NEW METHOD FOR CONSTRUCTION OF DIAPHRAGM WALLS

By Mohamed Emam Abd El-Razek[1]

ABSTRACT: Diaphragm walls are built to exclude earth and water from an area so that work may be performed under reasonably dry conditions. The range of applications for diaphragm walls includes earth-retaining and load-bearing walls for a variety of constructs such as underpasses, deep basements, underground stations, tunnels docks, and pump houses. In traditional construction methods, the concrete diaphragm wall consists of separate panels, which are not formed as a continuous monolithic construction. Vertical joints are used to divide the wall into panels, and horizontal reinforcement is not continuous from one panel to the next. Recently, a diaphragm wall, believed to be one of the largest ever built, was successfully constructed in Egypt with a continuous horizontal reinforcement. This paper describes in detail a new construction method for a diaphragm wall system. In addition, the difficulties encountered during construction are highlighted. Movements of the wall during excavation are reported. A comparison between the new and traditional construction methods is carried out in terms of cost and schedule. Applying the method presented in this paper offers substantial opportunity for reducing the steel reinforcement requirement and eliminating the use of shoring systems or ground anchors.

INTRODUCTION

A diaphragm wall is constructed by excavating a trench that is temporarily supported by a bentonite slurry. In conventional diaphragm wall systems, the reinforcement is lowered into the trench as a series of discrete elements. When the soil inside an unanchored or unbraced wall is excavated, the wall acts as a series of individual cantilever panels. Unless these panels are very heavily reinforced, there is a risk of differential movement, cracking, and water leakage. Recently, a circular diaphragm wall, believed to be one of the largest ever built, was constructed in Egypt with a continuous horizontal reinforcement. By virtue of reinforcement continuity, the wall acts as a homogenous cylinder, resisting earth pressure and water pressure through the development of tensile stresses. Therefore, the new construction method offers substantial opportunity for reducing the steel reinforcement requirement.

Fig. 1 shows a layout for the Bibliotheca Alexandrina, constructed in Egypt on the coast of the Mediterranean Sea. The old Bibliotheca Alexandrina, which contained more than 700,000 books, was built in 300 BC. Unfortunately, the old Bibliotheca Alexandria was destroyed at the end of the fourth century. It was decided to build a new Bibliotheca Alexandrina having a floor area of 40,000 m^2 and containing several buildings. These buildings serve to house cultural activities, books and periodical collections, administrative and technical services, an international school for information studies, and conference center auxiliary services. The main building of the project is a library that consists of four basements and six floors. The construction of the four basements for the library required an excavation of about 12 m. It was first considered to construct the basement within a circular sheet pile cofferdam, but the size (160 m in diameter) ruled out internal propping. In addition, Egyptian law would have banned the use of ground anchors under the buildings in proximity. A diaphragm wall, believed to be one of the largest ever built, was thus used to support the excavation for the library. A total of about 506 linear meters of diaphragm wall 1.2 m thick was constructed down 35.5 m. The library layout perimeter is a circle having a 160 m diameter. The library was close to an existing building, so the southwestern side of the diaphragm wall was distorted into a straight line, as shown in Fig. 1. This straight section was stiffened by external webs, and these webs were prestressed by posttensioning to avoid any possibility of tension cracking and to control the deflection. The corner part of the diaphragm wall was subjected to very large values of tensile stresses and bending moments due to the sudden change in the layout of the wall. After many trials, it was decided to stiffen the corners with closed boxes filled with grout.

This paper reports on a new construction method for the diaphragm walls. The novelty in this method is attributed to the continuity of horizontal reinforcement through the wall panels. The purpose is to eliminate the use of shoring systems or ground anchors to support the diaphragm wall. The objective of this paper is to document the significant aspects of construction so as to maintain awareness and share experience among constructors.

METHOD OF CONSTRUCTION

Excavation Method and Equipment

Before commencing construction, three trial panels having the same features as the library diaphragm wall panels were constructed down to the design depth to calibrate the construction procedures. A guide wall about 1.5 m deep below the ground level, conforming to the perimeter of the diaphragm wall, was built before commencing the excavation. A highly sophisticated hydromill-type cutter supported by heavy crawler crane, shown in Fig. 2, was used for the excavation process. The base of the hydromill has two drums fitted with tungsten carbide tipped cutters that rotate in opposite directions to perform the excavation for soil or rock. The type and dimensions of the drums are chosen according to the mechanical characteristics of the materials to be excavated. Just above the drums, a suction pump extracts the drilling fluid with cuttings and delivers it to the desanding plant through circulation lines. Before starting the excavation of each panel, the hydromill was located and maintained in the correct position by means of a steel guide frame fixed to the guide walls. The frame was tightly clamped to the inner faces of the guide walls by hydraulic jacks and remained fixed in position during the cutting and excavation process. The hydromill is equipped with transducers to measure the cutter depth, the inclination of the excavation in both the transverse and longitudinal directions, and the torque and rotational speed of the drums. These transducers are connected to a readout device located in the operator cabin. During the excavation for the diaphragm wall, bentonite/polymer slurry was continually fed into the excavation. The slurry level was maintained at ground level, thus ensuring a positive head on the sides of the trench.

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[1]Asst. Prof., Constr. Engrg. Dept., Facu. of Engrg., Zagazig Univ., Zagazig, Egypt.

