Design and performance of the piled raft foundation for Shanghai World Financial Center

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ABSTRACT

A case history of the piled raft foundation for Shanghai World Financial Center which is a 101-storey, 492 m high building is presented in this paper. To monitor the performance of the piled raft foundation system and to verify the foundation design work, field measurements were carried out on the raft settlements, pile head axial loads, contact pressures of the raft and pore-water pressures underneath the raft during the entire construction period. The measured raft settlements were comparable to the computed results. At six months after topping out, the maximum settlement was 130 mm in the tube area, decreasing to 90 mm at the edges. Axial loads at pile head increased gradually and varied in magnitude from 1000 to 5000 kN, less than the proposed compression capacities of the steel pipe piles. Both contact pressures of the raft and pore-water pressures beneath the raft varied considerably during the initial construction period but changed slightly after the end of construction. Based on the field measurement results, the piled raft foundation design proved to be appropriate.

Keywords: foundations, piled raft, design, settlement, field monitoring

1. INTRODUCTION

Shanghai is one of the fastest growing cities in terms of skyscraper construction in the world. In recent decades, an increasing number of high-rise buildings have been constructed or are under construction. Most of these tall buildings are founded on piled rafts. Since Burland et al. (1977) presented the concept of “settlement reducers”, there has been an increasing recognition that the use of piles to reduce raft settlements and differential settlements can lead to considerable economy without comprising the safety and performance of the foundation (Poulos, 2001). As the raft settlement is crucial to a piled raft foundation system, it is demanded to estimate the settlement distributions of a piled raft at the design stage by considering the complex interaction among the soil, raft and piles. In addition, field monitoring is required to verify the validity of the foundation design and to improve the understanding of the mechanics of behavior of piled rafts (O’Neill et al., 1996, Mandolini et al., 2005).

A case history of design and performance of the piled raft foundation for Shanghai World Financial Center (SWFC) is presented in this paper. The settlement behavior of the piled raft is analyzed by using a computer program PWMI which can take the pile-soil-raft interactions into account based on Geddes solution. To verify the design assumptions, extensive instruments were installed on site to monitor the raft settlements, pile head axial loads, contact pressures of the raft and pore-water pressures underneath the raft during the entire construction period. Comparisons are made between the observed raft settlements and computed values. Finally the performance of the piled raft is investigated based on the field monitoring results.
2 DESCRIPTIONS OF SHANGHAI WORLD FINANCIAL CENTER

Shanghai World Financial Center is a mixed-use skyscraper located in the heart of Pudong Lujiazui financial district on the eastern bank of Huangpu River in Shanghai. The building consists of a 101-storey, 492 m high main tower above the ground surface and a three-storey basement below ground. As shown in Fig. 1, the tower’s basic form is that of a square prism, 58 m on a side, intersected by two sweeping arcs to form a six-sided shape, and finally tapering into a single diagonal line at the apex (Katz and Robertson, 2008). To resist lateral loads from wind and earthquake, a unique structural system has been developed for this building. The system comprises three main components, i.e., the mega-frame structure consisting of mega-columns, diagonals and belt trusses, the concrete shear walls and the outrigger trusses connecting the mega-columns and the concrete shear walls.

3 GEOLOGICAL CONDITIONS

Shanghai is situated on the Yangtze River delta where the geology is generally composed of alluvial and marine sediments deposited during the Quaternary period. The ground conditions at this site comprise variable horizontally stratified clayey and sand strata due to alternating climates and sea level changes. The upper clay layers are underlain by successions of various aquifers inter-bedded with silt and clay layers. Field exploration and laboratory tests show that the sub-soils down to a depth of about 28.7 m can be divided into ① fill (0-1.7 m), ② silty clay (1.7-3.0 m), ③ soft silty clay (3.0-7.0 m), ④ soft clay (7.0-17.7 m), ⑤ firm silty clay (17.7-23.7 m), ⑥ stiff silty clay (23.7-28.7 m). Between depths of 28.7-71.1 m, there lies fine sand and silt (layer ⑦). A fine-coarse sand layer (layer ⑨) is located below a depth of 71.1 m. Layers ⑦ and ⑨ are artesian and referred to as Aquifer I and II, respectively. These two sandy aquifers are inter-connected as a silty clay layer (layer ⑧) is not found between them at this site. Groundwater levels are generally high across the site and located about 0.5m below the ground surface. A typical ground profile and geotechnical parameters derived from the investigation data and experience of similar soils on adjacent sites are summarized in Table 1.

4 FOUNDATION DESIGN

4.1 Foundation layout

Fig. 2 shows the schematic diagram of the foundation for the main tower of SWFC which occupies a total square footprint of 70 m by 70m. The foundation consists of a piled raft with 985 steel pipe piles, each 0.7 m in diameter. The raft is embedded at 14.5 m below the ground and constructed using C40 concrete (28-day compressive strength is 19.1 MPa). The central part of the raft is 4.5 m thick, decreasing to 4.0 m at the edges. There are 225 piles underneath the

- Table 1 Summary of soil profile and geotechnical parameters
- Fig. 2 Piled raft foundation for the main tower of SWFC
central portion of the raft. Each pile is 60.7 m long and has a wall thickness of 18 mm. These piles are embedded in coarse sand (layer ⑨) and have a compression capacity of 5750 kN. The rest pipe piles whose wall thickness is 15 mm are driven into the fine sand layer at a depth of 41.7 m beneath the raft and have a compression capacity of 4250 kN.

