Engineering Geological Problems of Foundation Pit Construction in Quaternary Strata: Taking Suzhou Area as an Example

Xinyu Luo, Peng Yin, Yongsheng Zheng, Xuedong Li, Yi Zhang, and Qiang Tang

Abstract The Quaternary strata in Suzhou, China, are typical because of its abundant water system and intricate geological conditions. The characteristics of Quaternary sediments in Suzhou area were analyzed and integrated through borehole sampling, field investigation, and data collection. The results show that the thickness of Quaternary sediments in Suzhou area is approximately 200 m. Each aquifer group is divided into water-bearing stratum and water-resisting stratum with a thickness of approximately 15 m and 30 m, respectively. The soil layers are mostly silty clay with approximately 30% water content, which has a loose structure and poor engineering properties. Meanwhile, there are multiple fault zones, mainly East-North and East–West trending, accompanied by North–North-East trending tectonic traces. This common geological situation in coastal and lakeside areas often leads to several problems in foundation pit construction: failure of supporting structure and instability of foundation pit slope, seepage deformation, land subsidence and ground subsidence, and heave and inrush at the bottom of the pit. In this paper, considering the excavation depth, excavation mode, soil properties, and surrounding loads and other key influencing factors, the corresponding prevention and control measures are put forward for practical engineering. Meanwhile, a variety of protective drainage measures are used to enclose and lower the water for its foundation pit project, which effectively reduces the construction risk of the foundation pit project.

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1 Introduction

With the acceleration of China's urbanization process, the urban population is highly concentrated, and some infrastructure cannot satisfy the demands of people's production and living. In order to improve the pressure of urban life and traffic congestion, many developed areas, especially some coastal cities, have seen a lot of new or renovation projects [1]. However, with the continuous construction of various buildings, it brings the problem of increasing ground load. In order to improve the bearing capacity of foundation and the stability of buildings, the depth of foundation pit excavation becomes larger and larger. At the same time, urban road and railway construction have entered a period of rapid development, many road constructions will adopt deep foundation pit construction method as well. This is the development direction of foundation pit engineering at present [2, 3].

At present, the study of quaternary has become global, and the classification of quaternary strata is mainly based on the confirmation of mammal fossils and paleoclimate analysis [4]. This paper mainly divides the strata by analyzing the lithology, color, bedding structure, sedimentary cycle, mineral combination, animal and plant fossils, and geological age of the borehole sediments [5]. Quaternary sediments are widely distributed in the world. They are loosely formed since 2.6 Ma and basically preserve their original morphology [6, 7]. Fluvial, lacustrine, glacial, eolian, Marine, and cave deposits are the main sedimentary types, while fluvial, residual, slope, pluvial, biological, and volcanic deposits are the secondary sedimentary types. Most of the earth's surface is covered by quaternary sediments, with the exception of steep rocky slopes [8].

As one of the developed cities in the southeast coastal area of China, Suzhou, Jiangsu province, has a very representative Quaternary stratigraphy. The total area of this city is 8657.30 km^2, and the built-up area is 477.63 km^2. Deep layers of Quaternary sediments, generally 150–260 m thick, are widely distributed in Suzhou area, which have been in a state of slow decline since the Quaternary crustal movement. In the process of Quaternary deposition, influenced by many factors, the lithology and genesis are complex, with the basic characteristics of the alternation of multilayer viscous soil layer and loose sand layer, and the deep and large foundation pit engineering just lies in these soft soil layers. And foundation pit engineering is a temporary project, generally speaking, the design safety factor is small, and a little careless will occur engineering accidents [9], for example, support structure failure, slope instability of foundation pit, seepage deformation, ground settlement, ground settlement, bottom uplift water inrush, and other problems [10].

This paper is to introduce the characteristics of the fourth layer of the sediment in Suzhou area, according to these characteristics summed up the problems that may occur in the foundation pit engineering, and according to these problems summed up the corresponding solutions, to provide a theoretical basis for the actual project.

