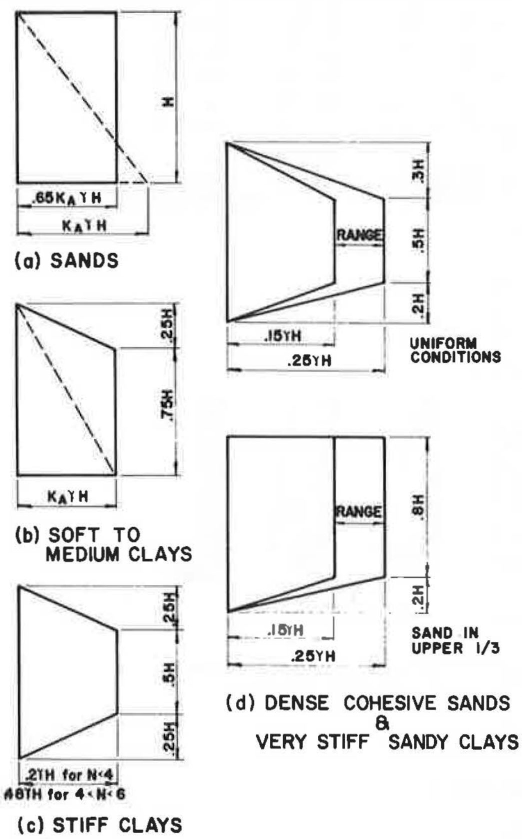


Figure 3 defines the recommended loading conditions on a braced diaphragm wall. Once the wall is incorporated into the permanent structure, earth pressures change with time. For buried structures, at-rest pressures are recommended (6). There is also always the distinct possibility of unbalanced asymmetrical earth pressures on the adjacent sides of an underground structure since these pressures do not necessarily develop equally. The unbalanced load is taken by friction along the bottom of the structure. One-half at-rest pressures acting on one side, without consideration of the temporary bracing loading conditions, and full at-rest pressure action on the other side are recommended. Any change in water levels during and after construction must also be considered.

These loading conditions on the permanent structure are shown in Figure 4. Figure 4 shows that the diaphragm wall must be designed for the loads shown in Figure 3 plus the increment of at-rest pressure that results from incorporation of the wall into the permanent structure. The loads on the remainder of the permanent structure and its interaction with the diaphragm wall will also cause additional stresses in the diaphragm wall. Some continuity at the junctures must be provided, or the permanent structure will be unstable.

Additional loads on the permanent structure are the roof loads and the base reaction. To accommodate both external and internal continuity conditions, some sort of soil-structure interaction at the base is required. A finite number of individual springs that corresponds to the number of discrete elements used in the structural analysis is used. The soil modulus or stiffness of these springs is varied to obtain an overall pressure pattern consistent with observed behavior. An example of this approach is shown in Figure 5 for a station design in the Washington, D.C., subway system. The shape of the pressure diagram was established from principles of soil mechanics. The subgrade modulus was varied as shown in the figure to obtain the shapes desired.

This approach is used in Figure 6 to show the loading on the diaphragm wall before backfilling operations.

Figure 3. Loading conditions for braced wall.

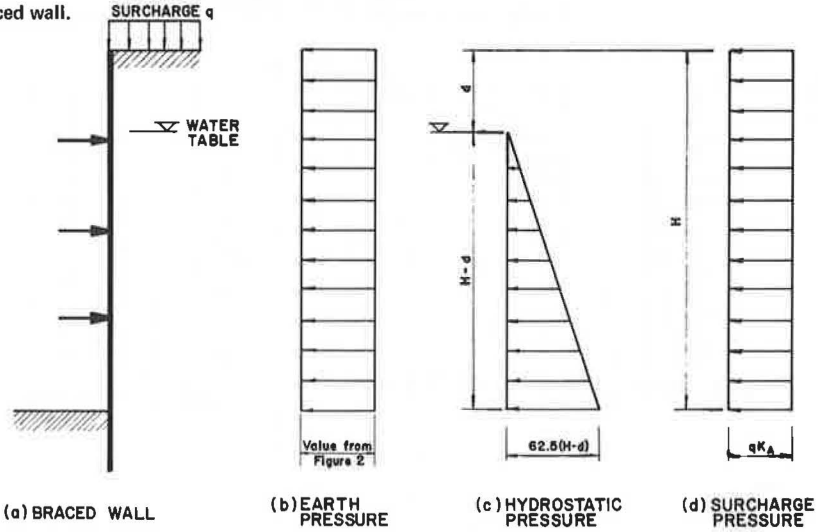


Figure 4. Loading conditions on permanent structure.

