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Evaluation of environmental effects of subway in Nanjing city

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ABSTRACT: Subway is the symbol of transportation modernization. Construction of subway can promote the city's economy. However, subway can also cause environmental disturbance during its construction or after operation. The dynamic condition of ground water and the circulation-and movement of soil-water system can also be changed. Geological conditions, especially the in-situ stress condition in bedrock can be altered notably. Consequently, a series of environment hazards, such as surface subsidence, ground splitting, spring disappearance, drainage systems collapse will occur in neighboring area and operating noise will also be the main concerns. The author takes Nanjing subway for an example to demonstrate environmental effects of subway.

1 INTRODUCTION

Subway will play an important role in passenger transportation systems in big cities in China in the future. Beijing, Hongkong , Shanghai and Guangzhou already have their subway systems. The city of Nanjing is planning to build a subway in the near future. Environmental effects of the subway have caught much attention This paper makes an evaluation of the effects resulted from construction of subway and it can be of much use to local administrators.

2 GEOGRAPHY AND GEOLOGY SETTINGS

The city of Nanjing locates in South bank of Yangtse River in Qinhuaihe outlet. Geomorphology can be classified as erosion tectonic low mountain, erosion monadnock, valley terrace and alluvial plain. Erosion monadnock, valley terrace and alluvial plain are related to subway construction

The monadnock is mainly consisted of Jurassic quartz gravel, quartz sandstone and Cretaceous "red strata", elevation is about 60~80 *m*. Rock types relating to subway are Tertiary red mud silt sandstone. silty sandstone, and Jurassic white quartz sandstone. and Quaternary sediments.

The excavation method adopted will be shallow buried excavation and shield tunneling.

2.1 *Bedrock geology*

The petrologic characteristics are listed in Table 1.

Table1 Geological strata and petrologic characteristics

System	Series	Depth (*m*)	Petrologic characteristic
Qarter-nary	Holocene	25~72	Modern alluvium: gray silty sand and argillaceous sand
	Pleistocene	10~65	Brown sand soil, Silty with gravel and black puddly soil,
Cretace-ous	Upper	>240	Brown gravel silty sandstone,
	Lower	>610	Brick red gravel, silty mudstone

3 HYDRO-GEOLOGY OF THE SITE

There are four aquifers in the city of Nanjing. According to buried conditions, hydraulic characters and petrologic features of the aquifers, they can be classified as fissured ground water in Quaternary loose sediments and artesian water in bedrock, Water-bearing strata are carbonate, dolomite, sandstone, gravel, and shale. Head of water of the artesian aquifer varies from 25 meter to 150 meter. Permeability of ground water strata is 1~5 meter per day. Permeability of Xiashu soil along the subway line is very small; thus it can be treated as water-resisting stratum.

4 GEOTECHNICAL CHARACTERISTICS OF SOIL

Engineering geological characteristics of the host rocks are essential for subway construction. Thorough studies on geo-technical properties have been made on relating rock and soil.

4.1 *Geotechnical properties of soil*

Xiashu soil: Brown porphyritic textures, results of geo-technical tests are listed in Table 2.

Table 2 Geo-technical properties of the Xiashu soil

	range	average	Adopted value
Natural moisture content %	33.3~16.8	24.06	~
Natural density g/m^3	1.90~2.06	2.016	~
Plastic limit %	17~27.4	18.4	~
Liquid limit %	31.2~41.8	31.8	~
Plastic index	11.5~21.4	13.4	~
Degree of saturation	80~100	~	~
Compression coefficient	0.004~0.019	0.0112	0.0131
Cohesion Kg/cm^2	0.32~1.18	0.64	0.57
Angle of inner friction	16° 10′ ~ 27° 28′	22° 47′	20° 9′
Free swelling ratio	49~81.5%	63.25%	Disturbed sample

From the data, the soil can be sorted as medium-high plastic organic soil, with high pore ratio, and compression coefficient is above 0.05 cm^2/kg, large settlement of the soil under load will be anticipated. The interaction of clay minerals is face-edge style, bonding force is weak, which can cause thixotropy when the soils undergo vibration.

Problems of silty soil are due to its low strength, large compressibility and possible thixotropy under vibration.See Table 3. If it is utilized as foundations of the subway, lime piles or deep mixed lime piles are suggested to enforce soil mass.

Table3 Geotechnical properties of silty clay

	Range	Average	Adopted value
Natural moisture content %	36~67.7	46.7	/
Natural density g/m^3	1.58~1.80	1.75	/
Liquid limit %	35.2~64.2	43.4	/
Plastic index	12.2~28.5	13.4	/
Compression coefficient	0.052~0.142	0.08	0.097
Cohesion Kg/cm^2	0.1~0.27	0.153	0.126
Angle of inner friction	12° 57′ ~ 21° 18′	15° 39′	14° 51′

4.2 *Subdivision of the soil*

Soils in subway routes can be subdivided as follows.