2 Geological and Hydrogeological Characteristics of Suzhou

2.1 Stratigraphic Division of Suzhou

Suzhou city is located in the Yangtze River delta with dense population, developed economy, high level of urbanization and industrialization, and many deep and large foundation pit projects [11]. Due to the continuous improvement of foundation pit depth, the research of Quaternary strata has become a key issue. Quaternary Stratigraphy refers to a recent geological unit in the history of earth development. The lower limit of the stratification and age determination of the Quaternary stratification and age determination in Suzhou city and other Yangtze River delta areas have always been controversial in various regions. Many paleontologists claim 1.8 Ma (Megaannus, means a million years), while paleomagnetic scholars claim 2.48 Ma. However, because 2.6 Ma is the age of loess deposition in China, Chinese geologists tend to regard 2.6 Ma as the bottom boundary of the Quaternary [12, 13]. This paper also adopts this definition, that is, the strata formed after this period become the Quaternary strata [14]. Through borehole sampling and related data collection in some areas, the Quaternary stratigraphy in Suzhou area was observed and described, including soil lithology, color, stratum elevation, and some stratification in the soil layer, as shown in Table 1. Drilling samples were taken from Xiangcheng, Kunshan, Industrial Park, Wuzhong, and Wujiang in Suzhou. The hole diameter of drilling rig is 129 mm. The thickness of the Quaternary strata in Suzhou area is about 180 m, so the drilling depth is 200 m. When the drilling reaches 200 m, the formation is half lithified and no further drilling is required.

Based on the sampling data and relevant data, the aquifer groups of the Quaternary strata in Suzhou area are divided, and the results are shown in Table 1. There are three confined aquifer groups in Suzhou area: The I confined aquifer group has a depth of 5.3–41.2 m, of which 37.0–41.2 m is the first confined aquifer with a thickness of 4.2 m. The II confined aquifer group has a depth of 41.2–87.7 m, of which 74.4–87.7 m is the II confined aquifer with a thickness of 13.4 m. Confined aquifer group III has a depth elevation of 87.7–162.1 m, of which 137.9–151 m is confined aquifer III with a thickness of 13.1 m. It should be noted that the III confined aquifer group contains two weakly permeable layers at depths of 97.1–137.9 m and 151–165.1 m, respectively. It can also be seen from the table that the aquifer is generally fine sand and fine-medium sand, the weakly permeable layer is generally silt and cohesive soil mixed with silt, and the waterproof layer is cohesive soil and silty soil. The strata below the confined aquifer group III are generally low in water content, hard and close to diagenesis [15].

Table 1 Strata distribution and distribution of groundwater layer in Suzhou

Chronostratigraphic		Code name	Depth (m)	Lithology	Confined aquifer group	
Holocene Series		Qh	2	Filled soil		
			5.3	Bluish gray mucky clay		
Pleistocene	Upper Pleistocene	Qp3	19.8	Bluish gray, yellowish-gray silty clay	Group I	Water-resisting layer (I - 1)
			24.55	Bluish gray, brown clay		
			25.95	Bluish gray mucky clay		
			31.53	Grayish yellow, cyan silty clay		
			37	Cyan silty clay		
			41.2	Gray powder sand		Water-bearing stratum (I - 2)
	Middle Pleistocene	Qp2	50.9	Silty clay of bluish gray and taupe	Group II	Water-resisting layer (II - 1)
			57.2	Gray, gray-green silty clay		
			68.5	Polychromatic silty clay, silty sand		
			74.35	Gray-green, gray-brown silty clay		
			87.7	Gray, light gray silt		Water-bearing stratum (II - 2)
	Lower Pleistocene	Qp1	97.1	Gray-green silty clay	Group III	Water-resisting layer (III - 1)
			100.1	Gray-green, gray-brown silty clay, silty sand		Aquitard (III - 2)
			107	Gray-green silty clay, silty sand		
			113.2	Cyan silty clay		
			124.5	Gray-green, yellow–brown silty clay, silty sand		

(continued)

Table 1 (continued)