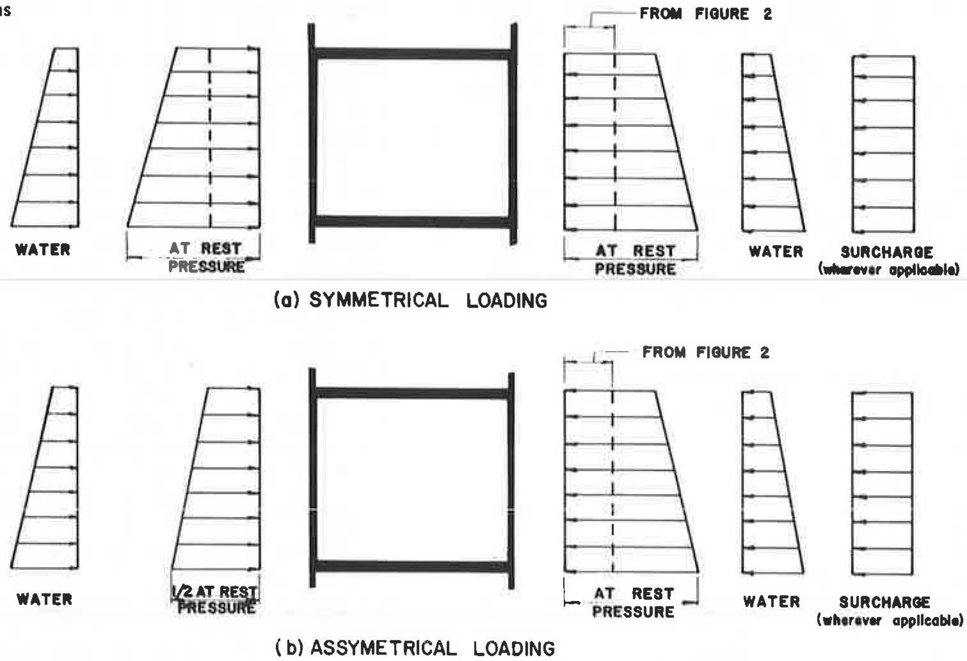


Figure 5. Station arch in Washington, D.C., subway system: long-term design loads.

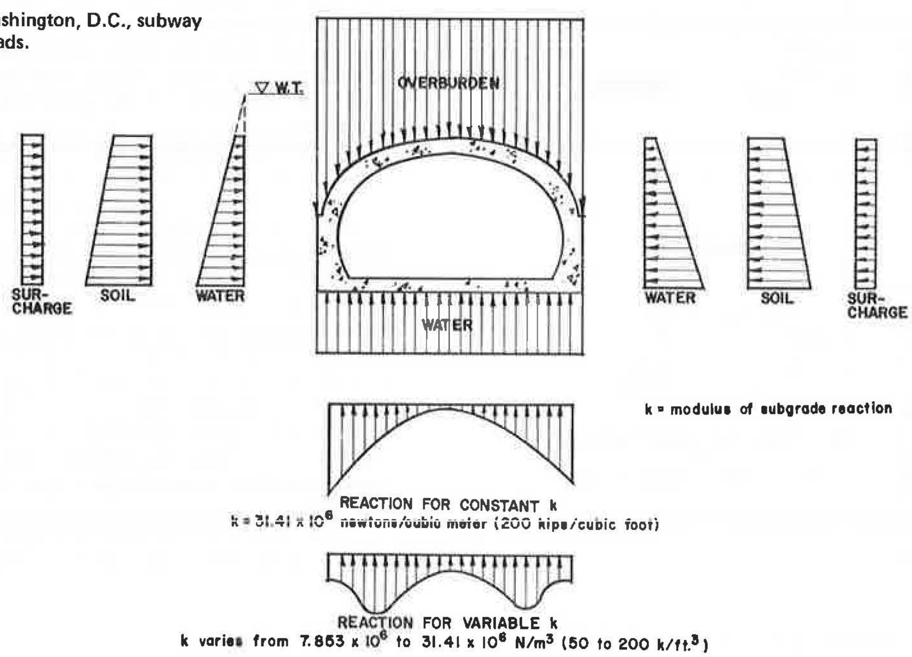
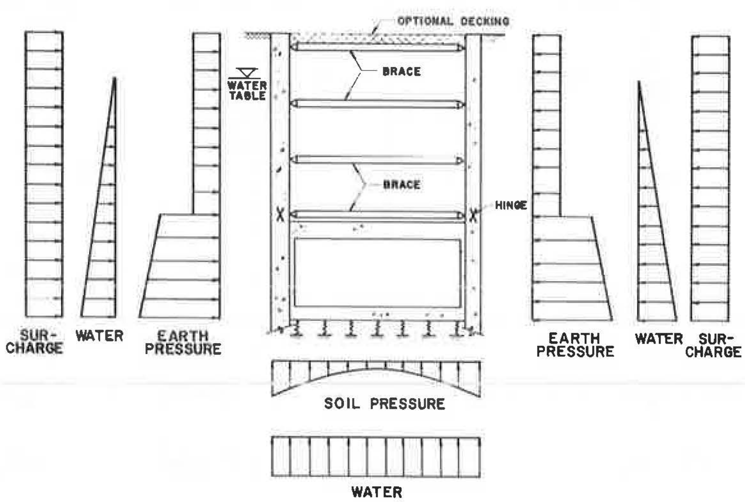