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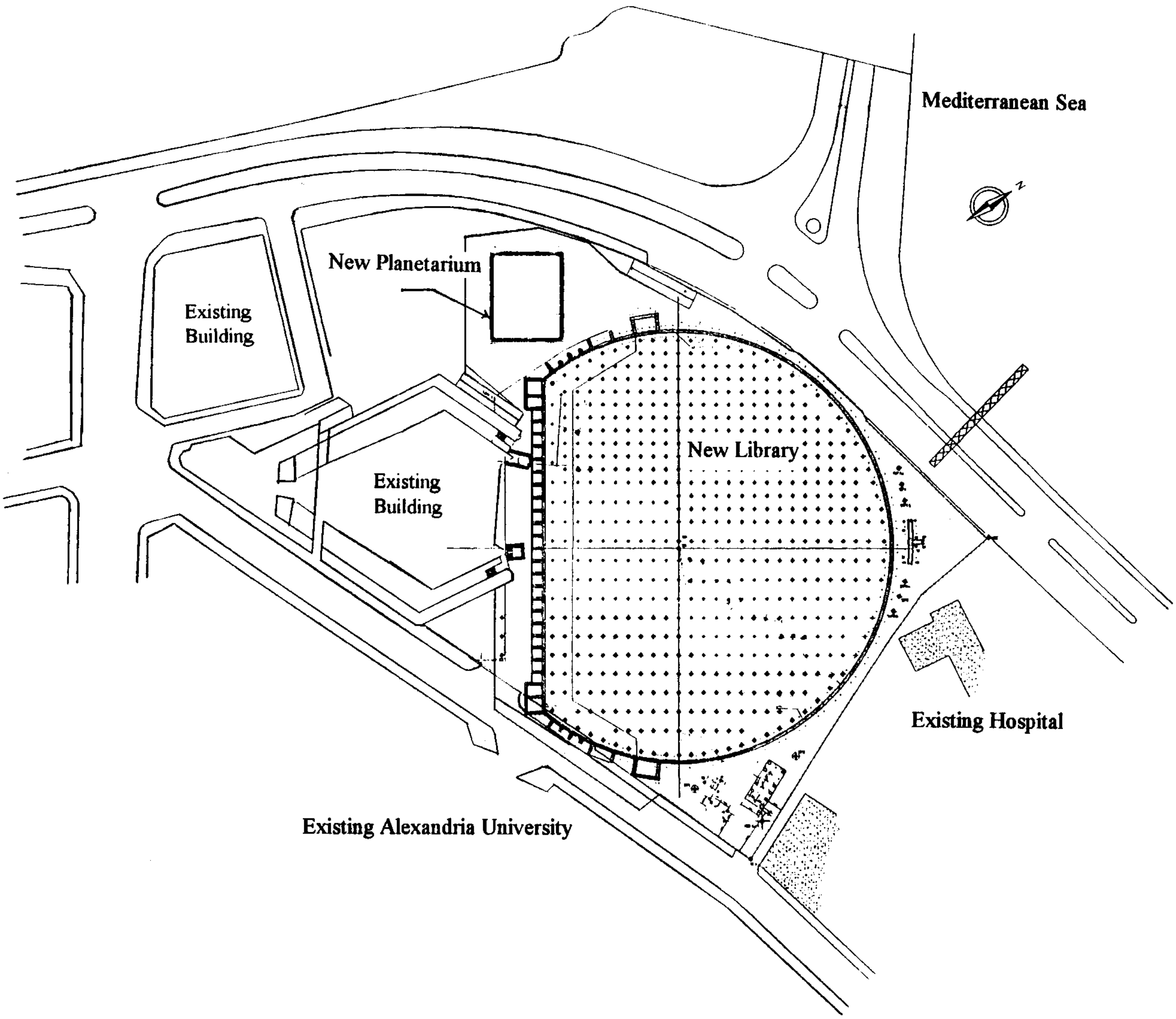

FIG. 1. Bibliotheca Alexandrina Layout

Reinforcing Cage Construction and Placement

The diaphragm wall panels may be classified according to the construction procedures as primary and secondary panels. The cages installed in primary and secondary panels had quite different features; a schematic of the joint between the primary and secondary panel cages is shown in Fig. 3. As can be seen, the reinforcing cages were designed to provide a continuous horizontal reinforcement through the diaphragm wall. In the primary panel cage, two steel end-plates, 6 mm thick, 1,160 mm wide, and 35,500 mm deep, were welded to the cage to provide a barrier between the concreted and unconcreted sections. The horizontal reinforcement was extended through holes in the end-plate to allow splicing with the steel cage inserted afterwards into the adjacent secondary panel. Horizontal angles and stiffening stirrups were installed to improve the plate stability under the concrete pressure. Vertical angles were installed both to improve plate stability at the edges and to guide and fix horizontal bars. Angles and stiffening stirrups were welded to the end-plate. As can be seen in Fig. 4, a canvas, made of synthetic sheet, was fixed to the vertical edge of the steel end-plate by means of a continuous steel angle, continuous rubber strip, nonmetallic bolts, and nuts. This fabric also surrounded the bottom of the cage to provide maximum protection against leakage of concrete beyond the partition steel end-plate. The vertical angle used to fix the canvas and rubber strip was made of galvanized steel, and the bolts used to fix it were nonmetallic bolts. The secondary panel cage was designed to allow a proper splicing between the primary and secondary panel cages. This was obtained by using horizontal bars properly bent at the cage edges, as shown in Fig. 3.

Each steel reinforcement cage was assembled horizontally on the ground in a single longitudinal section. Each cage was stiffened, using convenient stiffening frames placed between the main reinforcing bars, to provide the cage rigidity needed to avoid deformations during lifting and lowering into the trench. In addition, proper welding was performed to increase the stiffness of the cage during handling and lifting. Appropriate concrete spacers were placed on the faces of the cage to ensure the correct concrete cover. All the cages were equipped with a number of 50-mm-diameter steel sonic pipes to measure the concrete integrity. The distance between the sonic pipes was not greater than 2.5 m. A limited number of cages were equipped with inclinometer pipes and strain gauges. The inclinometers were used to measure the wall displacement during the work inside the diaphragm wall. The strain gauges were used to measure the concrete strains due to thermal effects after concrete placement.