Chronostratigraphic		Code name	Depth (m)	Lithology	Confined aquifer group	
			137.9	Polychromatic silty clay		
			145.8	Dark gray, gray-green silty clay, silty sand		Water-bearing stratum (III - 3)
Pliocene		N2	151	Dark gray, gray fine sand		
			155.4	Gray-green silty clay, silty sand		Aquitard (III - 4)
			158.3	Gray-green silty clay and fine sand		
			160.3	Tan fine sand		
			165.1	Tawny fine sand, silty sand		
Miocene		N1	169.5	Yellowish brown, cyan silty clay	Semi-solid layer	
			172.7	Yellowish brown, bluish gray fine-medium sand		
			180	Gray yellowish-brown silty clay, fine sand		
			185.1	Cyan gray, tan clay, fine sand		
			186.5	Grayish yellow medium-coarse sand		
			189.7	Yellow silty clay, silty sand		
			193.5	Dark gray, gray-green silty clay, fine sand		
			198.1	Yellowish brown, gray-green silty clay, fine sand		
			200	Bluish gray gravel sand		

2.2 Characteristics of Quaternary Strata Soil

Table 2 shows the basic physical and mechanical properties of Quaternary soils in Suzhou area except surface fill. According to the difference of genesis type, age, lithology, and physical and mechanical properties, considering the requirements of foundation engineering, it is divided into 10 engineering geological layers and several sub-layers.

Soil layer 1 is tillage soil. Soil layer 2 is gray, grayish-brown silt clay, silty clay, with high water content, large void ratio, low bearing capacity characteristics. Soil layer 3 is gray, blue gray clay and silty clay, water content and void ratio lower than the previous layer, higher bearing capacity. Soil 4a is yellowish-brown clay with low water content and high standard bearing capacity. Soil layer 4b is yellowish-brown silty clay with high bearing capacity and other properties similar to soil layer 2. Soil layer 4c is yellowish-brown silt and silty sand with low plastic index and high liquid index. Soil 5a is gray-brown silt with low plastic index and high liquid index. Soil layer 5b is gray silt, which has a high standard bearing capacity. Soil 6a is gray-yellow and brown-yellow silty clay with low void ratio and high standard bearing capacity. Soil 6b is composed of gray-brown silty clay, silty soil, clay, and silty sand, with high water content and high liquid index. Soil layer 7 is gray, light gray silty sand, silty soil mixed with silty clay, and the gap is relatively low. Soil layer 8a is dark green, yellow-green, and yellow–brown clay, which is characterized by low water content, large natural weight, low void ratio, and high standard bearing capacity. Soil layer 8b is yellowish-brown and grayish-brown silty clay with low void ratio and high standard bearing capacity. Soil layer 9a is bluish gray and light gray silty clay. 9b is blue gray, gray silt, and silt. Soil layer 10 consists of grayish brown and gray silty clay, clay, and silt, with high water content and high plasticity index [16].

2.3 Fracture Structure

Suzhou, Jiangsu Province, is located in the second uplift zone of the Neocaysian system in eastern China, and the eastern section of the southern branch of the east–west Qinling structural belt is in the composite zone of the southern and northern Parts of Jiangsu. The distribution of the Suzhou fault zone is shown in Fig. 1. The EN and EW trending structures are obviously strengthened in the Yanshan area, and the NNE trending structural traces are also formed. The NWW trending (290°–300°) and NNW trending (340°–350°) faults were associated with the development of these structures. Since Quaternary, there have been basalt eruptions along the fault zone with strong activity. A series of NE and NW trending faults are developed in Yanshan granites. The occurrence of fault planes is generally steep, and the fault structure is cataclasite with a width of 0.3–1.5 m [17–19].

