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Base shear reaction and resisting capacity of deep diaphragm for tall buildings

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Absract

Generally diaphragm walls are built to exclude water and soil from an area so that work can 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 deep basements, underpasses, underground stations, tunnels docks etc. Although there are numerous literatures which address the integrated soil-foundation-structure system of tall buildings, the impacts of diaphragm walls have been rarely investigated especially. The design of dual-purpose diaphragm walls means that the walls are used as retaining walls as well as outside walls of the basement. The diaphragm is always used to bear partial vertical loadings, but whether the diaphragm can bear the horizontal loading is still a controversial question. A case study example is presented to demonstrate the process of modeling the complex interaction between the structure an soils using finite element program.The results show the diaphragm walls bear most of the base shear while the pile's reaction is small compared to its own resisting capacity.The real project in this paper may provide some 'benchmark values' upon which can be used as references for practicing engineers.

Key words: Diaphragm walls, Deep foundation, Soil -structure interaction, Tall buildings

1. Introduction

Generally diaphragm walls are built to exclude water and soil from an area, so that work can be performed under reasonably dry condition，especially when the environment protection is severe. The diaphragm walls have the advantage of high stiffness, good integrity, and small deformation. It always adopted as 'dual-purpose diaphragm walls'. The design of dual-purpose diaphragm walls means that the walls are used as retaining walls as well as outside walls of the basement. The diaphragm walls were used to bear vertical and horizontal loadings in normal service stages. It has been proved that the dual-purpose diaphragm walls are economic. Chen (2015) adopted dual-purpose diaphragm wall to optimize a deep excavation engineering.

When it serves as supporting structure, its bearing capacity should be predicated and calculated. Many works devote to the vertical bearing capacity of diaphragm walls. El-Razek (1999) reports 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. Wang (2005) discussed some key techniques for diaphragm walls design based on the research and practice. SUN (2014) take an excavation in Wuhan project as an example, the field monitoring results of static load tests are combined with the post-settlement calculation method to analyze the vertical ultimate bearing capacity of the diaphragm wall. Moreover, Ng et al. (1995) carried out an approximate analysis of the three-dimensional effects consisting of a simultaneous plan (plane stress) and vertical (plane strain) analysis. Chu E Ho et al. (2014) demonstrate the process of modeling the complex interaction between the diaphragm walls and bracing elements for a subway station box. Emilios M. Comodromos (2013) proposed a new approach for simulating the excavation and construction of subsequent panels is proposed to investigate the effects from the installation of diaphragm walls on the surrounding and adjacent buildings.

As we all know, the basement of tall buildings bears a great base shear under wind load. Designers always don't consider shear resisting capacity of diaphragm in a normal design while the shear resisting system of the deep foundation contains two parts: diaphragm walls and piles. If we consider the shear resisting capacity of diaphragms, there would be a substantial opportunity for reducing the steel reinforcement requirement of piles. Thinking it was important to investigate this, a computational simulation was carried to verify the base shear resisting capacity of diaphragm walls.

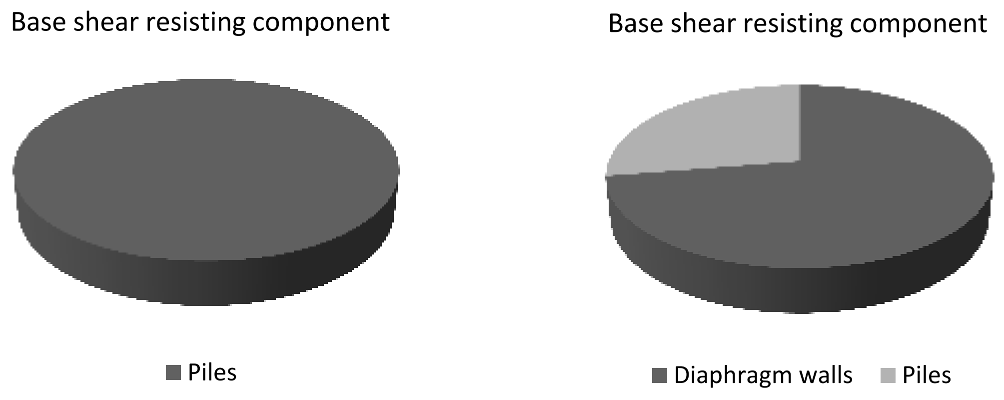
2. Resisting capacity design

The diaphragm wall was designed as a dual-purpose diaphragm wall, which is adopted as retaining wall as well as outside wall of the basement. The wind loads or seismic loads acting on the tower would transfer to basement and then pass to lateral soils.