The weights of each primary and secondary cage were about 30 and 45 tons, respectively. The handling process for reinforcing cages was performed by two cranes of 120 and 40 ton capacities with booms up to 50 m in length. Each cage, assembled in a horizontal position due to its exceptional length, was lifted from its horizontal position and suspended vertically by means of the two service cranes. The two hooks of each crane were connected to four levels of the cage—i.e., the top and three other intermediate levels—in order to reduce the bending stresses and deformations during lifting. Each link was connected to the cage by means of a strong bracket (lifting frame) to avoid any localized overstress to the cage assembly. Once the cage was in the vertical position, the 120 ton crane supported the cage from the top and moved it to the open trench. The cage was slowly lowered into the trench and, once down, was suspended on the guide walls through bars welded to the main longitudinal bars. Therefore, the reinforcement cage did not rest on the bottom of the trench, and the clear distance between the reinforcement and the bottom of the trench was not less than 150 mm.

FIG. 2. Hydromill and Reinforcing Cage for Primary Pan

Execution Sequence and Concreting

The typical construction sequence for the diaphragm wall is described below and illustrated in Fig. 5. As a starting point, a primary panel location of 6.2 m width was excavated by the hydromill to 35.5 m depth. After the execution of excavation, the reinforcing cage for the primary panel was lowered into place. The primary panel was divided into three sections, as shown in Fig. 5(a). Section 1 (the concreted section) was 2.2 m in width at the central part of the panel and was enclosed by the two end plates. Sections 2 and 3 (the unconcreted sections) were each 2 m in width and were located between the end plates and the panel edges. Before concrete placement, gravel was poured into the two unconcreted sections using a convenient hopper from the bottom up to a height of 2–3 m in both ends. This was done to keep the steel end-plate fixed and to allow the fabric sheet to accomplish its function. Furthermore, both concrete and water/cement/sand slurry leakage from the bottom would be avoided due to the presence of this gravel. Next, concrete was placed into the concreted section by means of a tremie in such a manner that the concrete displaced the slurry from the bottom of the panel. The rising speed of the tremie pipes was controlled to avoid any deformation or damage to the steel end-plate; the rate of rise of concrete was about 6 m/hr. During concreting, the rise of the concrete was periodically checked to detect the presence of any concrete leakage inside the two unconcreted sections. After completion of the concreted section of the primary panel, the presence of any concrete leakage in the unconcreted sections was cleaned using special chisels and a bailer. The chisel was lowered into the empty space to scratch and clean the