Table 2 Physical and mechanical properties of stratums in Suzhou

Layer number	Water content ω (%)	Natural gravity ρ (kN/m^3)	Void ratio €	Saturation Sr (%)	Plasticity index IP	Liquidity index IL	Cohesive force C (kPa)	Internal friction angle φ (rad)	Bearing capacity value fk (kPa)
1	–	–	–	–	–	–	–	–	–
2	37.2–59.4	16.8–18.4	1.02–1.62	96.0–100.0	15.9–24.5	0.76–1.50	11.0–35.0	4.0–12.5	55–90
3	25.5–35.1	18.7–19.9	0.72–0.98	95.0–100.0	12.6–22.8	0.41–0.95	12.0–51.0	7.5–13.7	95–180
4a	23.1–29.1	18.4–20.3	0.68–0.79	94.7–100.0	16.4–23.5	0.18–0.44	38.0–67.0	7.8–14.8	180–260
4b	22.7–34.8	18.4–20.3	0.70–0.96	92.7–99.5	11.2–16.2	0.45–0.88	22.0–57.0	9.5–19.1	150–200
4c	30.9–37.7	18.0–19.2	0.84–1.02	95.2–100.0	6.4–9.5	0.97–1.85	14.0–31.0	17.5–29.0	100–150
5a	31.6–38.9	18.0–19.3	0.82–1.07	96.4–100.0	6.6–12.1	0.80–1.95	12.0–35.0	10.6–24.2	100–140
5b	30.0–35.8	18.5–19.2	0.84–0.96	95.6–100.0	–	–	3.0–14.0	11.5–29.5	120–180
6a	27.1–32.6	19.0–19.8	0.74–0.89	94.7–99.5	10.7–15.4	0.45–0.95	19.0–37.0	9.8–20.0	145–200
6b	29.5–38.7	18.7–19.4	0.83–1.04	96.3–100.0	6.2–17.6	0.65–1.78	6.0–32.0	10.2–28.0	100–160
7	29.5–33.4	18.5–19.1	0.84–0.96	93.6–100.0	–	–	–	–	140–200
8a	21.3–26.6	19.5–20.5	0.62–0.75	94.7–99.6	14.6–20.9	0.17–0.38	36.0–74.0	14.6–20.5	240–300
8b	24.3–31.3	19.2–20.2	0.68–0.86	96.0–99.1	10.5–15.7	0.26–0.64	27.0–61.0	13.0–24.5	160–280
9a	24.7–33.0	19.1–19.8	0.73–0.91	97.1–99.7	9.9–14.3	0.56–0.97	18.0–34.0	13.8–26.5	120–180
9b	25.1–30.0	19.2–19.8	0.69–0.82	95.2–99.7	–	–	–	–	180–220
10	28.9–39.2	18.4–19.3	0.82–1.09	96.0–100.0	12.0–20.8	0.64–1.07	13.0–41.0	11.7–18.0	100–160

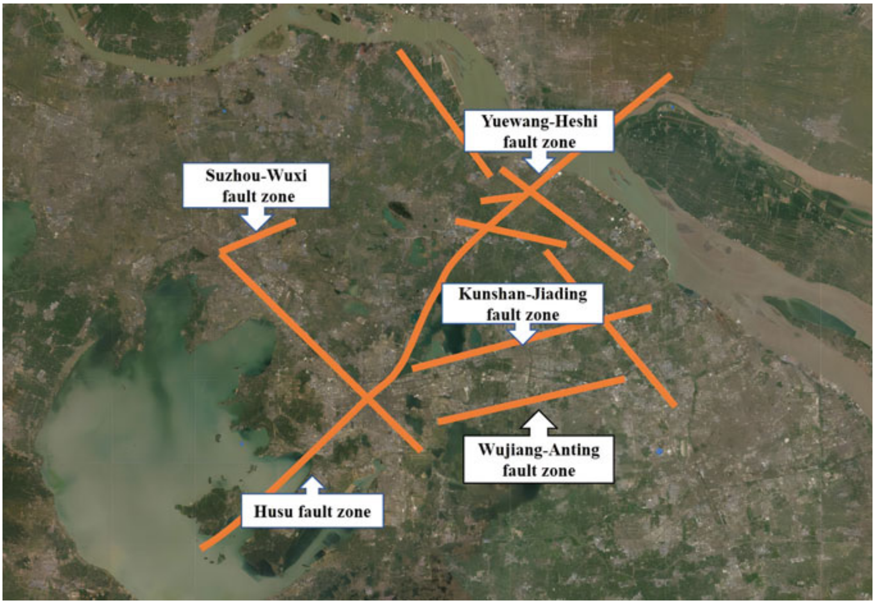

Fig. 1 Distribution of Suzhou fault zones

3 Major Engineering Problems and Solutions

3.1 Main Engineering Geological Problems in Foundation Pit Construction

According to the above analysis, thick soft soil is widely distributed in Suzhou, and its engineering properties are poor. The main manifestations are high content of clay minerals, loose structure, high void ratio and water content, low strength, large compressibility, and easy to produce flow deformation [20, 21]. Therefore, several problems often appear in foundation pit construction: (1) failure of supporting structure and instability of foundation pit slope; (2) seepage deformation; (3) land subsidence and ground subsidence; and (4) heave and inrush at the bottom of the pit.

