Innovative Central Opening Strut System for Foundation Excavation

Min-Lung Yang[1]; Sheng-Jin Chen[2]; and Shun-Tyan Chen[3]

Abstract: A central opening strut system is used to support a diaphragm wall for foundation excavation. This system contains at least one regular polygon module and a number of straight strut members. These strut members connect the diaphragm wall and the regular polygon module together, so that the earth pressure acting on the diaphragm wall in one direction can be transmitted to the diaphragm wall in the other directions by the arch action of this polygon module. In this research, the basic structural behavior of the central opening strut system is examined. A full-scale structural testing of the joint subassemblage is also performed to examine the ultimate strength of the joint. A construction site with five excavation stages and four layers of strut systems is chosen as the case study. The *ABAQUS* finite-element program is employed in the study of the behavior of this system during various construction stages. From these studies, it is found that the proposed central opening strut system is able to provide a large working space and greatly increases the efficiency of the construction work. Through proper design of the member and the joints, this system provides a better safety factor as compared with the traditional strut system.

DOI: 10.1061/(ASCE)0733-9364(2006)132:1(58)

CE Database subject headings: Foundations; Excavation; Struts; Diaphragm wall.

Introduction

Foundation excavation is an important working item in construction works. For a deep excavation on soft foundation soil, or for providing protection for neighboring buildings, it is necessary to construct a diaphragm wall supported by strut members (Fig. 1). Although this conventional construction method has become almost a standard procedure in foundation excavation work, it is both costly and time consuming, and it also carries a potential risk. Failures of current strut systems have frequently been reported. These cases have caused a huge amount of property loss and have become public issues. The major problems of the strut system used in current practice are as follows:

1. The crowded arrangement of the strut members in the conventional system (Fig. 1) provides a limited working space in a construction site, making it difficult to move in and operate heavy construction equipment. Furthermore, within such a limited working space, collisions of construction equipment with strut members might occur, resulting in serious construction failure.
2. The limited working space offered by the conventional strut system affects the transport and placement of longer reinforcing bars. In such a case, the need for splicing of reinforcing bars will increase; hence, the material and labor costs will also increase.
3. The limited working space will slow down the pace of the foundation excavation. As the foundation excavation is the most critical part of the entire construction project, extension of the excavation duration will substantially increase the risk of construction work.
4. The conventional strut system is rather complicated in its member assemblage, demanding excessive materials and labor work, and it is hence more costly and more risky.
5. The function of the strut member is to transmit earth pressure acting on the diaphragm wall on one side of the construction site to that of the opposite side, thereby forming a self-balanced system. In a large foundation site, the distance between the diaphragm walls on the two opposite excavation sides is quite large and long strut members are assembled from many short members, which requires many joints. The force transmission function of the long assembled strut members is thus less effective. Any defect in workmanship will cause failure of the system.

In order to resolve the aforementioned problems existing in the conventional strut system for foundation excavation work, the writers propose a central opening strut system: a highly safe, material-saving modular system that offers a large working space. The diameter of the center hole can be 15–25 m, and the excavation site of a single module can be as large as 30 m wide. This system contains at least one regular polygon module and a number of straight strut members. These strut members connect the diaphragm wall and the regular polygon module together, so that the earth pressure acting on the diaphragm wall in one direction can be transmitted to the diaphragm wall in the other directions

[1]PhD Student, Dept. of Construction Engineering, National Taiwan Univ. of Science and Technology, P.O. Box 90-130, Taipei, Taiwan.

[2]Professor, Dept. of Construction Engineering, National Taiwan Univ. of Science and Technology, P.O. Box 90-130, Taipei, Taiwan.

[3]Professor, Dept. of Construction Engineering, National Taiwan Univ. of Science and Technology, P.O. Box 90-130, Taipei, Taiwan.

Note. Discussion open until June 1, 2006. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on September 23, 2003; approved on April 6, 2005. This paper is part of the ***Journal of Construction Engineering and Management***, Vol. 132, No. 1, January 1, 2006. ©ASCE, ISSN 0733-9364/2006/1-58–66/$25.00.

J. Constr. Eng. Manage., 2006, 132(1): 58-66

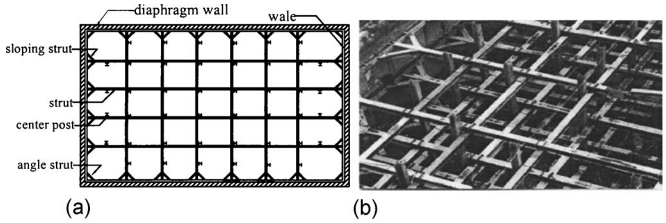

Fig. 1. Configuration of conventional strut system in foundation excavation: (a) conventional strut system; (b) photo of typical conventional strut system

by the arch action of the polygon module. Earth pressure on the diaphragm walls is transmitted via the regular-polygon-shaped frame module from the first direction to a second direction through the arch action of this polygon module structure. The following section describes the development of this system.

Central Opening Strut System

The basic theory of the proposed central opening strut system can be explained by the circular structure shown in Fig. 2. As external loads are applied to this circular structure, the circular structure will deform and force will be transmitted to other directions if the deformation is restrained [Fig. 2(a)]. When a uniform external pressure is applied to the circular structure, a uniform internal stress will be induced inside the circular structure [Fig. 2(b)]. In general, a circular or ring structure is stable and of high strength.