4.2 Settlement analysis

In order to estimate the raft settlements, a computer program PWMI developed by Wang et al. (2007) has been used as a preliminary design tool. In PWMI, the raft is modeled as a thick plate, the soil-pile interactions are analyzed based on Geddes solution and the walls are treated as beam elements. At each raft node, the equivalent piled raft stiffness is formed by adding the soil-pile stiffness, the raft stiffness and the wall stiffness together. Based on the equivalent raft stiffness, the settlements and stresses of the raft subjected to vertical loads can be determined once the displacement compatibility condition is satisfied.

In the deformation analysis, the vertical loads transferred to the raft from the columns are modeled as concentrated loads, while the loads from shear walls are considered as knife edge loads. All the loads from the superstructures are directly applied on the raft nodes. The numerical model of the raft consists of 30591 quadrilateral and 1010 triangular elements. Soil parameters used in the analyses are given in Table 1.

Fig. 3 Contours of computed raft settlements (unit: mm)

Fig. 3 shows the contours of the computed raft settlements for the area enclosed by the dashed line as illustrated in Fig. 2 under both static and live loads. The raft for the main tower shows a basin-shaped settlement profile. The maximum settlement is about 113 mm in the center, decreasing gradually to about 72 mm at the edges. The largest computed differential settlement of the raft is 41 mm, giving rise to an angular rotation of around 1/850.

5 FIELD MONITORING

5.1 Instrumentation

The raft settlements were measured by precise levelling of settlement markers which were made of stainless steel rods, 10 cm long and 16 mm in diameter. They were set up in the raft before the concrete hardened and had a slightly protruding rounded head that was always findable by a surveyor. A total of 29 settlement monitoring points were placed over the entire raft as shown in Fig. 4. Three strain gauges were installed at the head of each instrumented pile to investigate the axial load distribution. Earth pressure cells and piezometers were installed beneath the raft near the instrumented piles to register earth pressures and pore water pressures, respectively. The field monitoring extended from the completion of raft construction to about six months after topping out. Due to paper length limit, monitoring points for pile-head axial loads, contact pressures and pore pressures are not shown in Fig. 4.

5.2 Field monitoring results

Raft settlements

For clarity, only the raft settlements along cross-section A-A (see Fig. 4) is presented in this paper and shown in Fig. 5. The initial values of settlement were taken right after the completion of casting the foundation slab. The settlement curves for the monitoring points in the tube area are almost overlapped, suggesting the raft settled uniformly in the area. The raft settlement increased gradually to about 40 mm about 20 months after the monitoring began.
Thereafter, the raft settlement increased significantly with construction progress. When the building was topped out in December 2007, the raft settlement reached about 100 mm in the tube area. Additional 30 mm settlement took place in a period of six months after topping out. Raft settlements at edges show a similar trend to those in the tube but with smaller magnitudes. The raft settlements seemed to reach a steady value at the end of the monitoring period.

The measured results. The computed settlements are also included in this figure for comparison. The maximum raft settlement was found to be 36 mm, giving rise to an angular rotation of 1/500. The computed settlements are also included in this figure for comparison. The measured raft settlement profile along cross-section A-A is shown in Fig. 6. It is clear that the observed settlements in the tube area were larger than those at edges. At the time when the building was topped out, the maximum settlement at the north side (point 14) was 75 mm that was larger than the value of 64 mm at the south side (point 22), suggesting the raft was tilted. The largest differential settlement was found to be 36 mm, giving rise to an angular rotation of 1/500. The computed settlements are also included in this figure for comparison. The maximum raft settlement computed by using PWMI is comparable to the measured results.

Pile-head axial loads, contact pressures and pore water pressures

The pile-head axial loads kept increasing during the construction period. At the end of construction, the pile-head axial loads for piles beneath the raft varied from 1000 to 5000 kN, less than the proposed compression capacities. The measured contact pressures between raft and soil and pore water pressures beneath the raft agreed fairly well with each. Both of them increased significantly in the initial construction period (before the fifth floor), varied slightly thereafter and tended to decrease after the end of construction. The contact pressures varied considerably from 80 to 140 kPa, while the pore pressures were in the range of 100-190 kPa.

6 CONCLUSIONS

The design of the piled-raft foundation for Shanghai World Financial Center, 101-storey and 492 m high, is presented in this paper. The raft settlement was estimated by using a computer program PWMI. To monitor the performance of the piled raft foundation system and to confirm the foundation design work, field measurements were carried out on the raft settlements, pile head axial loads, contact pressures of the raft and pore-water pressures underneath the raft during the entire construction period. The measured raft settlements were comparable to the computed results. At six months after topping out, the maximum settlement was 130 mm in the tube area, decreasing to 90 mm at the edges. The pile-head axial loads increased gradually and varied in magnitude from 1000 to 5000 kN, less than proposed compression capacities. Contact pressures of the raft and pore-water pressures underneath the raft agreed fairly well with each. Both of them varied considerably in the initial construction period but changed slightly after the end of construction. Based on the field measurement results, the piled raft foundation design for the SWFC proved to be appropriate.

REFERENCES