Figure 6. Diaphragm-wall loading condition before backfilling operations.



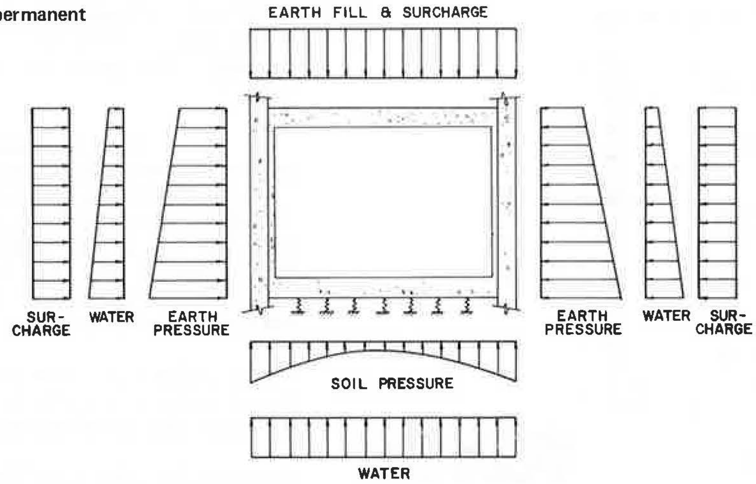


Figure 7. Final loading condition for permanent structure.

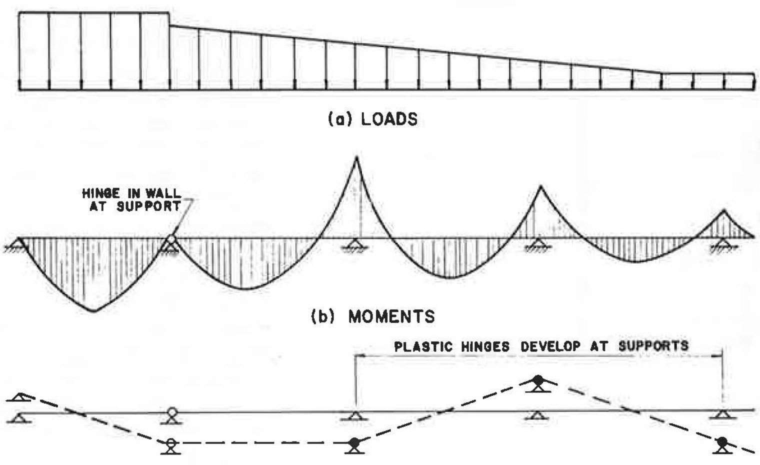


Figure 8. Effect of support movement in plastic analysis.