In practical applications, a regular polygon structure can be adopted to simulate a ring structure so that the arch effect can be induced. An N-sided regular polygon (Fig. 3) has a sum of internal angles of $(N-2)\cdot 180°$, and each of its internal angles is $180°-360°/N$. Let R be the radius of the external intersection circle of this polygon and S be the length of each side of this polygon; then

$$S = 2R\cos(\beta/2) \tag{1}$$

As N increases, the polygon will be closer and closer to a circle in shape, and the perimeter of the polygon will approach $2\pi R$, the perimeter of the circle. Table 1 shows the degree of approximation of polygons with varying numbers of sides to a circle. It is seen from Table 1 that a six-sided polygon has a 95.5% approximation to a circle, while a 12-sided polygon has about a 99% approximation.

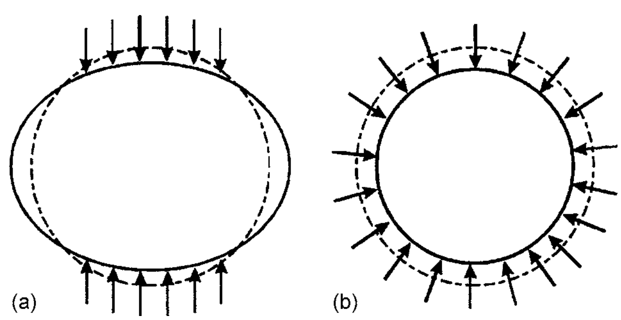

Fig. 2. Behavior of circular structure: (a) circular structure deformed by external load on opposite sides; (b) deformation of circular structure under uniform external pressure

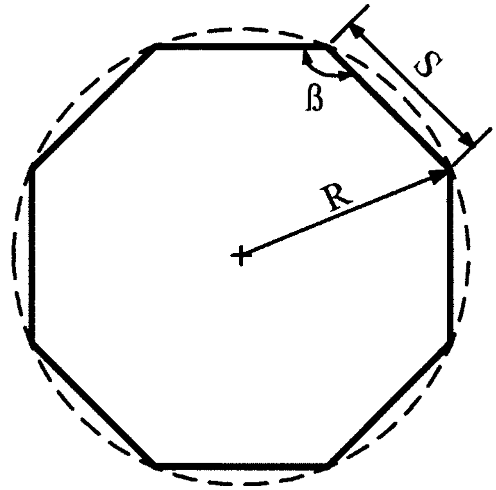

Fig. 3. N-sided regular polygon intersects to an excircle

The first example of a practical application is illustrated in Fig. 4. The central opening strut system consists of a 12-sided-polygon-shaped module structure and a number of strut members arranged in the longitudinal and transverse direction. The strut members are connected in between the diaphragm wall and the polygon module frame. As the diaphragm walls are subjected to earth pressure, the pressure can be transmitted to the diaphragm wall on the other sides by the arch action of the polygon structure, as shown in Fig. 4. Fig. 5 shows the application of two regular polygon modules to support diaphragm walls for a construction site of rectangular shape. The 12-sided-regular-polygon-shaped frame module comprises two concentric strut frames. By this arrangement, the factor of safety can be significantly increased. In addition, the space provided by the central opening system can be used to transport the construction material and equipment and increase the efficiency of the work.

The conventional internal bracing system is a determinate system, which is less reliable as compared with an indeterminate system. This is because the internal bracing system uses a lot of steel members to support the diaphragm walls and each member is connected with the wall on the opposite sides (Xanthakos 1994). Thus, the strut members are acting alone in resisting the earth pressure on the wall, and the force on an individual strut member cannot be transmitted to the other strut members. The proposed method takes advantage of the behavior of the circumferential stress. It is able to transmit earth pressure on a wall in one direction to the other directions so that the surrounding dia-

Table 1. Approximation of Regular Polygons to a Circle

Number of polygon sides, N	Perimeter of polygon	Perimeter of circle with radius R	Ratio of perimeter of polygon to that of circle
5	5.88R	6.28R	93.6%
6	6.00R	6.28R	95.5%
8	6.12R	6.28R	97.5%
9	6.16R	6.28R	98.1%
10	6.18R	6.28R	98.4%
12	6.21R	6.28R	98.9%
16	6.24R	6.28R	99.4%
20	6.26R	6.28R	99.6%

J. Constr. Eng. Manage., 2006, 132(1): 58-66

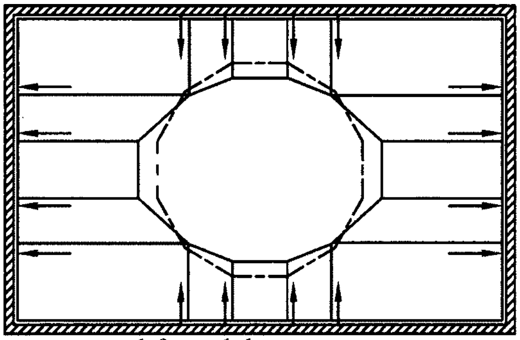

Fig. 4. Earth pressure transmits via arch action

phragm walls all participate in resisting the earth pressure and the whole strutted excavation system becomes an indeterminate system, which is very effective and reliable.

The conventional strut system utilizes the straight steel members to transmit the earth pressure to the opposite walls (Das 1995). However, the fabrication process of steel members usually results in a certain amount of initial crookedness. This initial crookedness usually induces a second-order moment on the steel member when it is subjected to high axial force and finally causes instability, especially when the steel strut member is long. The proposed central opening strut system utilizes the characteristics of circular members that are less sensitive to the initial crookedness and are thus able to increase the safety factor of the strutted excavation system.

