SOME ASPECTS OF THE CONSTRUCTION SPECIFICATIONS OF THE DIAPHRAGM WALL

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INTRODUCTION

The technique of constructing a concrete diaphragm wall using the slurry trench method has been successfully adopted in many construction projects around the world. Unlike other types of underground construction project, the entire structural body is cast in slurry, where the quality and integrity of the structural element can not be visually inspected until completion and exposure. Eventually, if there is any defect, it will be extremely difficult, or even impossible, to repair or reinforce. It is, therefore, important to have more thorough construction specifications to improve the quality of construction and to ensure the structural integrity and reliability of the diaphragm wall system.

The specifications recommended by FPS (1973) presented a fairly complete view of diaphragm wall design and construction. Millet & Perez (1981) provide further critical views on the tolerance of excavation and concrete placement. From the construction point of view, the objectives of diaphragm wall specifications should give a clear guide line on the following aspects.

1. Excavation tolerance
2. Assembly and placement of steel reinforcement cage
3. Tremie concrete process
4. Control of slurry and stability of trench

In the following paragraphes, the implementation of these basic aspects will be examined.

TRENCH EXCAVATION

The minimum plumbness is often specified for the trench excavation, and the maximum tolerance of width and depth are sometimes indicated. Table 1 lists the normal practices in Japan and Taiwan. Recommendations given by FPS (1973) and Millet and Perez (1981) are also included. In most of these cases, the plumbness of the trench is dependent on structural or architectural considerations. When the diaphragm wall is selected only for the retaining of excavation, 1/80 to 1/100 will be satisfactory. However, more strict specifications may be required, i.e. less than 1/300 when the wall is utilized as a permanent structural wall.

TABLE 1 SPECIFICATIONS FOR TRENCH EXCAVATION

SOURCE	RECOMMENDATION/PRACTICE
FPS	(1) Plumbness shall be within 1/80. (2) 100 mm tolerance shall be allowed for wall surface irregularities. (3) Clear distance between the faces of the guidwall shall be the specified diaphragm wall thickness plus 25 mm to 50 mm. (4) Top of the guide wall should, preferably, be not less than 1.5 m above ground water level.
Millet & Perez	Plumbness shall be from 1/80 to 1/100.
Japan	(1) Plumbness is normally less than 1/100 to 1/200. (2) Guide wall is usually 1 to 1.2 m deep and up to 1.5 m deep when necessary. (3) Clearance between guide wall shall be the specified wall width plus 50 mm. (4) Top of guide wall is not less than 1.0 m above ground water level. (5) Ultra sonic devices are often ultilized to examine the plumbness of the trench after excavation.
Taiwan	(1) For permanent wall, plumbness shall be within 1/300, otherwise 1/100. (2) Minimum depth of guide wall shall be 1.5 m. (3) Clearance between guide wall shall be the specified wall width plus 50 mm. (4) Ultra sonic devices are used to monitor trench width and plumbness. (5) Stabilization fluid in the trench shall be maintained at a level at least 1.0 m above the standing ground water table.

There have been many excavation machines developed in recent years with built-in inclinometers and self-adjustable devices to facilitate a more accurate control during the trench excavation. The MHL, BW systems, for examples, can provide a verticality as accurate as 1/300. Some systems operated by Kelly bar may also provide same degree of verticalit;y. After the excavation, it is also common in Japan and Taiwan to use ultra sonic devices for the determination of effective width and verticality of the trench. Any remedy work can be performed immediately after any inaccuracies are discovered.

PLACEMENT OF STEEL REINFORCEMENT CAGE

The specifications recommendated by FPS stress that the techniques used for welding the steel cage should be such that the full strength of the structural reinforcement is maintained. It is important to emphasize in the specifications that the integrity and plumbness of the steel cage must be maintained during lifting and placement. In Japan and Taiwan, it has become a common practice to utilize a concrete platform for steel cage assembly work in order to ensure its plumbness. Nevertheless, as recommended by Millet & Perez, it is of equal important that spacers by installed on the external reforcement bars of the reinforcing cage in order to guarantee proper placement of the steel cage. When the steel cage is to be installed in soft clay stratum, a minimum width of 150 mm may be considered to give a better performance. In general, the minimum coverage of the main bars is 75 mm.

It is important to remember that the diaphragm wall is cast panel by panel. Thus, the bentonite slurry is likely to accumulate in the joints of the previously completed panel which will lead to structural discontinuity and water leakage of wall. And, the specifications should clearly spell out the importance of cleaning the joints with a steel brush prior to placement of the steel cage. In Taiwan, where a joint must stand more than 72 hours before next panel is cast. Crushed stone is placed in the trench at this particular joint to prevent the adhesion and hardening of the bentonite slurry.

During the assembly of the steel cage, the clear spacing between the main bars should be large enough so that tremie concrete can flow through without difficulty. The minimum spacing of 100 mm as recommended by FPS appears to be satisfactory.