Layer one: main consisted of Xiashu soil, with low permeability, it can be treated as water-resisting strata, medium compressibility, and it can be used as foundation of the subway. However, attention must be taken for the soil may be expansible after been disturbed. If used for back-fill material, improvement should be made.

Layer two: Fine silt sand, this strata are main underground layer in the city of Nanjing. Its permeability K=1~5 meter/day, potential liquefaction can be caused under No.7-intensity earthquake.

Layer three: This layer is mainly consisted of soft soil with lower permeability (K=0.1~1 meter/day, high porosity and large compressibility. It cannot be used as subway foundations.

Bedrock types in the area are silty sandstone with thin seams of gypsum, red gravel, sandstone, limestone and dolomite and black carbonic shale.

4.3 *Some notes*

Due to the potential swelling pressure, and soften rapidly meet with water, when passing through the gypsum-bearing strata, heading should be bulkheaded to prevent water inflow. NATM can be selected as the tunneling excavation method.

When the tunnel cuts through Qinhuai River, considering the river depth is about 10 meter, in this area the subway has to lie at a depth of 18 meter beneath ground surface. Consequently, the drainage system during construction can cause large settlement. Then viaduct may be the better choice, either from economy meaning or from environment concern. In this section, pressure shield may be adopted as construction method.

5 ENVIRONMENTAL EFFECT ON URBAN AREA DUE TO SUBWAY CONSTRUCTION

Construction of subway destroys the balance between rock and soil in the area; ground water system is also disturbed. Consequently, Nanjing subway will cause much effect on visual environment.

5.1 *Uneven settlement*

Uneven settlement can be brought from the construction of subway. The reason for this is that uneven settlement during excavation owing to draining system to lower the ground water level during the construction.

In cross section, uneven settlement of the ground due to subway construction is in accordance with a normal distribution curve; the settlement area (β) and maximum value (S_{max}) are controlled by diameter (D) and depth (Z) of tunnel, as well as properties of engineering materials. Maximum settlement is denoted by: $S_{max}=Z/200$

Settlement area is influenced by properties of host rock. for sub-water sand, β can reach 50 degree. for soft soil, settlement angle β range is 30 to 50 degree, contrasted with a small range (β=11°~26°)for hard clay and rock 。

Settlement in a certain point in the soil can be calculated follow the empirical equation:

$$S = S_{max} \cdot e^{-\frac{x^2}{2i^2}} \quad (1)$$

x: distance from a certain point to axial line of the tunnel;
i: distance of f settlement fringe to inflexion

The settlement value can be limited through due support. Take subway in HongKong for example, settlement during subway construction in HongKong was less than 5 centimeter. If open excavation method is suggested settlement due to excavation can be overlooked.

5.2 *Settlement due to drainage during construction*

When passing through old watercourse, the silt sand and sludge soil are water-bearing strata, water level is about 1 or 2 meter beneath surface ground, water level must be lowered during construction for open excavation method. In addition, the process will change the stress state of the soil mass, therefore, pore water pressure will be reduced, and effective stress increased. Consequently, settlement of ground is inevitable. The scale of settlement relates to depth of drainage and engineering properties of soil.

Settlement due to water pumping can be calculated through the process as follows. The confined hydraulic gradient to avoid quicksand is 0.2, and 15 meter is the suggested depth for the subway. Then the drainage depth can also be 15 meter. Settlement range based on these assumptions is about 75 meter around the subway axial line.

Settlement resulted from drainage can be calculated as follows:

$$S_\infty = \frac{a_{1-2}}{1+e_0} \cdot \Delta p \cdot H \quad (2)$$

$$\Delta p = \frac{\Delta h}{2} \cdot \gamma_w \quad (3)$$

Where S_∞: Final settlement of the soil; e_0: Initial pore ratio; H: Depth of the related soil mass; Δp: Additional stress due to drainage; γ_w: Density of soil

Settlement of cohesive soil at a certain time S_t:

$$U = 1 - \frac{8}{\pi^2} \cdot \sum_{m=0}^{\infty} \frac{1}{(2m+1)^2} \cdot e^{-(2m+1)^2 \cdot \frac{\pi^2 C_v}{4H^2} \cdot t}$$

$$S_t = U \cdot S_\infty \quad (4)$$

U: Degree of consolidation; t: Time;
H: Thickness of the calculated soil strata;
C_v: Coefficient of consolidation;

For sand layer, its deformation can be finished instantaneously, and then Hocke's law can be applied in settlement estimates.

$$S_t = \frac{\Delta P}{E} \cdot H \quad (5)$$

S_t: Deformation modulus of sand; E: Compression modulus of sand ($E=1+e_0/a_{1-2}$); H: Thickness of sand; Δp: Additional stress due to drainage ($\Delta p=\gamma_w/2 \cdot \Delta h$);

Suggested drainage depth in calculations is 15 meter.