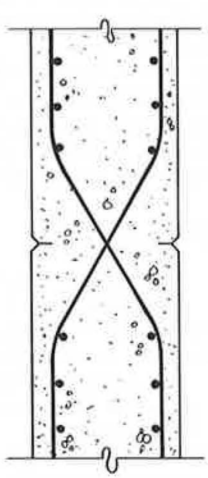


Figure 9. Detail of full hinge.

Note that the surcharge on each side of the structure can be different. Another loading condition, which is not shown, would be the asymmetrical earth-loading condition previously discussed. Active earth pressures could be used at this stage of the loading. However, because the lower portion of the diaphragm wall will eventually be subjected to at-rest pressures, these pressures are used in the design since it is questionable how long it takes for them to develop.

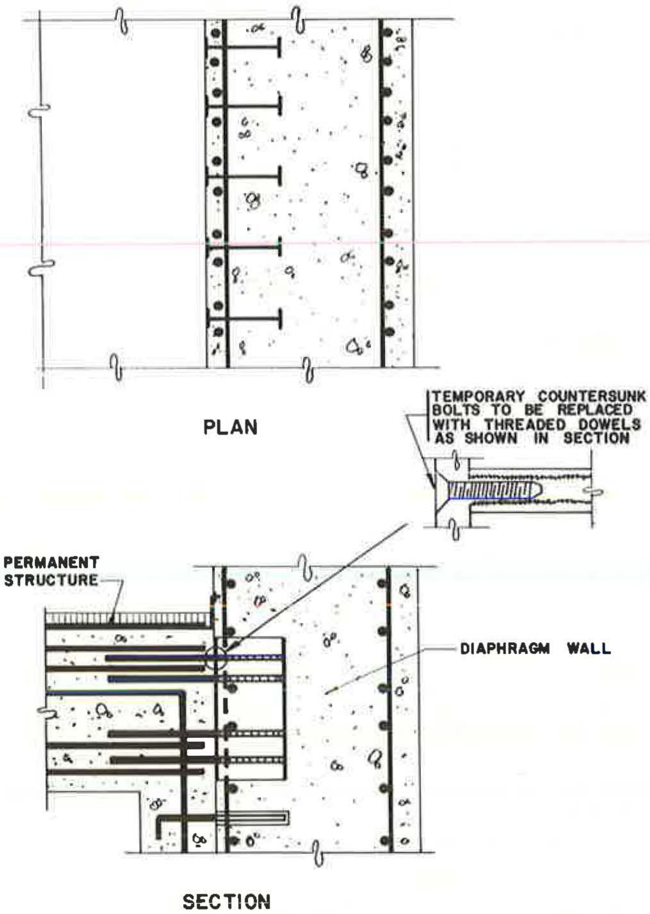
Finally, backfilling and removal of the bracing take place, and the final loading condition is shown in Figure 7. The asymmetrical condition and any water table changes related to the construction process or future conditions must also be investigated.

Plastic Analysis

What has been neglected so far in the synthesis of the problem is the movements and stresses that take place in the diaphragm wall as braces are prestressed, unstressed, relocated, wedged, adjusted, loosened, and finally removed. It is also one of the reasons for introduction of hinges in the diaphragm walls at the lower brace indicated in Figure 6.

The designer has only nominal control over the movements and the associated stresses that take place during the installation and removal of braces. The spacing can be specified, and other criteria, such as the amount of prestressing in the cross braces, can be prescribed. Traditionally, however, their design and installation are the prerogative of the contractor. Even if a rigidly specified procedure is mandated, field conditions usually develop in such a way as to invalidate conformity. To overcome this difficulty, plastic analysis of the bracing system is advocated. This

Figure 10. Detail of continuity requirements.



method of analysis offers the following advantages over an elastic analysis (11):

1. In-and-out movement of one or more of the supports before loading does not affect the collapse load.
2. In-and-out movement of one or more of the supports during or after loading does not affect the collapse load.
3. The presence of initial residual stresses has no influence on the collapse load.
4. The collapse load is independent of the previous history of loading.

For these reasons, the use of plastic analysis eliminates the problems introduced by support movement, whatever the cause. This principle is shown in Figure 8.