The present central opening system also uses a standardized module strut system. Member sizes and connection types can be minimized to several predeterminate types. The frame module can be produced and assembled easily. The system also provides a large open space inside the central holes of the strut module. There are no horizontal strut members or vertical supporting columns in this open space. Thus, construction equipment can be operated easily in this area, which can also provide a transporting channel for construction materials. Construction time can be shortened greatly due to this handy open space during the construction work.

Design of Central Opening Strut System

The traditional strut system requires many strut members that interfere with the excavation work (Xanthakos 1994; Das 1995). The proposed central strut system provides an open space, which is convenient for construction work. Although the polygon frame has better redundancy than the traditional straight strut system, the failure of one member of the single ring strut system may cause failure of the whole system. It is suggested instead to use a dual ring strut frame system in order to provide better redundancy and increase the safety factor. By using a dual ring system, even if one of the strut members failed, it would not cause catastrophic failure of the whole system. The following describes the basic structural behavior and the parametric study of the central strut system.

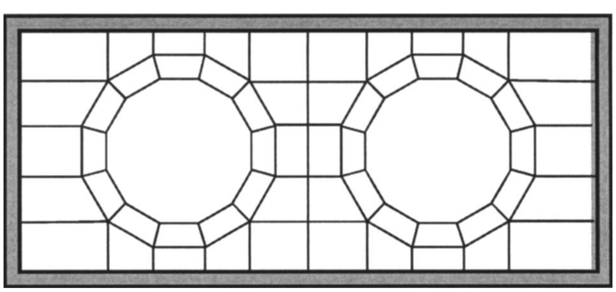

Fig. 5. Rectangular site with two modules of central opening strut system

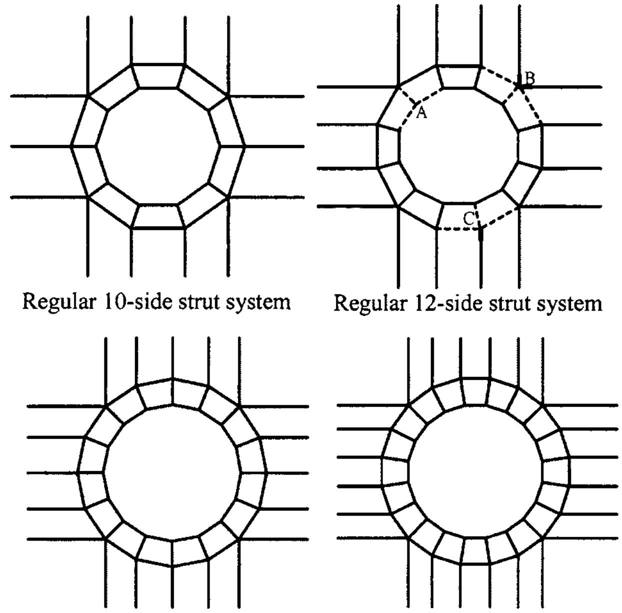

Fig. 6. Multisided regular polygon frames study

Design of Strut Member

By increasing the number of sides of the multisided regular polygon, the structural behavior of the polygon will closer approximate that of a circle frame. However, increasing the number of sides of the polygon will also increase the number of joints and the cost and time of the construction work. A series of studies were carried out to examine the effect of the number of sides of the regular polygon. The polygon frames studied are shown in Fig. 6. The member size selected was Box $300 \times 300 \times 20$ (mm). A double ring system was selected with a distance of 3 m between the two rings. The members of the polygon frames were designed as beam-column members following the current design specifications of a steel structure. The basic requirement of the

Table 2. Parametric Study of Number of System Sides

Number of sides, N	Maximum axial stress (MPa)	Maximum flexural stress (MPa)	Total stress (MPa)	Stress ratio (SR)
10	54.3	346.3	400.6	2.022
12	49.5	118.4	167.9	0.831
16	51.2	77.4	128.6	0.621
20	52.8	52.8	105.6	0.507

J. Constr. Eng. Manage., 2006, 132(1): 58-66

Table 3. Ring Distance and Stress Relationship

Distance (m)	Diameter of inner ring (m)	Axial stress (MPa)	Flexural stress (MPa)	Total stress (MPa)
2	20	47.5	117.2	164.7
3	18	49.5	118.4	167.9
4	16	51.1	117.7	168.8
5	14	52.5	114.1	166.6

beam-column design was that the stress ratio (SR) should be less than 1.0 (SR=maximum stress in the member/allowable stress) (American Institute of Steel Construction 1989).

Table 2 shows the results of the parametric study. From Table 2, it is found that the flexural stress and the total stress decrease with the increase in number of sides of the polygon. The stress decreases significantly from the 10-sided polygon to the 12-sided polygon. Also, the 10-sided polygon needs four different types of joint, while the 12-sided polygon only requires three types of joint, as shown in Fig. 6. Although the stress can be further reduced with a 16-sided or even 20-sided polygon, this would increase the total number of joints greatly. Based on the aforementioned considerations, a 12-sided polygon is selected for the module frame system in this study.

Distance between Two Rings

In order to provide a better safety factor for the central strut system, a double ring system was suggested in the previous section. However, the distance between the two rings must be examined. A 12-sided regular polygon frame with an outer ring diameter of 24 m is selected as the basic module. The member size is of Box $300 \times 300 \times 20$ fabricated from ASTM-A572 Gr. 50 steel (F_y=350 MPa). The inner ring adopted the same member size and steel grade but with a different distance between the two rings. The system is subjected to an external force of 1,000 kN on the straight strut members connecting the diaphragm wall and the polygon frame. Table 3 shows the analytical results. It is found that the distance between the two rings does not affect the magnitude of member stress greatly. It seems that if the two rings are closer, the interior space can be increased, which is beneficial for construction work. However, due to the requirement of the joints, a distance of 3 m is suggested.