Failure of supporting structure and instability of foundation pit slope

Due to its remarkable rheological and thixotropic properties, soft soil will creep slowly under the action of various forms of load during construction. Especially, the structure of the water-rich soft soil in Suzhou is more seriously damaged under dynamic load, which is prone to liquefaction, suspension, flow, and settlement. Therefore, the rheological and thixotropy of soft soil have a great influence on the stability of foundation pit and the deformation of supporting structure, and it is toilless to cause the overturning failure of the supporting structure of foundation pit, such as the kicking of the lower part of the supporting structure, the swelling of the middle part, and the overturning of the upper part of the supporting structure. In serious cases, the instability of the foundation pit slope will be caused.

Seepage deformation

The distribution area of soft soil in Suzhou has high groundwater level and high water content, and soft soil often intersects with silt and fine sand aquifers. During the excavation of the foundation pit, there is a large water level difference between the inside and outside of the pit, which is prone to gushing sand and water, resulting in deformation and collapse of the sidewalls of the foundation pit.

Land subsidence and ground subsidence

When the foundation pit is drained, it often causes soil erosion and potential erosion, resulting in uneven ground settlement around the pit, causing cracking and damage to surrounding buildings, municipal roads, and pipelines. At the same time, the thixotropy of soft soil under dynamic load can also cause ground settlement around the foundation pit, and even extensive ground settlement.

Heave and inrush at the bottom of the pit

The excavation of the foundation pit destroys the natural stress state of the soil. During the excavation of the foundation pit, the lateral and bottom of the foundation pit are unloaded, and the lateral soil is prone to extrusion and uplift at the bottom of the foundation pit. Especially when the soil layer at the bottom of the foundation pit is double geological structure, the upper soft soil with poor permeability is the waterproof layer, and the lower fine sand layer is the pressurized water-bearing layer. When the pit is excavated on the soft ground, the damage of the bottom of the pit is very easy to happen because of the low shear strength of the soft ground.

3.2 Influencing Factors of Engineering Problems

Foundation pit engineering is a typical geological engineering, and the safety of foundation pit is greatly affected by the nature of geological body. Therefore, the design and construction of foundation pit support in Suzhou soft soil area is more difficult than that in common rock and soil area, and the deformation control is difficult [22, 23]. In order to ensure the safety of foundation pit construction, it is necessary to find out the main factors affecting the stability of foundation pit and put forward the safe and reasonable supporting form with pertinence. Based on the analysis of foundation pit engineering in many water-rich soft soil areas such as sampling area and historical accident data, the main factors affecting the safety of foundation pit are preliminarily identified and summarized as follows [24–26].

Depth of foundation pit

Soft soil has low strength and poor self-stability. Therefore, the deeper the foundation pit is excavated, the more difficult it is to support the foundation pit. At the same time, the larger the deformation of the supporting structure, the larger its risk coefficient is, which is the main risk target.

Physical and mechanical properties of soft soil and thickness of soft soil

Soft soils are susceptible to thixotropy and rheology due to their high water content, loose structure, and high sensitivity. At the same time, the greater the thickness of soft soil, the more obvious its deformation. It is conducive to the safety of the foundation pit.

For the complex foundation pit engineering in soft soil area, the plastic strain of soil is mainly concentrated in the bottom excavation surface attachment, and the influence of soil plastic parameters on the deformation of foundation pit is mainly concentrated in the bottom excavation surface attachment. Therefore, it is beneficial for soil consolidation and soil parameters improvement to take precipitation measures for the excavation surface and the following areas at a certain time before excavation.

Combination of soft soil and non-soft soil

Generally, the silty sand is located below the soft soil. The silty sand layer has good water capacity and is mostly confined water, which is not conducive to the stability of the foundation pit bottom.