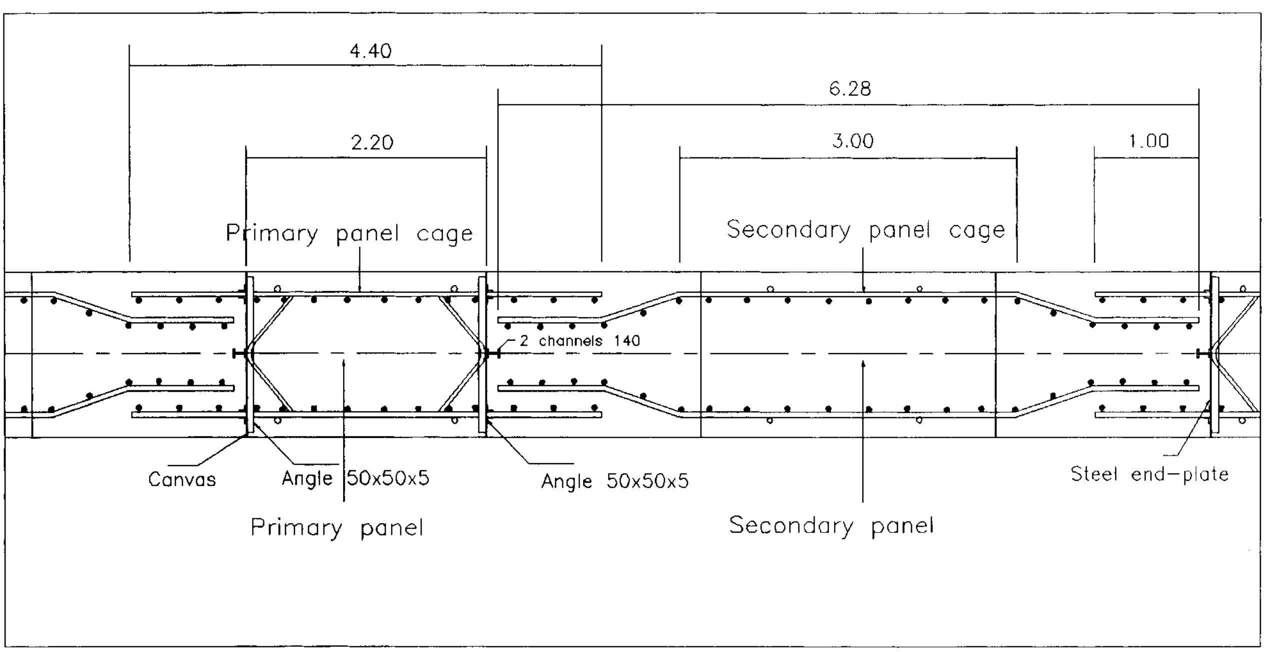

FIG. 3. Schematic of Joint between Primary and Secondary Panel

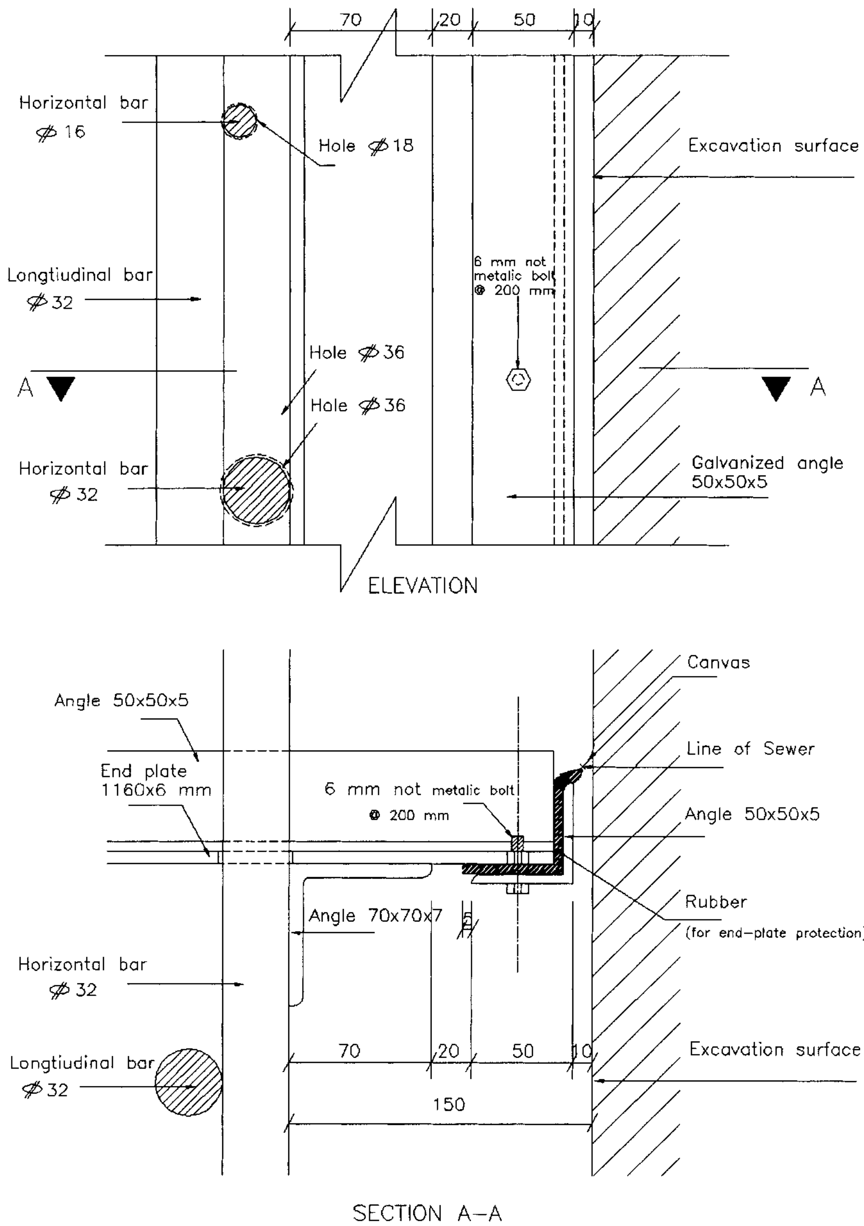

FIG. 4. Detail of Connection between Canvas and Steel End-Plate

end-plate of any concrete that might have leaked. The bailer was used to remove any debris or gravel that might have fallen to the bottom of the unconcreted sections through the holes for the rebar or the connection between the canvas and steel end-plate. The same procedures for excavating and concreting the primary panel were repeated in an adjacent primary panel, as shown in Fig. 5(b). The distance between adjacent ends of the adjacent primary panels was 2.48 m, as shown in Fig. 5(b). When at least two adjacent primary panels were concreted, the hydromill excavated the secondary panel in between. Upon completion of the secondary panel excavation, shown in Fig. 5(c), the joints cleaning operation was carried out. Next, the reinforcing cage for the secondary panel was lowered into the trench, as shown in Fig. 5(d). Finally, the secondary panel and two of the contiguous unconcreteed sections of the primary panel were concreted simultaneously, as shown in Fig. 5(e). The previous procedures were repeated until concreting of all the diaphragm wall panels was completed. It should be noted here that ground movement was not observed during the excavation and concreting operations for either the primary or secondary panels.

INSTRUMENTATION AND MONITORING

The Koden, the sonic log, and the inclinometer are the most important instruments used to control the construction of the diaphragm wall. The Koden generates ultrasound (transversally and longitudinally to the side wall) and measures the return time by means of geophones. The recorded sonic logs were a document proving the side wall profiles. Fig. 6 illustrates the actual geometry of the excavation for a diaphragm wall panel in the transverse direction.

After at least one week of concrete curing, nondestructive sonic integrity tests were performed using the cross-hole technique, with signals traveling between pairs of tubes. Fig. 7 illustrates the integrity of a concrete panel measured by sonic logging.