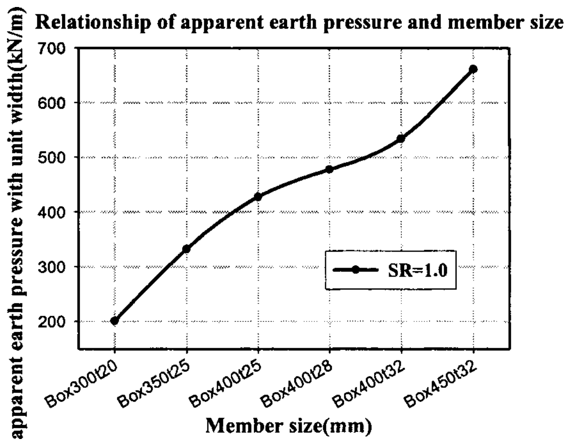

Fig. 7. Relationship of member size and allowable pressure

Central Opening Strut System under Four Sides of Earth Pressure

After the erection of the strut system, the stress on the strut may be affected by dewatering, excavation, and the erection or removal of the strut system on the other layer. It is important to study the relationships between the allowable member strength of the strut and the apparent earth pressure. In order to simplify the analytical work, it is assumed that all the earth pressure is the same and is applied on the external straight strut member. Fig. 7 shows the relationships of the member size and the allowable apparent earth pressure when the strut reaches its allowable stress. This can be used as a quick check to ensure the strut has enough strength during the excavation and the assembling and disassembling of the strut frame at different layers. For example, if the member size is of Box $300 \times 300 \times 20$, the system is able to resist an apparent earth pressure of 200.6 kN/m, which is equivalent to 1,203 kN on the exterior struts connecting the diaphragm wall and the polygon frame. If the member size is Box $350 \times 350 \times 25$, then the allowable external force is 1,992 kN at the exterior straight strut. If the member size is Box $400 \times 400 \times 32$, then the allowable external force is 3,205 kN at the exterior strut. These can be used as a quick estimation of the required member size in the design of the strut system.

Experimental Study of Typical Joint

Although the design of the regular polygon frame can be done following the current design practice for a steel structure, the

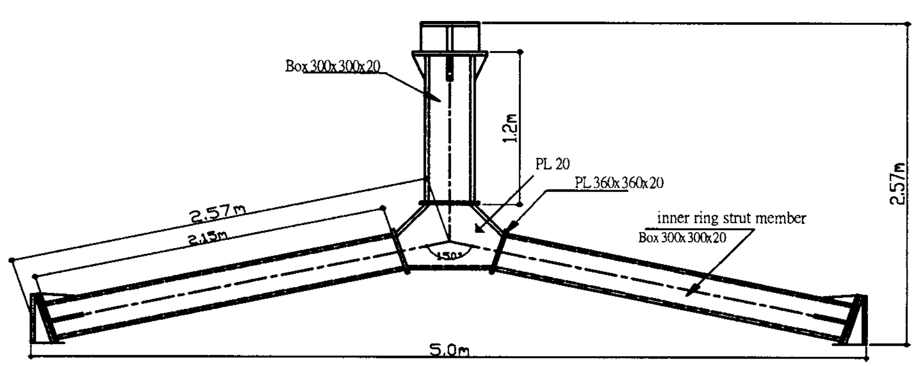

Fig. 8. Configuration of full-scale joint test

Table 4. Mechanical Properties of Strut Member

Member type	Thickness (mm)	A (cm^2)	I (cm^4)	γ (cm)	S (cm^3)	F_y (MPa)	F_u (MPa)
Box 300×300×20	20	224	29,419	11.46	1,961	416	585

design of the joint needs special attention. For a 12-sided-regular-polygon system, there are three different types of joint—Type A, Type B, and Type C, as shown in Fig. 6. From stress analysis of the strut frame system, it is found that the Type A joint is subjected to the highest stress. It was decided therefore to perform a full-scale test on this type of joint. The subassemblage of the joint is shown in Fig. 8. The strut member was Box 300×300×20 of A572 Gr. 50 steel. The mechanical properties of the steel are shown in Table 4. A complete penetration weld was adopted to connect the three struts to form a joint. The detail of the connection is shown in Fig. 8. The test setup is shown in Fig. 9, and Fig. 10 gives the load-deformation relationship. From nonlinear stress analysis performed using *ANSYS*, it was found that the maximum stress is at the corner of the joint as shown in Fig. 11, and Fig. 12 shows the stress status at these points. According to the current design criteria, the allowable working load is 900 kN (when $SR=1.0$), while the analytical yielding load is at 1,560 kN and the experimental yielding load is 1,800 kN. At the load of 3,000 kN, significant yielding can be found, as shown in Fig. 11. Because the ultimate strength is more than three times larger than the design value (900 kN), and also approaches the loading capacity of the actuator, it was decided to unload at 3,000 kN. This test shows that the joint of the strut frame system has adequate strength and is able to provide a safety factor of more than 3.