Peripheral load of foundation pit

The building loads, vehicle loads, and other piles around the foundation pit will have adverse effects on the safety of the foundation pit. Pit unloading and pit side loading are very common in foundation pit excavation. However, this common phenomenon is the most unfavorable to the stability of the foundation pit, so the pile load should be reduced as much as possible in the foundation pit construction.

The closer the surrounding load is to the pit, the greater the settlement. The settlement near the middle of the pit is more important than the settlement at the ends of the pit. This may be related to the disturbance of the soil around the pit; the greater the disturbance, the greater the relative settlement.

Excavation mode of foundation pit

Excavation of foundation pit is a stress release process, and the soil confining pressure decreases and the shear strength decreases. When excavation of foundation pit, too fast and too large range of soil stress release will lead to sudden deformation of side wall and failure.

3.3 Measures for Prevention and Treatment

Through the analysis of the main problems and influencing factors mentioned above, foundation pit support should be based on site conditions and geological conditions around the pit [27, 28]. The construction should ensure a reasonable number of support forms and choose the correct construction method to minimize the risk factor of the foundation pit [29]. Preventive measures should be considered in the design and construction of engineering geological problems from the following aspects [30–32].

(1) According to the overall consideration of the project, a reasonable supporting form must be adopted according to the conditions of the foundation pit itself to ensure the safety and effectiveness of the supporting structure and prevent the instability of the foundation pit slope. In design and construction, upper unloading and bottom reinforcement are often used. Or the way of back pressure, increase the safety of foundation pit.
(2) Appropriate drainage measures should be selected according to the hydrogeological conditions of the soil layer of the foundation pit. The water cutting curtain is added outside the foundation pit to prevent groundwater seepage and reduce the creep of soft soil. Most foundation pit projects in Suzhou often adopt grouting method, double- and three-axis cement soil mixing pile, high pressure rotary jet grouting pile, and so on as the water curtain. Combined with the surrounding environmental conditions of the foundation pit, if there are important buildings requiring deformation control, recharge Wells should be set up within a certain distance outside the pit for recharge.
(3) The excavation of the foundation pit soil is carried out in three ways: block, strip, and layer. This can make full use of the bearing capacity of the soil, but also effectively control the deformation of the foundation pit side walls and the bottom of the foundation pit.
(4) Adopt a variety of reinforcement measures to reduce the uplift deformation in the pit and eliminate the uplift damage at the bottom of the pit. The passive area is prone to uplift of foundation pit, and effective reinforcement of passive area is the most direct and effective method to reduce uplift. Slope release support can use the bottom of the slope back pressure, driving piles. Vertical support can be adopted by increasing the embedment ratio of support body and reinforcing the bottom of the pit.
(5) Foundation pit supporting structure design, choose the appropriate supporting structure type, can consider the support structure and permanent structure organic combination. If the underground continuous wall pit wall retaining pile is combined with the basement side wall, the pit bottom anti-uplift pile is joined with anti-floating pile. The supporting structure can be combined with the ring beam, purlin and beam in the basement, and the excavation of the foundation pit is convenient. Truly achieve economic reasonable, convenient construction.
(6) Information construction should be adopted. During construction, the construction progress and construction method should be timely controlled and adjusted

according to the monitoring data, and the whole construction process shall be dynamically controlled.

3.4 Case Analysis

Taking Caohu Road improvement project in Suzhou as an example, the project is located in Taidong Road, Xiangcheng, Suzhou, with a total length of 4689 m. The proposed tunnel engineering foundation pit excavation depth of the project is about 0–17 m. Because the characteristics of soil layers at different depths of foundation pit are different, this project also adopts a variety of different maintenance schemes for foundation pit, respectively. Plate type maintenance system is used when 0– m, steel sheet pile or SMW construction pile + support system is used when 4–10 m, and underground continuous wall or bored cast-in-place pile + support system is used when 10–17 m. It can be seen from Table 2 that the upper layer is mostly soil with low permeability, and the precipitation scheme of open ditch and catchment drainage is mainly adopted here. For the deeper layers, gushing may occur. Therefore, the artesian water level observation well was set up and decompression precipitation was adopted, and the water stop curtain was also installed.