The monitoring system for the lateral movement of the wall was devised and carried out by the main contractor. A total of 17 reference stations, consisting of inclinometer tubes inserted in the reinforcing cages, were installed along the perimeter of the diaphragm wall. The deflection measurements started one week before commencement of dewatering and were contin-

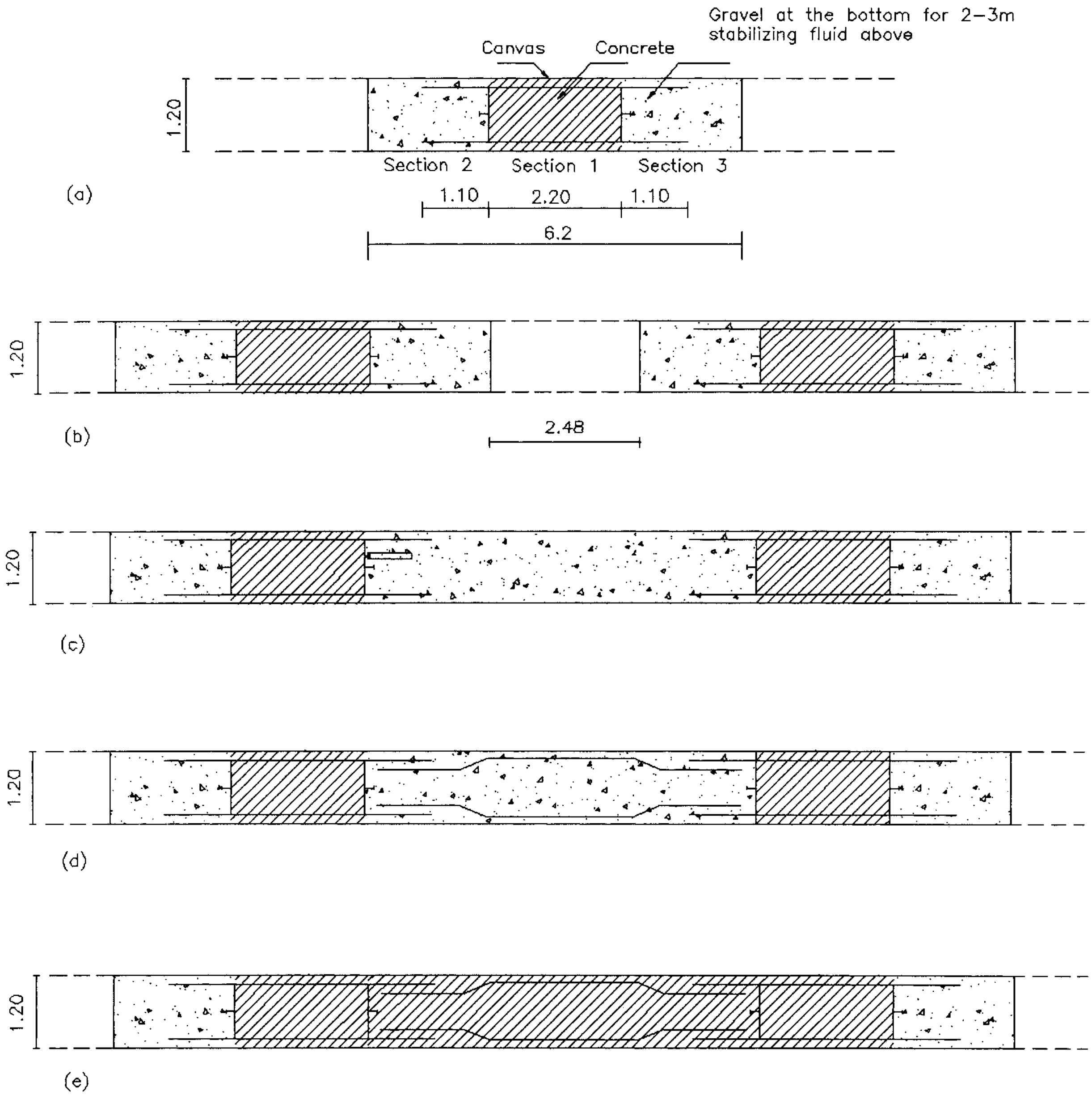

FIG. 5. Construction Sequence: (a) Primary Panel: Concreting; (b) Adjacent Primary Panel Construction; (c) Secondary Panel: Joints Cleaning; (d) Reinforcement Cage Installation for Secondary Panel; (e) Secondary Panel: Concreting

ued until the end of the work inside the diaphragm wall. Fig. 8 illustrates that the maximum lateral displacement observed at the end of the work inside the wall is about 33 mm, which represents about 0.09% of the wall depth.

DIFFICULTIES ENCOUNTERED DURING CONSTRUCTION

1. An excessive slurry loss was observed during excavation for eight panels, 7% of the total panels. This difficulty was overcome by removing the hydromill and adding plugging material (sand) to the slurry in the trench. The sand carried by the leaking slurry dispersed into the surrounding fissures, forming a plug some distance from the trench. Consequently, after a few days, the excavation was resumed through the backfill material.
2. During excavation for ten panels, 9% of the total panels, it was found that the verticality and twisting were not complying with limits of tolerance. To correct the deviation of the panel side walls, a chisel specially designed for this operation was lowered along the soil surface to trim the side walls.
3. Leakage of concrete beyond the partition steel end-plate is one of the most important risks in construction of a diaphragm wall with a continuous horizontal reinforcement. During placement of the concreted sections for five primary panels, 9% of the total primary panels, leakage was observed in the unconcreted sections. The concrete placing was stopped, then gravel was poured into the unconcreted sections using a hopper. Once the level of gravel reached the same level as where leakage occurred, concreting was started again. Two hours after the completion of concreting, the gravel and concrete leaked were removed from the unconcreted sections where leakage occurred, by means of a chisel and a bailer. It might be noted here that 80% of the primary panels that experienced out-of-tolerance excavation and were realigned by chisel, subsequently leaked when the concrete was placed.
4. After the excavation inside the diaphragm wall, leakage of water was observed through a few joints. This difficulty was overcome by jet-grouting treatment behind the panel, which successfully closed the joints.