Plastic analysis and design are not currently accepted by U.S. codes and specifications. However, this approach is now under study for braced structures that include the diaphragm wall. Plastic analysis and design are currently acceptable in many European standards including those of the British Standards Institute (8). Furlong (4) presents a plastic design methodology based on limit design concepts for reinforced concrete that can be used in proportioning the diaphragm wall. The method uses limit values for coefficients of maximum moments in simple beams and is compatible with concrete design in the United States. The detailed procedure suggested by Furlong is not repeated here.

Although the diaphragm wall is designed so that plastic hinges can form at all points of support by the braces, it is suggested that an actual full hinge be detailed in the diaphragm walls at points of support of the lowest brace. This hinge is designed to transmit zero moment. The purpose of this full-hinge design is twofold:

1. It will prevent transmittal of wall diaphragm moments into the permanent structure.
2. It facilitates disconnecting the diaphragm wall, which is not part of the permanent structure, from the permanent structure before backfilling. This permits the diaphragm wall to be (a) left in place after it is disconnected or (b) removed without any effect on the permanent structure.

The use of a precast concrete diaphragm wall, which is discussed below, facilitates detailing these full hinges. A method that provides this hinge is shown in Figure 9.

Concrete Durability and Quality

The problem of concrete durability and quality, including geometrical alignment, can be solved by using precast concrete diaphragm walls. Precast concrete segments placed in a slurry trench to construct a diaphragm-wall system have been used successfully in the past (9, 13). The precast concrete diaphragm wall can vary in size and configuration. It includes tongue-and-groove continuous panels or T-beam and panel combinations. Some of the systems are patented. The procedure of wall excavation is similar to that for the cast-in-place slurry wall system. The grout slurry is an important component of the system since the precast concrete units do not completely fill the trench as do cast-in-place slurry walls. The setting of the grout, which is equal in strength to the surrounding soil, ensures elimination of voids and filling of all irregularities in the trench, thus stabilizing the position of the precast concrete units and also minimizing potential settlement of the adjacent soil.

Besides being assured of satisfactory and acceptable concrete quality and wall alignment, the use of a precast concrete diaphragm wall permits accurate installation of dowels, keys, recesses, bearing plates, and other details for the required continuity connections to the permanent structure built within the excavation. The full-hinge detail suggested in the previous section can also be satisfactorily detailed. The various aspects of precast concrete diaphragm walls are discussed in detail by Wickham and Tiedemann (13). Several applications have been reported in detail (9).

Watertightness

Use of a precast concrete diaphragm wall also facilitates the problem of obtaining a watertight wall. Bentonite waterproofing systems have proved to be effective if properly installed. In the precast concrete diaphragm wall system, the bentonite slurry used during excavation of the trench and remaining on both sides of the panels after the panels have been installed can be displaced and replaced by a combination portland cement-bentonite grout that eventually sets up to solidify the excavation. This grout can be satisfactorily designed to provide the appropriate watertightness on the rear face where any thickness can be prescribed. The grout on the front face is held to a minimum and can be subsequently removed if the precast concrete panels are pretreated with an appropriate bond breaker. Patented grouts are available for this use. Other acceptable formulations can also be derived if desired.

Continuity Requirements

As stated before, the diaphragm wall must be made to act continuously with the cast-in-place remainder of the permanent underground structure. Full continuity is neither needed nor necessarily desired. Use of precast concrete panels for the diaphragm wall also facilitates providing for these continuity details. One such detail is shown in Figure 10. The pertinent features of this detail are the following:

1. Use of an embedded wide-flange structural steel section permits maximum bond development and distribution of stress concentrations with the reinforced concrete. It also permits a flush surface that does not interfere with forming or with subsequent erection.
2. The embedded steel units can be staggered between vertical reinforcing steel. This facilitates fabrication of the precast panel.
3. The flush steel surface permits alternate welded connection details if the threaded inserts for the horizontal dowel connections shown are not desired.
4. Flexible flashing is continuously attached to the continuous steel T-insert in the diaphragm wall and lapped with membrane waterproofing on the roof to provide a watertight joint.

A similar detail is required at the concrete-box base slab where the degree of continuity will be much more than that required at the concrete-box roof slab. Development of full continuity at both points is possible if desired.