In this paper, 2D numerical analysis software is used to simulate the cross-section structure of a certain foundation pit in the project, and the schematic diagram of the calculation model is shown in Fig. 2. The main loads on beam elements include concentrated load, distributed load, temperature load, and prestressed load. In addition, it also includes the dead weight of the structure, pile side earth pressure, and the lateral overloading of the foundation pit. In this structure, the pile body and crown beam are made of C25 concrete, and the elastic modulus is 3.0×10^4 MPa. The horizontal inner support in the foundation pit adopts steel pipe with outer diameter of 600 mm, wall thickness of 9 mm, and elastic modulus of 2.0×10^5 MPa.

The simulation analysis results show that the maximum horizontal displacement of ground wall is 0.01522 m, the maximum shear force is 226.0 kN/m, and the maximum bending moment is 316.8 kN/m. The maximum axial force of transverse support is 1285.79 kN, the maximum vertical displacement of ground is 0.016 m, and the maximum horizontal displacement is 0.013 m. All the data are less than the characteristic value of the allowable bearing capacity of the structure, indicating that the correct retaining method can effectively ensure the safety of the foundation pit structure in soft stratum.

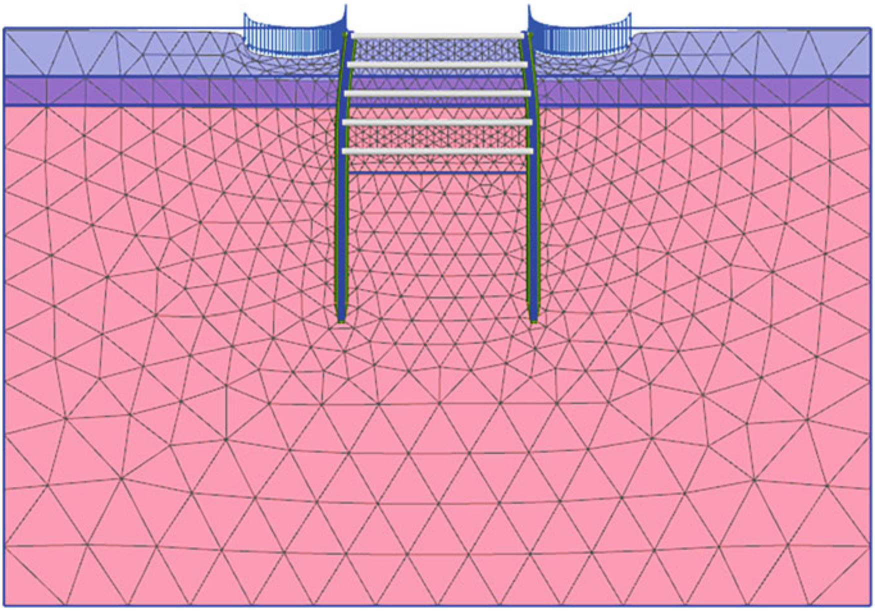

Fig. 2 2D integral structure calculation diagram

4 Conclusions

The Quaternary strata in Suzhou, China, are typical because of its abundant water system and intricate geological conditions. The characteristics of Quaternary sediments in Suzhou area were analyzed and integrated through borehole sampling, field investigation, and data collection. The results are as following.

(1) The thickness of Quaternary sediments in Suzhou is approximately 200 m, which can be divided into three aquifer groups or ten different layers. Each aquifer group is divided into water-bearing stratum and water-resisting stratum with a thickness of approximately 15 m and 30 m, respectively. The soil layers are mostly silty clay with approximately 30% water content, which has a loose structure and poor engineering properties.
(2) There are many fault zones, mainly in the direction of East-North and East–West, accompanied by the structural track of North–North-East.
(3) The geological conditions in Suzhou area often lead to the failure of the supporting structure, the instability of the foundation pit slope, seepage deformation, ground settlement, ground settlement, and water inrush at the bottom of the pit. Therefore, it is necessary to consider the excavation depth, excavation mode, soil properties, and surrounding loads and other key influencing factors and put forward corresponding prevention and control measures for the actual project.

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