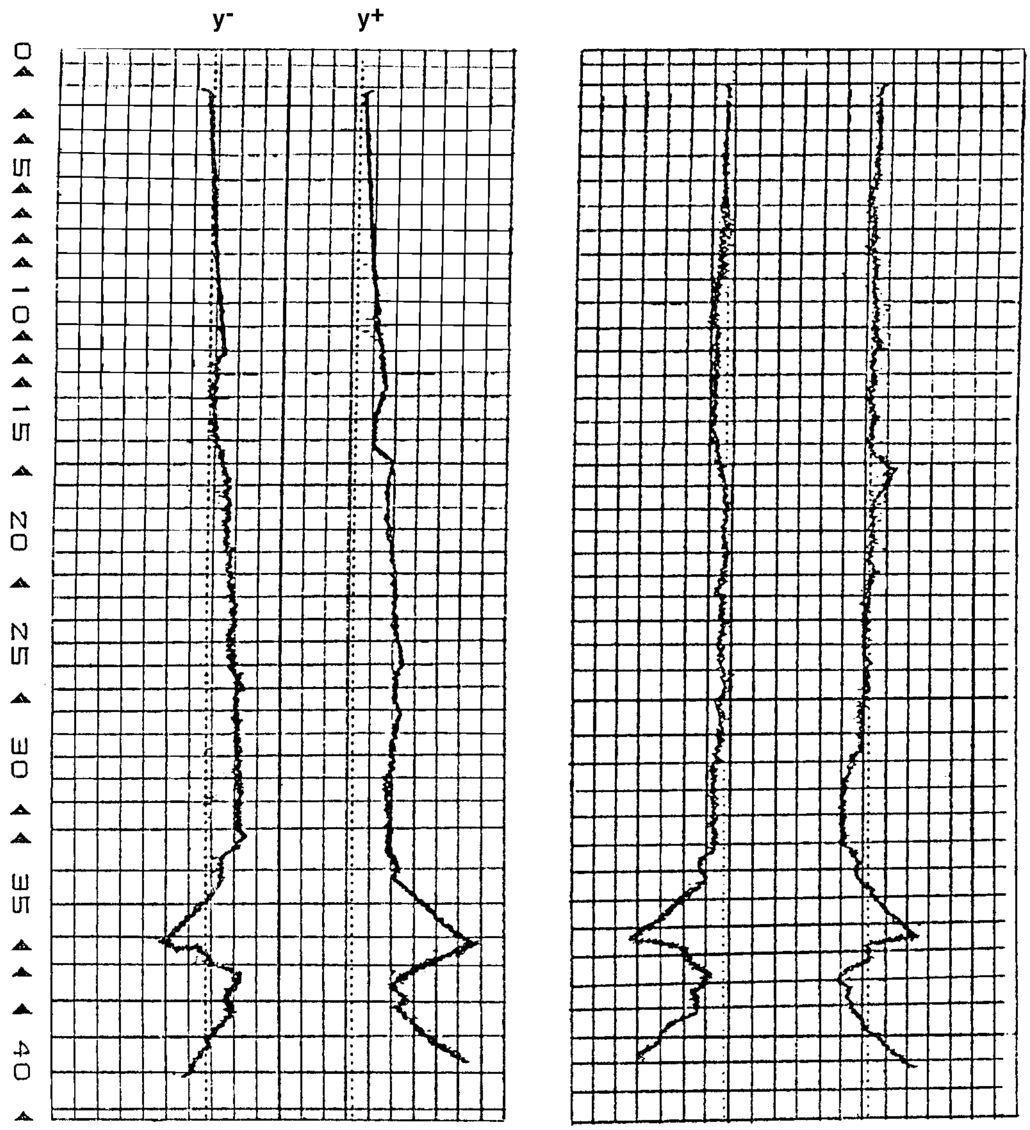

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FIG. 6. Result of Koden Test

EVALUATION OF NEW SYSTEM

In the following sections, the diaphragm wall constructed with a continuous horizontal reinforcement is compared with the traditional construction method for the diaphragm walls, i.e., those constructed without continuous horizontal reinforcement. The comparison is based on cost and schedule. The data for the traditional wall system was recorded from the construction of a planetarium diaphragm wall that was part of the same project. The planetarium layout perimeter, shown in Fig. 1, was a rectangle 28 × 33 m, and the wall depth was 27 m, 1.2 m thick. Continuity of horizontal reinforcement was not required for the planetarium diaphragm wall. It may be noted here that both the library and planetarium walls were constructed using the same equipment for excavation, concreting, and monitoring.

Cost

A summary of costs for the library and planetarium diaphragm walls is presented in Table 1. The total direct costs for the library and planetarium walls are L.E. 23,684,064 ($6,966,000) and L.E. 3,696,157 ($1,087,000), respectively, based on a unit-price contract. The excavation cost represents about 22% of the total direct cost for both walls. This is based on a renting cost of about L.E. 38,000 ($11,176) per day for the hydromill.

The reinforcing cost represents about 25% and 15% of the total direct costs for the library and planetarium walls, respectively. In addition, the cost of stiffening cages and plates represents about 18% and 8% of the steel reinforcement costs, respectively, for walls with and without continuous horizontal reinforcement. The diaphragm wall constructed with continuous horizontal reinforcement contained a higher percentage of steel reinforcement. It is worth mentioning here that the library wall, constructed with a continuous horizontal reinforcement, was designed to participate in resisting seismic effects by providing a stiff connection with the permanent structural elements. This obviously has a significant effect on increasing the steel reinforcement requirement for the new wall system in this particular job. However, in general, the diaphragm wall with a continuous horizontal reinforcement behaves as continuous shell elements; hence, bending stresses are distributed in two directions. In comparison, the diaphragm wall without continuous horizontal reinforcement behaves as separate beam elements; hence, bending stresses are distributed in one direction. This requires steel reinforcement higher than that for the

