Computers and Geotechnics 55 (2014) 482–493

Contents lists available at ScienceDirect

Computers and Geotechnics

journal homepage: www.elsevier.com/locate/compgeo

Numerical investigation of the failure of a building in Shanghai, China

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ARTICLE INFO

Article history:
Received 26 July 2013
Received in revised form 8 September 2013
Accepted 10 October 2013
Available online 2 November 2013

Keywords:
Case study
Pile foundation
Soft ground
Finite element analysis
Excavation

ABSTRACT

The overturning failure of a 13 storey residential building in Shanghai, China, has been investigated by plane strain finite element analysis (FEA). The results of the FEA indicate that ultimate failure of the building was probably initiated by the formation of tensile cracking in the reinforced concrete piles located under the side of the building adjacent to an excavation. This eventually led to complete structural failure of the piles located along the excavation side, which probably caused further settlement of the building, leading eventually to a toppling failure resulting in overturning of the entire building. Excessive tensile stress in the piles was probably caused by the combination of excavation of soil at one side of the building and the temporary dumping of the excavated soil on the opposite side of the building. It is likely that the effect of temporary dumping of the excavated soil adjacent to the building was either not considered or not properly taken into account in the foundation design nor the construction operations. A simple but important lesson to be draw from this failure is the need for engineers who design foundations in soft soil regions to consider not only the final loading conditions, but also any temporary and transient loading conditions during the construction process.

1. Introduction

A residential complex has been developed at Minhang District, Shanghai, China, which consists of 11 residential buildings, each 11–13 stories, with a total constructed floor area of about 85,000 m^2. A plan layout of part of the project, including the building of interest in this study (Building No. 7) is shown in Fig. 1. After construction of the superstructure of Building No. 7 was complete, and during excavation and construction of an underground parking space at the southern side of Building No. 7, the building overturned during a short period of time in the direction of the excavation (Fig. 2) at around 17:30 pm Beijing time on June 27, 2009 [18]. After the failure, it was apparent that the building superstructure had rotated predominantly as a rigid body and was largely intact (although resting on its side), implying the possibility of foundation failure. Pictures of the failed building were posted on the internet, causing quite a shock in Chinese society and elsewhere. Access to the building site was subsequently restricted by the local authorities and no forensic investigation report on the failure has been released. Observations made from the picture taken from an adjacent area (Fig. 2) indicate that most if not all of the foundation piles had ruptured at about 1–3 m from the base of the foundation beam to which, presumably, they were originally attached. However, to date detail on: (1) where the failure initiated, for example by failure of the retaining structure for the excavation or the foundation piles; and (2) what was the trigger for or cause of the failure, perhaps the excavation or the dumping of the excavated soil at the northern side of the building; are not clear. In particular, what lessons geotechnical engineers can learn from this failure warrants further investigation.

In this study, the building construction and parking space excavation processes have been simulated using plane strain finite element analysis (FEA), based on known information and after making some assumptions, each of which is clearly identified in the text. By examining the deformations of the foundation and the stresses predicted to act in the retaining structure and the foundation piles, a possible mechanism of failure has been revealed and the likely cause of the overall failure identified. Some of the lessons learned from this study are also discussed.

2. Soil profile

Yin and Xu [15] reported a typical profile of the tip resistance in a cone penetration test (CPT) carried out at the site of Building No. 7, as shown in Fig. 3. Down to the sand used as a bearing layer for

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0266-352X/$ - see front matter
http://dx.doi.org/10.1016/j.compgeo.2013.10.001

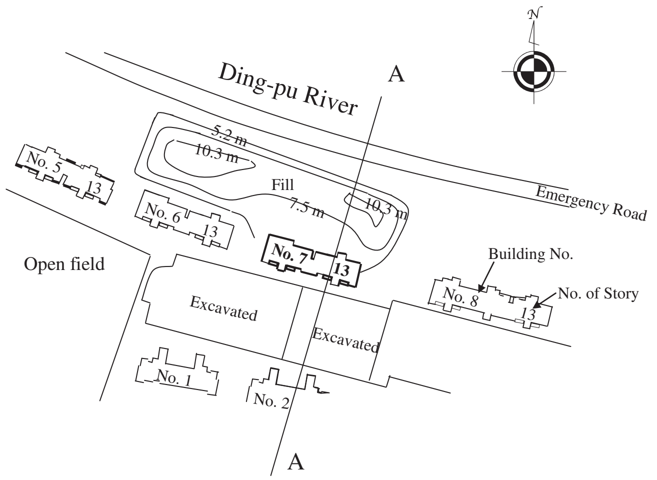

Fig. 1. Plan view of the development area and the location of the building failure (modified from Zhu et al. [18]).