The contribution of diaphragm walls to resist the base shear was not considered in a normal design while diaphragm wall is always used as earth-retaining wall. As we all known, the diaphragm wall showed a high stiffness and small deflection. Taking into account of soil-foundation-structure interaction, diaphragm walls have the ability to bear the most of the base shear.

Diaphragm walls and piles are all have the ability to resist the base shear. Assuming that the limit base shear resisting capacity of diaphragm walls (F_p) is bigger than the total base shear of the office tower (V), we could think the diaphragm walls carried almost of the base shear and the piles bear nothing or little. This new method of design would reduce the steel reinforcement requirement of piles.

Fig.1 show the differences between two designs, the first is a normal design which only using piles to resist the total base shear, and the second new design is proposed in this paper to consider the great base shear capacity of the diaphragm walls.



a) normal design b) new design

Fig.1 Resisting capacity design

3. Project description

The engineering located in Hongkou District Shanghai has total floor area of 430000 square meters, 170 meters from north to south and 225 meters from east to west. This tall building consists of two 33-storey office towers and a seven-storey commercial podium. The structure height of its tower is about 170m, and basement of the station is 23m below the ground surface.

The components of the structure include diaphragm walls, floors, columns and the drafts. The diaphragm wall is located outside of the basement and the thickness of diaphragm walls is 1.2m. The length and width of the column is 1000×1000mm. The thickness of the floor is 300mm, and the raft under the office tower is 2600mm. The entire site consists of four layers basement, and its foundation is 23m below the ground surface. This engineering uses bored piles (with post-grouting), the concrete grade is C50, and the bearing layer is silt clay located in ⑨ layer. The number of piles is 256, the diameter of the pile is 0.85m, and the space of piles is about 3m which using variable rigidity design for balance settlement.

4. Modeling techniques and design parameters

4.1 soil models

Numerical models involving finite element modeling (FEM) can offer several approximations to predict true solutions. The accuracy of this approximation depends on the modeler’s ability to portray what is happening in the field. Often the problem being modeled is complex and has to be simplified to obtain a solution. Finite element method has become more popular as a soil response prediction tool. This has led to increased pressure on researchers to develop more comprehensive descriptions for soil behavior, which in turn leads to more complex constitutive relationship.

Prevost and Popescu (1996) state that for a constitutive model to be satisfactory it must be able to: 1) define the material behavior for all stress and strain paths; 2) identify model parameters by means of standard material tests; and 3) physically represent the material response to changes in applied stress or strain.

Previous studies have explored constitutive models and found that the use of isotropic models such as elasto-plastic Mohr-Coulomb and Drucker-Prager models are sufficiently accurate and easy to use.

The initial pre-construction at-rest earth pressures (Ko) was determined based on an assessment of the site history. The Mohr-Coulomb soil model was adopted for the soil layers, assuming fully drained conditions apply at all excavation stages. Effective soil friction angles (φ') and effective cohesion (c') were determined from consolidated drained triaxial tests. $E_{S0.1\text{-}0.2}$ presents compression modulus when the test pressure varied from 100 kPa to 200 kPa. In real soils, the stiffness depends significantly on the stress level, which means that the stiffness generally increases with depth. When using the Mohr-Coulomb model, the stiffness is a constant value. It should be noticed that using a constant stiffness modulus to represent soil behavior one should choose a value that is consistent with the stress level and the stress path development.