TREMIE CONCRETE PROCESS

The potential for contamination of concrete is extremely high when the diaphragm wall is cast in slurry by the tremie process. Strength reduction factors of 0.8 to 0.9 are often applied in the design. However, it is a normal practice to specify the minimum cement content as well as the water-cement ratio of the concrete to further ensure its quality. Minimum cement content of 390 to 400 kg/m^3 and 0.5 to 0.6 water-content ratio are commonly used. Table 2 summarizes the recommendations of FPS and the practice in Japan and Taiwan on the specifications concrete process.

It is important to maintain continuous casting of the concrete and to ensure sufficient embeddment of tremie pipes in the concrete so as not to creat horizontal joints and/or clay seams in the wall panel. The embeddment of the tremie pipe should be at least one to two meters deep. If it is essential to provide up and down motion of the tremie pipe, it is advisable for the embeddment to be not less than 2 meters. Millet & Perez have suggested that one tremie pipe should be used per 4.6 m width of panel. Yet, it is common in Taiwan to specify two tremie pipes for casting each panel longer than 4 m to maintain equal leveling of the concrete surface. The slump is often specified between 170 mm to 200 mm to avoid segregation of concrete and to ensure an adequate flow of concrete in the tremie process.

CONTROL OF SLURRY

In respect to the stability of trench excavation and contamination of concrete, it is extremely important that the quality of bentonite slurry be controlled throughout the entire construction period of the diaphragm wall. The procedures, recommended by American Petroleum Institute (API) for the determination of bentonite qualities have been

TABLE 2 TREMIE CONCRETE PROCESS

SOURCE	RECOMMENDATION/PRACTICE
FPS	(1) Minimum cement content of 400 kg/m^3. (2) Water cement ratio shall not exceed 0.60. (3) Minimum slump shall be 150 mm. The desirable range is from 175mm to 200mm. (4) Aggregates must not be heated to more than 38°C. (5) Concrete, when being placed, msut have a minimum temperature of 5°C. (6) Concrete shall be placed continuously by one or more tremie pipes. (7) Sufficient embeddment of the tremie pipe in concrete shall be maintained. (8) 4 test cubes are suggested to be taken for every panel.
Millet & Perez	(1) The tremie pipe should be embedded at least 1.5 meters in the concrete. (2) One tremie pipe per 4.6 meters of panel is recommended. (3) Slump is in the range of 180 mm to 230 mm. (4) Sufficient volume of concrete should be on hand to ensure continuous casting without interruption. (5) Normal American Concrete Institute Specifications are followed upon specifying the required strength of the concrete.
Japan	(1) Concrete specifications generally follow JASS5 and JISA5308 standards. (2) Slump is in the range of 180mm $\pm$ 20mm. (3) Water-cement ratio is no less than 0.42. (4) Minimum cement content of 390 kg/m^3 is often specified. (5) Minimum 28 days compression strength of 280 kg/cm^2 is commonly specified for the concrete tremied in slurry. (6) The embeddment of tremie pipe in the concrete is 2.0 m
Taiwan	(1) The quality of premixed concrete is according to CNS 3090 standards. (2) The water-cement ratio is 0.48 to 0.52. (3) Slump is in the range of 170 mm to 200 mm. (4) The minimum compression strength of the concrete for 7 days and 28 days should be 170 kg/cm^2 and 245 kg/cm^2 respectively. (5) Maximum size of the coarse aggregate is 20 mm. (6) The minimum embeddment of tremie pipe in the concrete should not be less than 1.0 m.

widely accepted in the diaphragm walling industries. The bentonite slurry specifications are quite complete as many modifications have been made to suit individual site conditions. The main items specified are as followings:

(1) Specific gravity and viscosity - if improperly controlled the trench stability and concrete quality may be affected.
(2) PH value - if it exceeds or fails to meet recommended specification, a resulting flucculence and settling of bentonite slurry may occur.
(3) Filtration loss and filter cake - may indicate instability of slurry and may possibly reduce the effective width of the concrete wall.

The specific gravity is generally specified to be between 1.02 and 1.20 in most slurry wall construction to provide minimum density for trenching stability, while not impeding tremie concrete procedures.

At the construction site, it is easily to determine the viscosity of bentonite slurry with a simple marsh funnel. As described by Millet & Perez, viscosity is a measure of the ability of a fluid to resist shearing, which in turn reflects the ability of the slurry to maintain the stability of the trench. Therefore, the viscosity value should be varies according to subsoil conditions. In Taiwan, the 23 to 30 marsh seconds is appropriate for slurry wall construction in sandy soil and 19 to 25 seconds in clay soil. Table gives the items of the control tests and range recommended by FPS and Millet & Perez. The practives in Japan and Taiwan are also summarized in Table 3. Due to the sedimantation of the soil practicles, the sand content of the bentonite slurry will also vary with the time of sampling after trench excavation. Figure 1 illustrates the variation of sand content with depth in the slurry trench. It should be noted that the viscosity of the bentonite slurry will be varies in the different locations and depths from the trench for the determination of its viscosity and specific gravity. Table 4 presents a series of test records on the samples of slurry taken at different depths in the trench, the variations of the slurry properties have been shown.