Case Study of Application

Three-Dimensional Analysis of Foundation Excavation

From the parametric study of the proposed central opening strut system, it has been found that the proposed strut system is a possible alternative bracing system for foundation excavation. However, these simplified analyses have not included the effect of the interaction between the soil, diaphragm wall, and strut system. The effect of the sequence of the construction procedure needed to be examined. A case study was thus performed on site of four

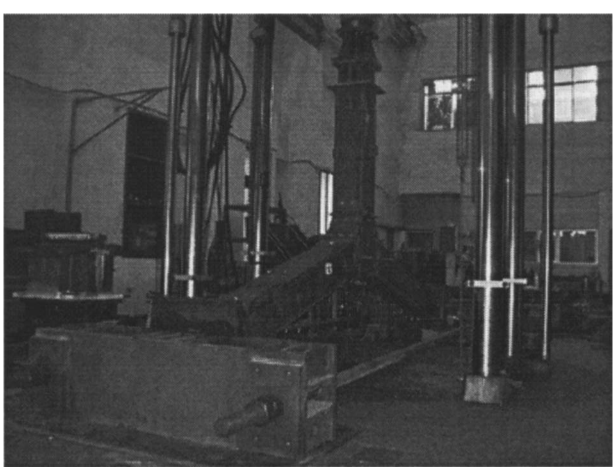

Fig. 9. Setup of joint in laboratory

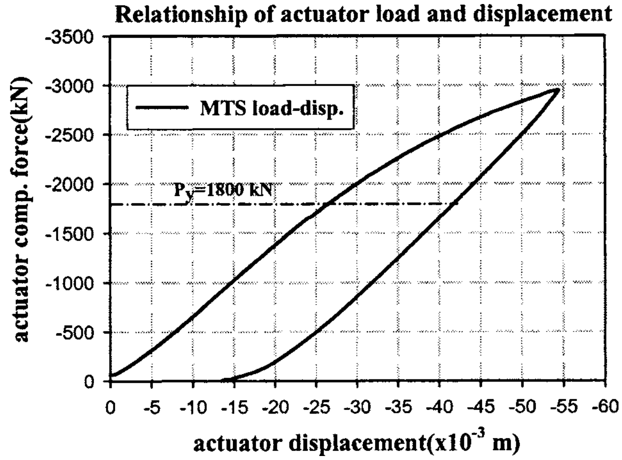

Fig. 10. Load-displacement relationship of test

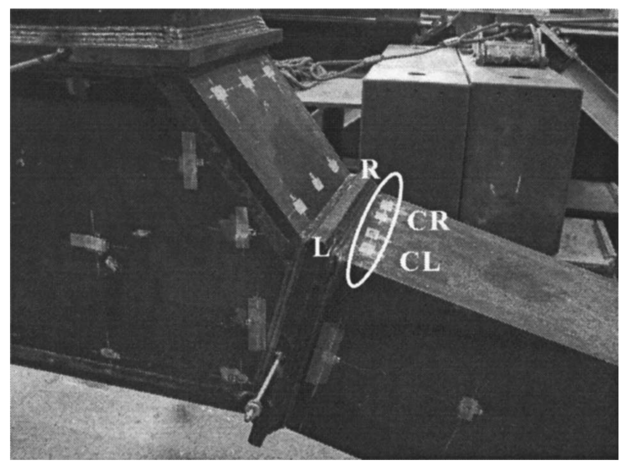

Fig. 11. Maximum concentrated stress of joint and test result

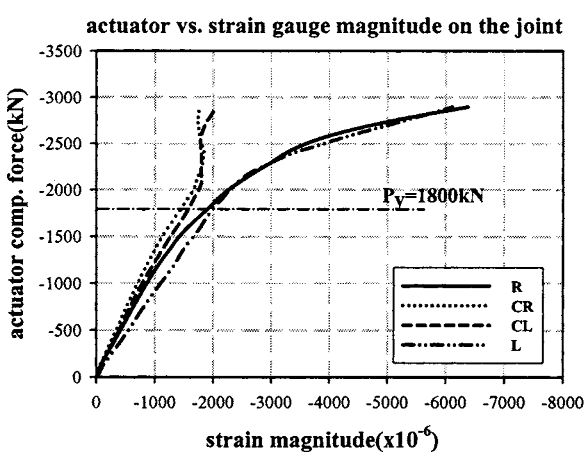

Fig. 12. Joint test results on maximum concentrated stress

J. Constr. Eng. Manage., 2006, 132(1): 58-66

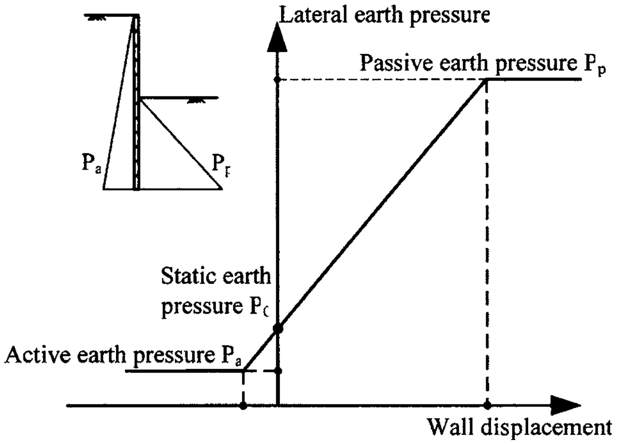

Fig. 13. Stress-deformation relationship of wall

layers of a strut system and scheduled with five stages in the foundation excavation. Due to the nature of the central opening strut system, the earth pressure from one direction is transmitted to the whole system. A three-dimensional analysis is necessary to capture the structural behavior of this new system in transmitting the earth pressure. The three-dimensional nonlinear finite-element program *ABAQUS* was selected and three-dimensional excavation analysis was carried out (*ABAQUS* 1998). A 12-sided-regular-polygon-shaped strut system with two rings was selected as the strut frame. The effect of dewatering, excavation, assembly, and disassembly of the strut system was also examined.