Through computation, subsidence value in different area due to construction can be obtained. For thick sand strata in old watercourse, the range which subsidence value exceeds 5 centimeter is 60 meter around subway axial part. In order to control subsidence, drainage depth should be less than 3 meter. Therefor, shallow-buried excavation or pressure shields may be the proper construction methods.

Due to permanent deformation, subsidence resulted from pumping can rebound somewhat when water table resumed. Rebound value can be obtained from historical cases or through computation.

5.3 *Effects on urban geo-hydrology*

The subway pierces through ground water strata in Qinghuihe old watercourse. Surface Run-off will be changed. and ground water table in some area is risen. damp lands are consequently produced, quick sand may be potential problem. Accumulation of ions in water body can cause the deterioration of water quality. These need more information and farther research.

Dayaoshan tunnel in Beijing-Guangzhou railway, during its construction period, watercourses in the neighboring area are suddenly destroyed, and the springs disappeared, the groundwater table lowered rapidly. Later investigations showed that all the problems had been caused by fault zone in tunneling terrain.

5.4 *Sand liquefaction due to vibration of subway*

After putting into operation, the vibration of subway will be transferred to the surrounding soil; the possibility of liquefaction is a serious problem. Acceleration of subway train is equal to a 2 to 3 scale earthquake; it is assured that the vibration of subway cannot cause liquefaction of surrounding sand.

However, special attention should be put to Xiashu soil. although its swelling rate is 4% at natural moisture content, free swelling rate can reach 60% for disturbed soil. Large swelling pressure may be produced in back-fill soil, and ground heave or cracks may occur in superstructures of subway. Improvement of disturbed Xiashu soil is important during construction.

5.5 *Potential noise pollution*

The subway route passes through the most populated district of the city, after operation, the vibration of the train and the noises can be transferred to the ground surface. And the response of tunnel-surrounding rock and the supporting system may be increased progressively; furthermore the dynamic stability of supporting structures may be harmed.

Noise sources are friction of wheel-track and electric power transportation system, structure-rebound noise and aerodynamic noise. Generally speaking, noise of wheel-track is the predominant factor.

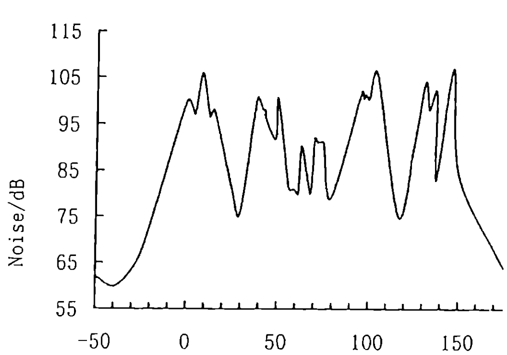

Figure 1 Acoustic field along train direction

The vibration of the subway trains can be treated as source of noise; C.S.Pan (1989) got the track acceleration curve of trains through measurement of accelerations of some trains, and achieved the acceleration expression of train tracks.

$$x(t) = \sum_{k=-\frac{N}{2}}^{N/2} (A_k \cos sk\omega t + B_k \cdot \sin k\omega t) \tag{6}$$

Where

$$A_k = \frac{2}{N}\sum_{j=0}^{N-1} x_j \cos\frac{2\pi kj}{N};\ B_k = \frac{2}{N}\sum_{j=0}^{N-1} x_j \sin\frac{2\pi kj}{N};\ \omega = 2\pi/(N\cdot\Delta t)$$

N : Sample numbers;

Intensity of subway noise is determined by train velocity, length of the train, depth of the subway and slope ratio. Peak value exceeds 95 dB, and frequency range is about 250~2000 Hz. Lotz(1972), suggested a prediction formula for noise in train tunnel wall:

$$L_A = 102 + 30\lg(\frac{v}{v_0}) \pm 6 \tag{7}$$

L_A:Train noise(dB); v :Velocity of train;
v_0 :Referenced velocity.

If the velocity of subway trains is 80km/h, noise L_A =99.7~105.7 dB. But for ground surface, due to attenuation of air, tunnel lining and soil and rock mass, when sound insulation boards and other measures are adopted, the noise can be reduced to government standard (Table 4).

Table 4. Environmental noise standard in China (dB)

Region	day	night
Residential area	50	40
Emporia	60	50
Industrial estate	65	55
Traffic main stem	70	55

6 CONCLUSION

Geological and hydrological conditions for Nanjing subway is rather complex, subway pierces through many different engineering geological units, varied excavation methods may bring changes in either urban environment or ground settlement. From our research work, some results can be achieved.

1. When cut through different strata, burying depth and construction method can be chosen based on geo-hydrological conditions and geo-technical properties of surrounding rocks.

2. Equations and parameters adopted in the paper can only be treated as theoretical analyses; reliability of the results needs to be proven during construction.
3. Possibility of sand liquefaction due to vibration of subway trains in some zones can be neglected.
4.Noise standard can be met if due measures are taken.

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