TABLE 3 CONTROL OF BENTONITE SLURRY

SOURCE	RECOMMENDATION/PRACTICE
FPS	(1) Bentonite material shall be in accordance with specification No. OFCP 4 of the Oil Companies Materials Associateion, Longon. (2) Bentonite powder shall be mixed with clean fresh water. (3) Control tests shall include the following tests: a. Density: less than 1.10 g/ml b. Viscosity: 33 to 75 seconds c. Shear strength: 1.4 to 10 N/m^2 (10 min gel strength) d. PH value: 9.5 to 12
Millet & Perez	(1) Minimum density has to be set slightly over that of ground water. (2) Maximum unit weight shall be on the order of 1.04 g/ml to 1.20 g/ml. (3) Sand content shall not exceed 5%. (4) Normal range of filter loss as determined by a standard filter press test (API) is from 15 to 30 cm^3. (5) The desirable range for PH is from 6.5 to 10. (6) The slurry in the trench shall be kept at a minimum 1.0 m to 1.5 m above the maximum ground water level.
Japan	(1) Specific gravity is in the range of 1.02 to 1.15. (2) Viscosity shall be in the range of 20 to 50. (3) PH value shall be 7 to 10. (4) Sand content shall not exceed 5% prior to concreting. (5) Filtration loss is within 20 cm^3
Taiwan	(1) Bentonite shall be mixed with fresh water. (2) While the slurry is poured into the trench, the drop down of bentonite slurry level shall not exceed 20 cm in six hours.
Taiwan	(3) Specific gravity shall be 1.02 to 1.10 as determined by mud balance. (4) Viscosity is in the range of 21 to 65 seconds. (5) Filtration loss shall be less than 25 cm^3, and the thickness of filter cake shall not exceed 2 mm. (6) PH value is in the range of 8.5 to 11.7. (7) Sand content shall be less than 7%.

TABLE 4 VARIATION OF SLURRY PROPERTIES WITH DEPTH IN THE TRENCH

SAMPLE LOCATION (elev. m)	SPECIFIC GRAVITY (g/ml)	VISCOSITY (sec)	PH	SAND CONTENT (%)
slurry tank	1.025	20.84	9.45	0
-10	1.04	21.29	9.50	0.4
-20	1.052	21.38	9.55	1.5
-30	1.057	20.84	9.55	2.0

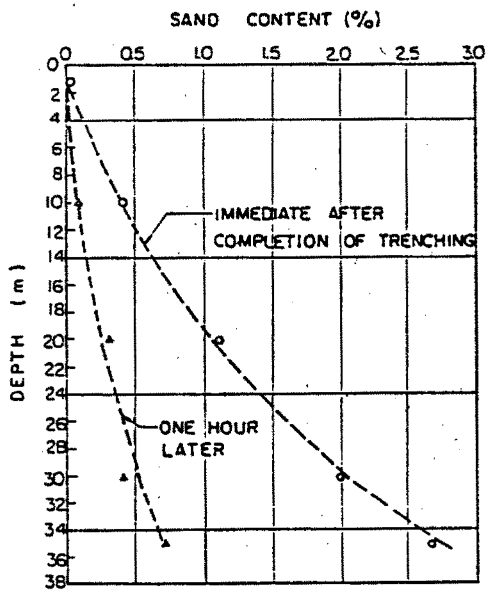

Fig. 1 Sand Content Of The Slurry In The Trench

It is also important to specify the frequency of such control tests throughout the period of construction. Table 5 presents the frequency commonly adopted in Taiwan.

TABLE 5 FREQUENCY AND EQUIPMENT OF SLURRY CONTROL TEST

ITEM	EQUIPMENT.	FREQUENCY
Specific gravity	Mud Balance	Once a day during excavation, after raining and before and after tremie concrete
Viscosity	Marsh Funnel	Same as above
Filtration loss	Filter press test	Once every three days
PH	PH meter	Once before and after concreting
Sand Content	Sand screening test	Once a day

CONCLUSION

The application of diaphragm wall construction in slurry has increased rapidly in the past. However, the various techniques and control factors still have to be further developed. Both the engineers and the contractors are facing a demand for more complete and reasonable specifications so that unnecessary restraint can be avoided while simultantously maintaining quality control. This paper briefly summarizes spacifications and practice of slurry wall construction in Taiwan and compares them with the practice and specifications elsewhere in the world, so that a better understanding may be gained.

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