In this study, the soil properties on both sides of the diaphragm wall were assumed to be linear elastic–perfect plastic, as used in the program *RIDO* (*RIDO* 1991), which is a popular commercial package for two-dimensional analysis. The stress-deformation relationship of the diaphragm wall is shown in Fig. 13. At the initial stage, the spring was preloaded to create an equivalent Rankine lateral earth pressure at rest on the diaphragm wall. Following the excavation step, the soil springs inside of the diaphragm wall were removed and these created an unbalanced soil pressure on the opposite side of the diaphragm. This unbalanced pressure

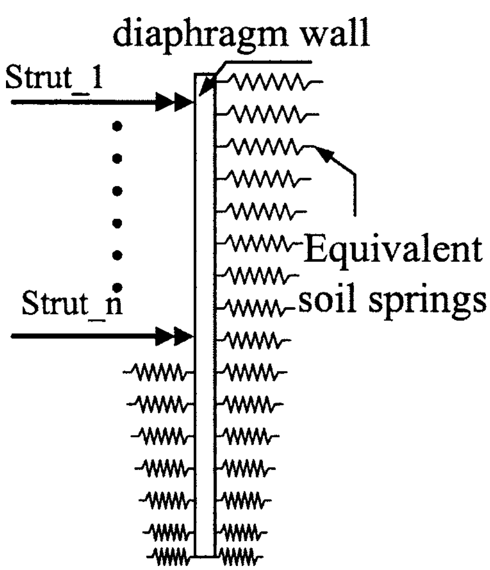

Fig. 14. Analysis procedures (dewatering, excavation, setup, and jack preload)

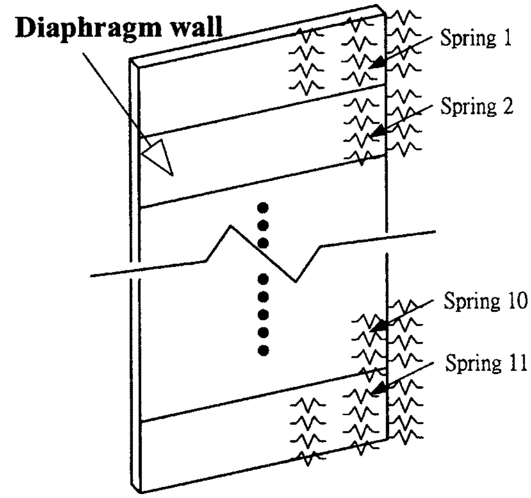

Fig. 15. Different properties of springs at different depth

caused deformation of the diaphragm wall. The analytical procedure is shown in Fig. 14.

The soil pressure on both sides of the diaphragm wall was modeled by the equivalent soil spring and eleven different properties were used to model the soil springs at different depths, as shown in Fig. 15. The active earth pressure P_a, passive earth pressure P_p, and earth pressure at rest P_0 are shown as follows (Terzaghi 1967; Bowles 1988):

$$\left.\begin{aligned} P_0 &= \gamma \cdot H \cdot A \cdot K_0 = P_v \cdot K_0 \\ P_a &= P_v \cdot \tan^2(45° - \phi/2) - 2c \cdot \tan(45° - \phi/2) \\ P_p &= P_v \cdot \tan^2(45° + \phi/2) + 2c \cdot \tan(45° + \phi/2) \end{aligned}\right\} \tag{2}$$

The diaphragm walls were modeled by a nine-node shell element, and the elastic modulus of the wall was $E_c = 2.35 \times 10^7$ kN/m^2. A soil spring was added at the nodes to model the behavior of the earth pressure. The strut member was modeled by the three-dimensional beam-column element. Four layers of strut frames were used. The member size and the preload of the strut frames are shown in Table 5. The parameters of the soil were assumed as $k_S = 4{,}800$ kN/m^3 (Bowles 1988), $K_0 = 0.5$, $c = 0$, and $\phi = 30°$, and the stress-deformation relationship of the soil spring is shown in Fig. 16. The gross hydrostatic pressure was assumed to be acting on both sides of the diaphragm wall. However, the permeability due to different water head on the two sides of the diaphragm wall was neglected.

Analytical Procedure

The excavation site was assumed to be 40 m × 40 m. The thickness of the slurry wall was 0.6 m and the penetration depth of the wall was 22 m. The excavation was scheduled with five stages

Table 5. Strut Size and Magnitude of Preload in 3D Analysis

Layer	Member size (mm)	Preload (kN)
1	Box 300×300×20	400
2	Box 350×350×25	800
3	Box 400×400×32	1,200
4	Box 400×400×32	1,600