Fig. 2. Overturned building.

the piles, the soil profile can be divided into 7 sub-layers. However, no values of the fundamental mechanical properties of these deposits have been reported in the literature. Ma et al. [6] reported a similar soil profile at another excavation site in Shanghai, and some of the mechanical and index properties at that site are given in Fig. 4. By comparing CPT results in Figs. 3 and 4, it can be concluded that the soil profiles at the two sites are similar. Therefore, the data in Fig. 4 will be referred to in determining soil parameters at the site of the failed Building No. 7.

3. Foundation, superstructure and excavation retaining system

3.1. Foundation

Unless otherwise specified, all information reported here about the foundation and the building superstructure is taken from Yin and Xu [15]. The foundation consisted of a pile-beam structure. 114 piles were used in total and the length of each pile was nominally 33 m, i.e., each pile penetrated into the fine sand layer, as shown in Fig. 3. The tops of the piles were at an elevation 2.0 m below the ground surface (personal communication with Dr. J. Yin 2011). The piles were made of pre-stressed concrete and steel bar reinforcement with an annular cross-section. The outside diameter of the pile was 0.4 m and the inner diameter was

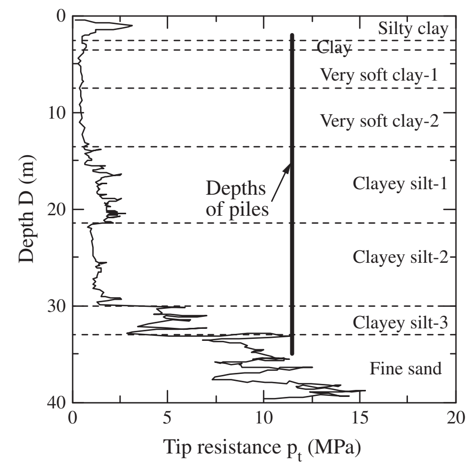

Fig. 3. Cone penetration tip resistance.

0.24 m, so that the thickness of the annular concrete wall of the pile was 80 mm. These piles are referred to as 'PHC AB' in the design code of Shanghai, and the arrangement of the steel reinforcement is typically as shown in Fig. 5 [11]. The design properties of the pile are summarised in Table 1.

There is no published detailed information about the structure of the foundation beam cast on top of the piles. In the following analysis it is assumed that the beam had a cross-sectional area of 1.5 m (width) by 2.0 m (height). Based on the information from Yin and Xu [15] and Zhu et al. [18], the foundation of Building No. 7 had plan dimensions of about 45 m in length by 12 m in width.

3.2. Superstructure

Building No. 7 had 13 stories and a cast-in-place reinforced concrete structure. In Shanghai, the height of one storey of a residential building is typically about 2.98 m (2.8 m headroom and about 0.18 m thick floor slab), so that the total height of the building would have been about 38.74 m. In China, for residential buildings with a cast-in-place reinforced concrete structure, the pressure exerted on the foundation by the superstructure is typically in the range from 10 to 15 kPa per storey [4]. Since no detailed information about the superstructure was available, a pressure of 12 kPa per storey has been assumed in this study, implying that the total pressure applied to the foundation by the entire building would be about 156 kPa.

3.3. Excavation retaining structure

The excavation at the southern side of Building No. 7 (see Fig. 1) was supported by a retaining wall formed by cement deep mixing. The width of the wall was about 0.7 m and the depth was about 10 m (personal communication with Dr. J. Yin 2011). The wall was further supported by 6–9 m long soil–nails. However, there is no detailed information available about the cross-section, nor the layout of the soil–nails. Ma et al. [6] reported a case history of an excavation in Shanghai with a similar support system. In Shanghai, generally the soil–nails are formed by a steel tube with a rough outer surface and an outer diameter of about ϕ_o = 48 mm and inner diameter of about ϕ_i = 41 mm. The spacing between the soil–nails is typically about 1.0 m. Each soil–nail is grouted in place using cement slurry with a water/cement ratio of about 0.5 under an injection pressure of 0.4–0.6 MPa. The soil–nails are generally inclined downward at an angle of 6–10° to the horizontal. By referring to the case reported by Ma et al. [6], it is assumed for the case considered here that there were 4 rows of soil–nails with a