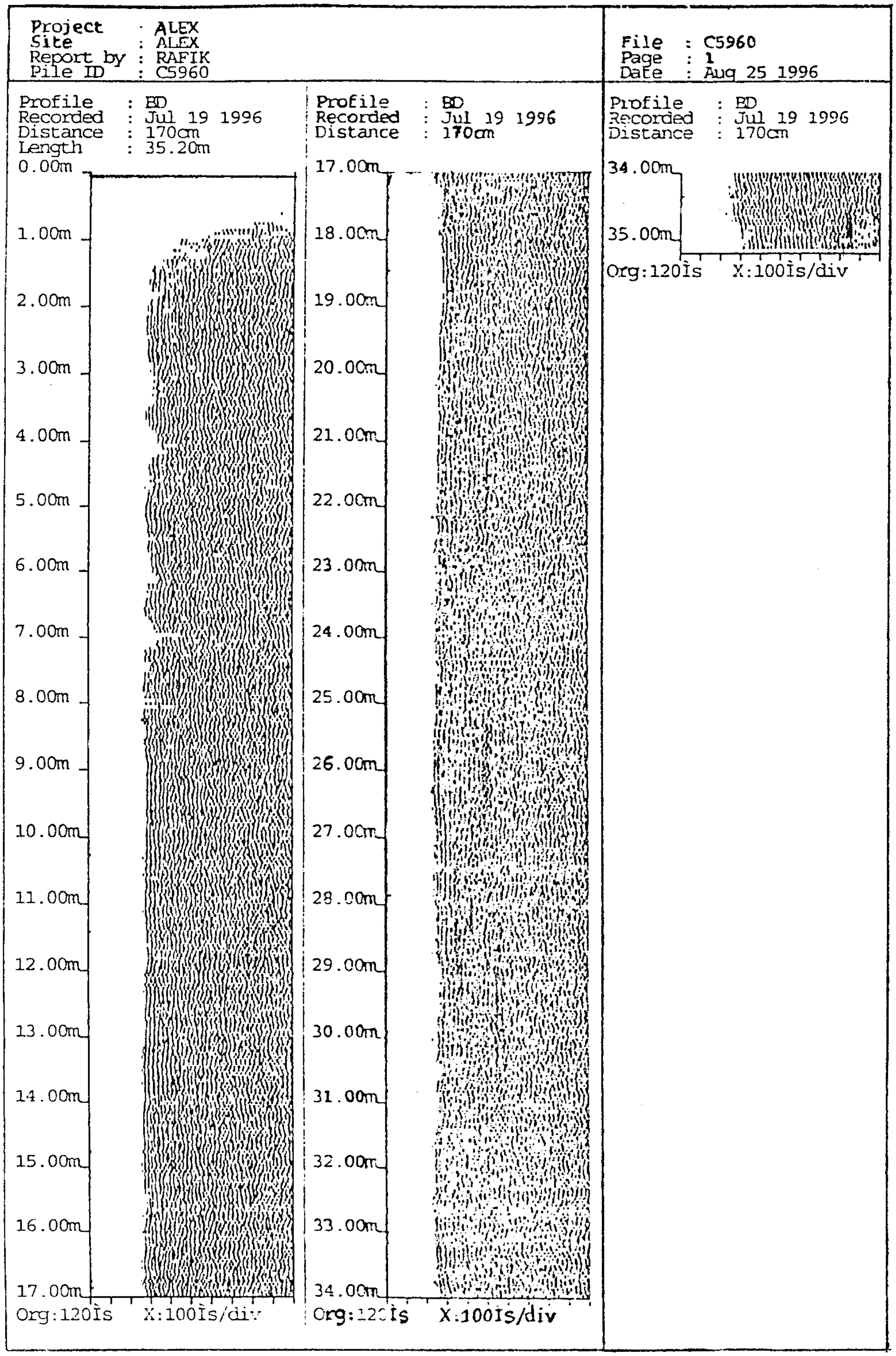

FIG. 7. Result of Sonic Logging Test

diaphragm wall with continuous horizontal reinforcement. Therefore, the cost of steel reinforcement for the new wall system, in general conditions, is expected to be lower than that for the traditional wall system.

The cost of concrete is about 46% of the total cost for both walls. Other cost items indicate close similarities for both wall systems. The salient cost saving for the new wall system is the cost of the shoring system, which represents about 10% of the total cost for the traditional wall system. It might be noted here that the cost of other temporary supporting systems for the diaphragm walls, such as ground anchors, may range from 13–17% of the total cost, as reported earlier (Hodgson 1975; Puller 1975). The unit costs for the library and planetarium diaphragm walls are 1,100 L.E./m^3 and 935 L.E./m^3, respectively. These figures reflect the comparison for this particular job. However, in general circumstances, the unit cost for the new wall system may be lower than that for the traditional wall system as a result of reducing the steel reinforcement requirement and saving the shoring system or ground anchor costs.

TABLE 1. Estimate of Cost Items for Library and Planetarium Diaphragm Walls in Bibliotheca Alexandrina Project