J. Constr. Eng. Manage., 2006, 132(1): 58-66

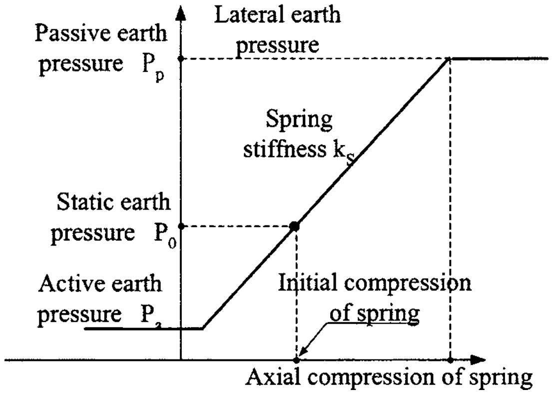

Fig. 16. Stress-deformation relationship of soil spring

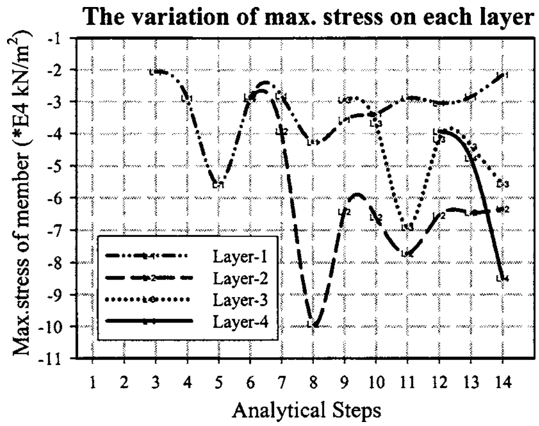

Fig. 18. Variation of maximum stress of strut member

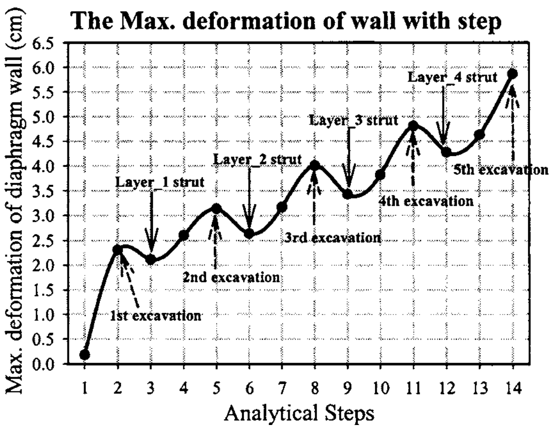

Fig. 17. Maximum displacement of wall at every stage

Table 6. Analytical Results of *ABAQUS*

Step	Maximum displacement ($\times 10^{-2}$ m)	Maximum stress of strut member (MPa)			
		Layer 1	Layer 2	Layer 3	Layer 4
1	0.182	—	—	—	—
2	2.305	—	—	—	—
3	2.112	−20.67	—	—	—
4	2.601	−28.90	—	—	—
5	3.132	−55.93	—	—	—
6	2.638	−29.10	−28.47	—	—
7	3.167	−28.25	−39.22	—	—
8	4.002	−42.66	−99.18	—	—
9	3.427	−35.69	−64.35	−29.44	—
10	3.819	−33.85	−66.06	−36.72	—
11	4.802	−29.02	−77.20	−69.22	—
12	4.273	−30.47	−65.44	−41.77	−39.25
13	4.626	−28.57	−64.66	−43.92	−47.66
14	5.862	−21.68	−63.50	−55.69	−84.86

and with four layers of the strut frame system. The following lists the step-by-step analysis according to the construction procedures:

- Step 1: The initial status before excavation. Earth pressure is acting on both sides of the diaphragm wall. After dewatering, the underground water level is −3 m inside the wall and −1 m outside of the wall.
- Step 2: Completion of the first stage of excavation. The depth of the excavation is −2 m from the ground.
- Step 3: Completion of assemblage of the first layer strut frame system. The elevation of the strut frame is −1.3 m from the ground and preloaded with 400 kN.
- Step 4: Dewatering of the second stage. The underground water level is −6 m inside the wall and −1 m outside of the wall.
- Step 5: Completion of the second stage of excavation. The depth of the excavation is −5 m from the ground.
- Step 6: Completion of assemblage of the second layer strut frame system. The elevation of the strut frame is −4.5 m from the ground and preloaded with 800 kN.
- Step 7: Dewatering of the third stage. The underground water level is −9 m inside the wall and −1 m outside of the wall.
- Step 8: Completion of the third stage of excavation. The depth of the excavation is −8 m from the ground.
- Step 9: Completion of assemblage of the third layer strut frame system. The elevation of the strut frame is −6.5 m from the ground and preloaded with 1,200 kN.
- Step 10: Dewatering of the fourth stage. The underground water level is −11 m inside the wall and −1 m outside of the wall.
- Step 11: Completion of the fourth stage of excavation. The depth of the excavation is −10 m from the ground.
- Step 12: Completion of assemblage of the fourth layer strut frame system. The elevation of the strut frame is −8.5 m from the ground and preloaded with 1,600 kN.

Table 7. Variation of Member Stress at Different Stages

Strut layer	*A* (cm^2)	Stress difference (MPa)	Force difference (kN)
Layer 1	224	35.26	789.8
Layer 2	325	70.71	2,298.1
Layer 3	417	39.78	1,873.6
Layer 4	417	45.61	2,148.2

J. Constr. Eng. Manage., 2006, 132(1): 58-66

Table 8. Effect of Maximum Axial Force Change by Dewatering (kN)

Strut layer	A (cm^2)	Axial force variation due to dewatering				Axial force variation due to excavation			
		2nd dewatering	3rd dewatering	4th dewatering	5th dewatering	2nd excavation	3rd excavation	4th excavation	5th excavation
Layer 1	224	−184.35	19.04	41.22	42.56	−605.47	−322.78	108.19	154.34
Layer 2	325	—	−349.38	−55.58	25.35	—	−1,131.98	−362.05	37.70
Layer 3	417	—	—	−342.89	−101.27	—	—	−1,530.75	−554.37
Layer 4	417	—	—	—	−396.11	—	—	—	−1,752.12

Note: Minus sign indicates increase in axial force.