Table1. Typical input soil parameters

No.	Soil Name	Thickness（m）	Weight (kN/m^3)	void ratio *e*	Compression modulus $E_{S0.1\text{-}0.2}$(kN/m^2)	Efftive cohesion *c´*(kPa)	Effective friction angle *φ´*（°）	Hydraulic conductivity k_x（m/d）	k_y（m/d）
①1	Miscellaneous fill	1	18.0	--	--	--	--	--	--
②2	clayey silt	1	18.6	0.837	8160	6	24	0.0272	0.0502
③1	clayey silt	5.8	18.6	0.841	8900	5	26	0.0687	0.1132
④	mucky silt	5.8	16.7	1.430	2488	10	12	0.0001	0.0001
⑤1	Clay	3.8	17.3	1.200	2800	13	12	0.0001	0.0002
⑤2	clayey silt and Sandy clay	26.4	18.5	0.839	9900	5	32	0.1771	0.2894
⑦	Silty clay	8	18.5	0.857	9920	5	32.5	0.1426	0.2376
⑧1-1	silty clay	9.2	18	0.993	4550	16	19	0.0003	0.0006
⑧1-2	Silty sand	6	18.4	0.913	4810	18	20	0.02	0.02
⑧	Silty sand	4	18.5	0.84	7450	9	29	0.02	0.02

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⑨	silty clay	27	19.0	0.731	13130	3	35	0.02	0.02
⑩	Granite		--	--	--	--	--	--	--

The hydraulic conductivity (k) for the soils is varied in different directions. Table 1 shows the hydraulic conductivity in X (k_x) and Y(k_y). In all cases, the diaphragm wall-soil interface friction angle was assumed to be 0.5φ'. Table 1 summarizes the soil model parameters adopted in this finite element program.

The structure and soil strata are modeled in the 2D finite element program (input window as show in Fig.2). The model includes soil strata and structural element, like the diaphragm, the column and the beam. For considering the boundary conditions, the model is taken as 240m and 140m, two times width and one time depth than the basement.

An implicit integration of linear elastic perfectly plastic model which called Mohr-Coulomb model was used in the process of calculation. In this model the stress increments can generally be written as:

$\Delta\sigma = D^e(\Delta\varepsilon - \Delta\varepsilon^p)$, (1)

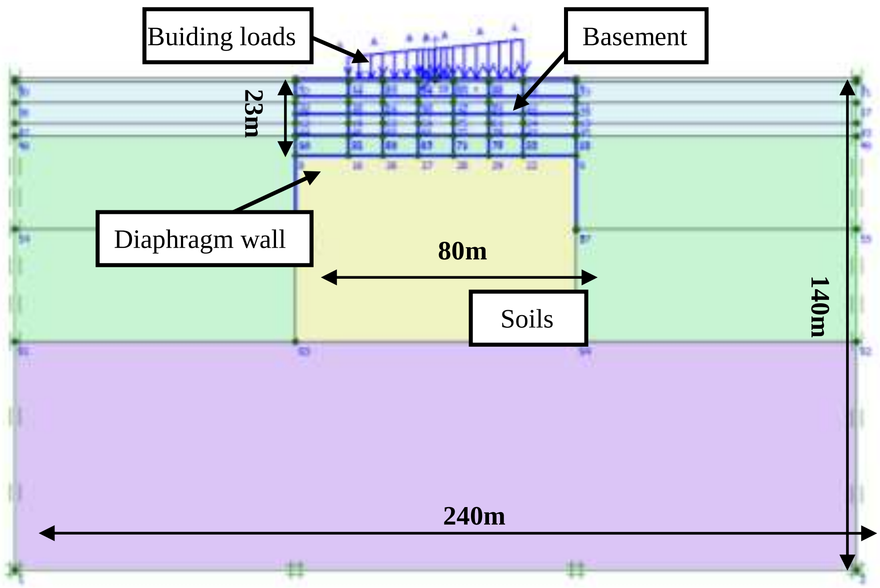

Fig.2 Numerical modeling

In this relation $\Delta\sigma$ represents the stress increment, D^e represents the elastic material matrix for the current increment. The strain increments are $\Delta\varepsilon$ obtained from the displacement increments using the strain interpolation matrix. For elastic material behavior, the plastic behavior, the plastic strain increment is zero. For plastic material behavior, the plastic strain increment $\Delta\varepsilon^p$ can be written as:

$$\Delta\varepsilon^{p} = \Delta\lambda\left[(1-\omega)(\frac{\partial g}{\partial\sigma})^{i-1} + \omega(\frac{\partial g}{\partial\sigma})^{i}\right], \quad (2)$$

In this equation $\Delta\lambda$ is the increment of the plastic multiplier and ω is a parameter indicating the type of time integration. For $\omega = 1$ the integration is called implicit.