Item number (1)	Definition (2)	Unit (3)	Quantity (4)	Material cost (L.E.) (5)	Labor cost (L.E.) (6)	Equipment cost (L.E.) (7)	Total direct cost (L.E.) (8)
I	Library						
I-a	Guide wall construction						
1	Excavation	m^3	4,262	—	924	20,240	21,164
2	Formwork	m^2	1,938	193,750	13,734	—	207,484
3	Steel reinforcement	ton	155	232,500	18,480	—	250,980
4	Concrete placing	m^3	1,163	129,038	9,240	5,500	143,778
	Total			555,288	42,378	25,740	623,406
I-b	Panels construction						
1	Excavation	m^3	24,358	—	—	5,092,000	5,092,000
2	Steel reinforcement	ton	3,178	4,767,000	53,256	9,750	4,830,000
3	Stiffening cages & plats	ton	580	870,000	960	180	871,140
4	Concrete placing	m^3	24,358	10,425,352	34,776	98,000	10,558,128
5	Prestressing cables	item	—	570,000	—	—	570,000
6	Sonic logging	m	31,680	15,840	—	250,000	265,840
7	Instrumentation	item	—	—	—	—	352,150
8	Guide wall removal	m^3	1,938	—	—	91,000	91,000
9	Top trimming	item	—	—	218,400	26,000	244,400
10	Wall trimming	item	—	—	126,000	60,000	186,000
	Total			16,648,192	433,392	5,626,930	23,060,658
II	Planetarium						
II-a	Guide wall construction						
1	Excavation	m^3	376	—	420	2,200	2,620
2	Formwork	m^2	342	34,200	980	—	35,180
3	Steel reinforcement	ton	13.2	19,800	1,260	—	21,060
4	Concrete placing	m^3	165	18,315	840	500	19,655
	Total			72,315	3,500	2,700	78,515
II-b	Panels construction						
1	Excavation	m^3	3,873	—	—	853,600	853,600
2	Steel reinforcement	ton	333.5	500,250	12,852	1,500	514,602
3	Stiffening cages & plats	ton	26	39,000	1,000	120	40,120
4	Concrete placing	m^3	3,873	1,657,644	3,360	1,250	1,662,254
5	Sonic logging	m	4,332	2,166	—	40,000	42,166
6	Instrumentation	item	—	—	—	—	106,300
7	Guide wall removal	m^3	165	—	—	7,000	7,000
8	Top trimming	item	—	—	33,600	2,000	35,600
9	Wall trimming	item	—	—	21,000	5,000	26,000
10	Shoring system	item	—	—	—	—	330,000
	Total			2,199,060	61,812	910,470	3,617,642

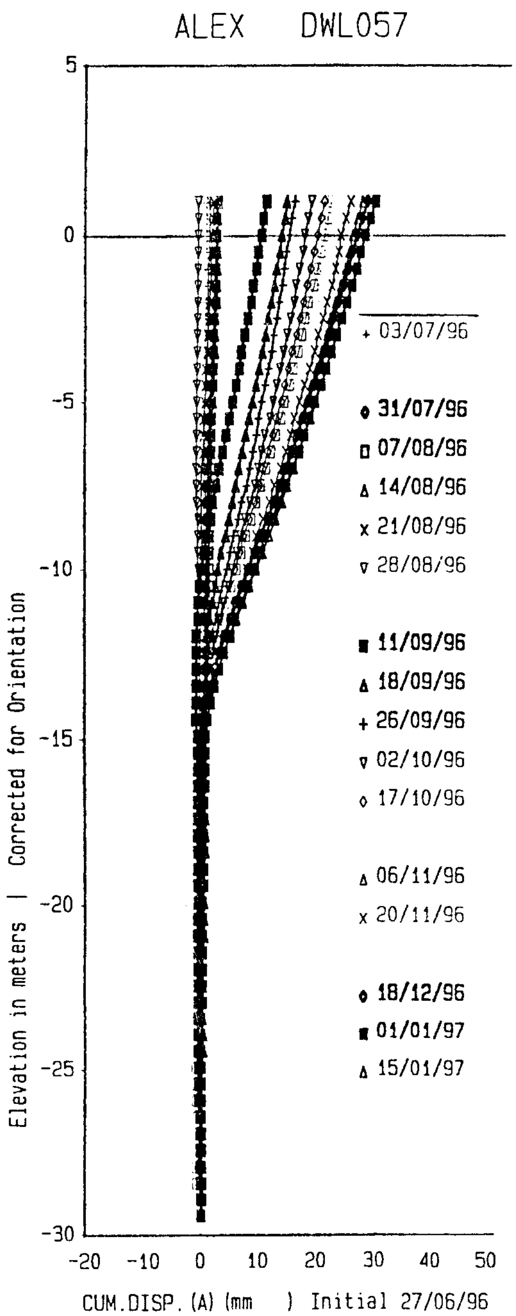

FIG. 8. Result of Inclinometer Test

Schedule

The library and planetarium diaphragm walls, new and traditional wall systems, were constructed in 309 and 58 days, respectively. The construction progress rates for the library and planetarium walls were about 69 and 67 m^3/day, respectively. As can be seen, the difference between the construction progress rates for both systems is not significant. This can be attributed to the fact that the construction progress rate for diaphragm walls is dominated by the production rate of the equipment used for excavation. Because of the high renting cost for the hydromill, the construction process for both walls was scheduled to allow for the hydromill to work with interruption. As a result of keeping a similar production rate for the hydromill, the construction progress rate for both walls indicated close similarity. Nevertheless, using a traditional wall system requires extra time for erecting and dismantling the shoring system, irrespective of its type.

CONCLUSIONS

This paper describes a new construction method for a diaphragm wall built in Egypt using a continuous horizontal reinforcement. Significant data related to the construction system were documented, and the difficulties encountered during construction were highlighted. In addition, evaluation of the new system was carried out based on terms of cost and schedule. Industry professionals involved in this field may find the description of the new construction method and the evaluation results of practical value. From evaluation of the system, the following conclusions were drawn:

1. The elimination of using a shoring system or ground anchors reduces the construction time and cost for the new wall system.
2. A cost comparison between the new and traditional wall systems in this particular job revealed that the cost increases by about 18% when continuous horizontal reinforcement is used. However, such comparisons may not yield the same results for other jobs under different circumstances.
3. The construction progress rate for both new and traditional wall systems indicates close similarity in this particular job.

APPENDIX. REFERENCES

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