- Step 13: Dewatering of the fifth stage. The underground water level is −13 m inside the wall and −1 m outside of the wall.
- Step 14: Completion of the fifth stage of excavation. The depth of the excavation is −12 m from the ground.

Discussion of Analytical Results

Fig. 17 shows the maximum displacement of the diaphragm wall at different excavation steps. From Fig. 17, the deformation of the diaphragm wall is seen to increase as the excavation and dewatering increase. However, the assembling and preloading of the strut frame system will decrease the deformation. From Table 6, it is found that the displacement of the wall due to dewatering is about 1.945×10^{-2} m and that due to excavation is 5.708×10^{-2} m. The ratio of displacement due to dewatering and excavation is about 1:2.93. If the effect of underground water is neglected in order to simplify the analytical procedure, the total displacement of the wall can be estimated by increasing by 1/3 the displacement obtained ignoring the effect of water. In this study, the maximum displacement of the wall is 5.862×10^{-2} m at −2 m under the excavation level.

The variation of the maximum stress of the strut member is shown in Fig. 18 and Table 6. The maximum stress of the strut member occurred at the dewatering and excavation. The member stress of the strut decreases with the assemblage of other layers of the strut frame system. Table 7 shows the variation of the member stress at different stages. It is shown that the maximum stress variation is about 2,148.2 kN and occurred at the fourth layer. This is because the fourth layer is subjected to the maximum earth pressure.

Table 8 lists the effect of dewatering and the excavation procedure on the axial force of the strut member. It is found that dewatering and excavation immediately after the erection of the strut frame are the major factors that induce highly compressive axial force on the strut. In comparing the effect of dewatering and excavation on the member force of the strut, it is found that the increase of axial force by excavation is about 3∼4.5 times larger than the force induced by the dewatering, the same as the total stresses at different steps caused by excavation and dewatering. This is because the dewatering only affects the previous layer of the strut frame, whereas the excavation will affect the member force of the previous two layers. As a quick estimation, the member force can be estimated by an increase of 20–30% to account for the effect of dewatering.

Summary and Suggestions

This research examines a new internal bracing system for foundation excavation. The basic concept is to utilize the arch action and transmit the earth pressure from one direction to the other directions. By this arrangement, a large open space can be provided at the center of the construction site. This new system is referred to as the central opening strut system. The following provides a summary and suggestions obtained from this study:

1. Considering the stress distribution on the strut and the number of joints, a 12-sided-regular-polygon central opening strut frame system is suggested.
2. The earth pressure is transmitted to a regular polygon strut frame system through the arch action. This will induce both axial force and bending moment on the strut member. It is suggested to adopt a box section for the strut member in order to provide better axial, flexural, and torsional strength.
3. The distance between two rings has a minor effect on the maximum stress of the strut member; however, considering the space of the central opening and the requirement for joints of the strut members, it is suggested to use 3 m as the distance between two rings.
4. Unbalanced earth pressure on two sides of the diaphragm wall due to excavation affects the member force of the strut greatly. Dewatering has only a minor effect on the axial force of the strut member. To simplify the calculation, the stress and deformation of the strut system can be estimated by increasing that due to excavation by 1/3 and ignoring the effect of the dewatering.
5. A full-scale experimental study demonstrated that a fully welded connection of the box strut joint can successfully develop its ultimate strength and can provide a safety factor larger than 3 times.
6. This study examines the possibility of a new internal bracing frame system for foundation excavation. From this pilot study, it is found that the proposed central opening strut system is able to provide a large working space and better strength for the bracing system. However, further study is necessary in order to develop design and construction guidelines for the application of this new system.

Acknowledgment

This research work was sponsored by the China Engineering Company, Inc.

Notation

The following symbols are used in this paper:

A = area of wall element under spring force (m^2);
c = cohesion of soil (kN);
E_c = elastic modulus of diaphragm wall (kN/m^2);
F_y = yielding stress;

J. Constr. Eng. Manage., 2006, 132(1): 58-66

H = depth from ground level (m);
K_0 = coefficient of earth pressure at rest;
k_S = soil stiffness (kN/m^3);
N = sides of regular polygon;
P_a = active earth pressure (kN);
P_P = passive earth pressure (kN);
P_v = vertical pressure of soil element (kN);
P_0 = rest earth pressure (kN);
R = radius of external intersection circle of polygon;
S = length of each side of regular polygon;
SR = stress ratio; i.e., $SR=f/F_a$ (f=maximum stress; F_a=allowable stress);
β = interior angle of regular polygon;
γ = unit weight of soil (kN/m^3); and
ϕ = drained friction angle (°).

References

ABAQUS standard user's manual. (1998). Hibbit, Karlsson & Sorensen, Pawtucket, R.I.

American Institute of Steel Construction (AISC). (1989). *Specification for the design, fabrication, and erection of structural steel for buildings*, Chicago.

Bowles, J. E. (1988). *Foundation analysis and design*, McGraw-Hill, New York.

Das, B. M. (1995). *Principles of foundation engineering*, PWL-Kent Publishing, Boston.

RIDO user's manual. (1991). Robert Fages Logiciels, Miribel, France.

Terzaghi, K. (1967). *Soil mechanics in engineering practice*, Wiley, New York.

Xanthakos, P. P. (1994). *Slurry walls as structural system*, McGraw-Hill, New York.

J. Constr. Eng. Manage., 2006, 132(1): 58-66