Biot's theory was used in this finite element program when considering the consolidation of the soils. Darcy's law for fluid flow and elastic behavior of the soil skeleton are also assumed.

4.2 structure models

The diaphragm walls and structural floors were modeled as elastic plate elements in finite element program, with full fixity at the connections. The contribution of the steel reinforcement in the concrete section was ignored. Table 2 summarizes the typical properties assumed for modeling the structural elements in program. γ represents the unit weight of the material. E presents elastic modulus, A presents the cross-section area, I represents geometrical moment of inertia.

Table2. Input parameters of structural element

Materials	models	$\gamma(kN/m^3)$	EA(kN/m)	EI (kN·m^2/m)
Diaphragm	Elasitc	25	4.20×10^7	5.04×10^6
column	Elasitc	25	5.04×10^7	6.05×10^6
Beams	Elasitc	25	1.75×10^7	3.68×10^5
Piles	Elasitc	25	6.62×10^6	5.98×10^5

5. Results

In this paper the base shear reaction and resisting capacity of diaphragm walls have been investigated using a new method for simulating this project. The results of the numerical analysis confirmed the diaphragm walls take the most of the base shear.

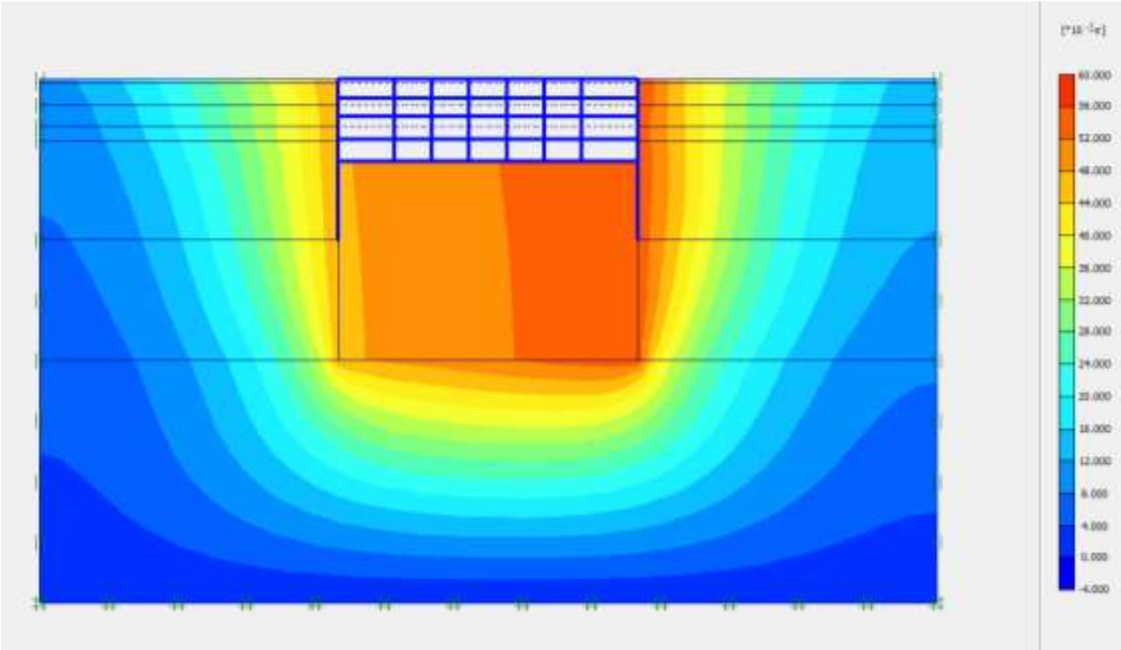

Fig.3 Displacement contour

The displacement contour of the deep foundation is shown in Fig.3. The results show that the deep foundation tilts to the right side under such loadings. The biggest settlement is about 56mm occurs in the top right of the basement. The soils in the right side of the basement are in a passive earth pressure area, while the left are in an active earth pressure area. And the deep foundation is in a balance state.