SUMMARY OF DESIGN SYNTHESIS

Based on the foregoing reasoning and related discussion, the suggested design synthesis for diaphragm walls to be incorporated into permanent underground structures may be summarized as follows:

1. Do not use an overall soil-structure model for design.
2. Determine average soil properties from basic soil parameters obtained from simple tests.
3. Use a constant, uniform design earth pressure loading on the braced diaphragm wall before the construction of the permanent underground structure. Add hydrostatic and surcharge loads when they are applicable.
4. Use plastic analysis and design for proportioning the diaphragm wall. Design the wall with a full hinge detailed at the lowest brace just above the permanent underground structure. Provide embedded flush inserts for future partial continuity connections and waterproofing details to the permanent underground structure.
5. Specify construction of the diaphragm wall by use of precast concrete panels and the like in a slurry-constructed trench in which excess slurry is displaced by a cement-bentonite grout for waterproofing requirements. Specify prestressing of the braces of the diaphragm walls.
6. After construction of the permanent underground structure, design this structure for the added increment of at-rest earth pressures by considering both the symmetrical and the asymmetrical cases. In this analysis, consider the structure to be supported on individual springs of varying magnitudes as required to simulate desired soil-bearing pressure distributions.
7. Specify construction of the required continuity connection and waterproofing details between the diaphragm wall and the permanent underground structure. Specify full separation of the diaphragm walls at the point of the full hinge before backfilling and removal of bracing.
8. Design the permanent underground structure for the additional backfill and overlying surcharge loads. Consider both symmetrical and asymmetrical cases, groundwater variations, and surcharges where applicable. Consider the structure supported on individual springs to simulate desired bearing pressure.

Under proper conditions—usually adjacent to heavy structures that would otherwise require substantial underpinning—braced diaphragm walls incorporated into the permanent structure can provide an economical solution for underground construction.

REFERENCES

1. M. Bealey and J. D. Lemons, eds. Concrete Pipe and the Soil-Structure System. Symposium presented at 79th Annual Meeting, ASTM, Chicago, June 27-July 2, 1976, ASTM Technical Publ. 630, Sept. 1977, 136 pp.
2. G. S. Clough and Y. Tsui. Performance of Tied-Back Walls in Clay. Journal of Geotechnical Engineering Division, Proc., ASCE, Vol. 100, No. GT 12, Paper 11028, Dec. 1974, pp. 1259-1273.
3. C. D. Desai, ed. Numerical Methods in Geomechanics. ASCE, New York, Vols. 1, 2, and 3, June 1976.
4. R. W. Furlong. Plastic Design for Reinforced Concrete Frames. ASCE National Structural Engineering Meeting, Cincinnati, Meeting Preprint 2214, April 22-26, 1974, 13 pp.
5. D. T. Goldberg, W. E. Jaworski, and M. D. Gordon. Lateral Support Systems and Underpinning: Volume 2—Design Fundamentals. Offices of Research and Development, Federal Highway Administration, Rept. FHWA-RD-76-129, April 1976; NTIS, Springfield, VA, PB 257 211.
6. J. P. Gould. Lateral Pressures on Rigid Permanent Structures. Specialty Conference on Lateral Stresses in Ground and Design of Earth Retaining Structures, Soil Mechanics and Foundations Division, ASCE, June 22-24, 1970, pp. 219-269.
7. H. Gudehus, ed. Finite Elements in Geomechanics. Wiley, New York, 1977, 573 pp.
8. B. P. Hughes. Limit State Theory for Reinforced Concrete Design. Van Nostrand, New York, 2nd Ed., 1976, 697 pp.
9. Diaphragm Walls and Anchorages. Proc., Institute of Civil Engineers Conference, London, Sept. 18-20, 1974, 223 pp.
10. W. E. Jaworski. An Evaluation of the Performance of a Braced Excavation. MIT, Cambridge, June 1973.
11. B. G. Neal. The Plastic Methods of Structural Analysis. Chapman and Hall, London, 1965, 358 pp.
12. K. Terzaghi and R. B. Peck. Soil Mechanics in Engineering Practice. Wiley, New York, 1968.
13. G. E. Wickham and H. R. Tiedemann. Cut-and-Cover Tunneling: Volume 1—Construction Methods, Design, and Activity Variations. Offices of Research and Development, Federal Highway Administration, Rept. FHWA-RD-76-28, May 1976; NTIS, Springfield, VA, PB 257 014.
14. I. H. Wong. Analysis of Braced Excavations. MIT, Cambridge, ScD thesis, 1971.