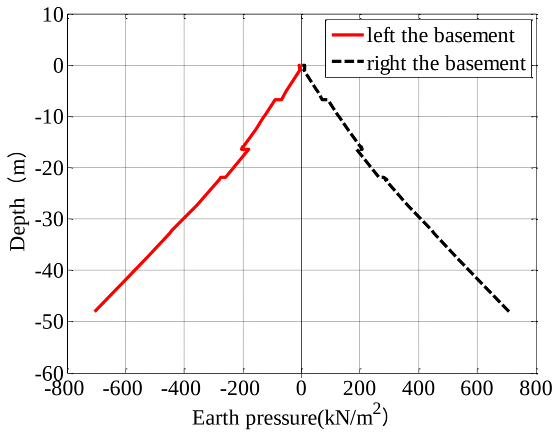

Fig.4 The earth pressure

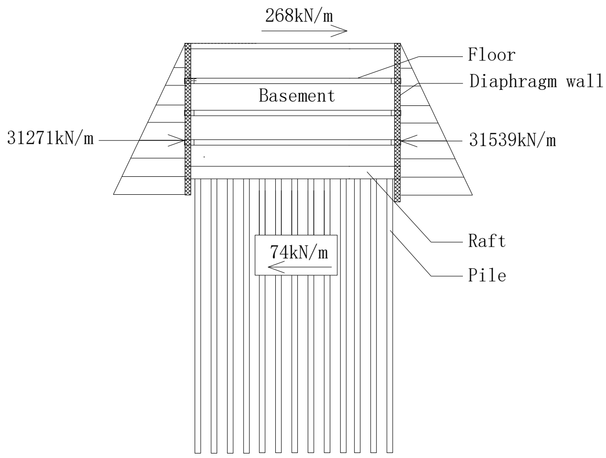

Fig.5 Horizontal loadings distribution

Fig.4 showed the earth pressures along the diaphragm walls. The pressure in active and passive pressure area has a similar distribution but different values. The total pressure in passive earth pressure area is bigger. And we calculate the total pressure in the left of the basement is 31271 kN/m, while 31539 kN/m in the right. While the horizontal loading transform from the upper structure is 268 kN/m. So we can easily judge that the piles bear the 74 kN/m. Each pile under the basement should be assigned only about 28.9 kN. The piles even without special reinforcement can satisfy the practical requirement. The horizontal loadings are shown in Fig.5.

Table3. The reaction and resisting capacity of diaphragm wall and single pile

	Reaction(kN)	Resisting capacity(kN)	Proportion
Diaphragm wall	19400	140600	7.2%
Single pile	28.9	80.1	36%

Table 3 demonstrates that the actual reaction of a single pile is only about 36% of the resisting capacity in this project. It's safe to not consider base shear resisting capacity of piles in design. Therefore, such a method offers substantial opportunity for reducing the steel reinforcement requirement.

6. Conclusions

Dual-purpose diaphragm walls have been widely used in China, especially in Shanghai. It was proved to be a technically and economically viable foundation system in structural support when using the rigid diaphragm to bear partial vertical and horizontal loading.

And we can conclude that:

1. The simple method proposed to solve this problem is reasonable. When the friction between the diaphragm and the soil is neglected, the result is conservative.

2. The results of numerical analysis showed that the actual reaction of a single pile is 36% of its resisting capacity while the diaphragm walls bear most of the base shear. For similar project, we can use the diaphragm to bear partial vertical and horizontal loading. But, in actual project we should verify it before making a judgment.

3. Whether the diaphragm can bear the horizontal loading is still a controversial question, and less engineering can reference. Under these circumstances, a full building modeling providing a more accurate soil–structure interaction, is required. This paper may provide some 'benchmark values' to engineers.

7. Acknowledgements

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