Research on Deformation Control Indicators and Standard of Urban Traffic Tunnel Construction Adjacent to High-rise Building

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Abstract: The biggest environmental problem caused by the construction of tunnels adjacent to high-rise buildings is the settlement of buildings. The paper analyzes the influence of tunnel excavation on the deformation of the superstructure and the deformation mode of the superstructure. It introduces the indicators and standards for the construction control of tunnel adjacent to the building at home and abroad. Combined with the Yuzhong tunnel project under construction in Chongqing, the main monitoring indicators and control standards of the Yuzhong Tunnel passing through the main buildings are given after comprehensive analysis and considerations, which provide a reference for the deformation control indicators of similar urban traffic tunnels adjacent to high-rise buildings.

Key words: Deformation Control Indicators; Urban Traffic Tunnel Construction; High-rise Building

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1 Preface

The urbanization construction will usher in the peak period of the construction of municipal facilities, and there will be a large number of urban traffic tunnels close to high-rise buildings. The current research and technology for tunnel monitoring has become mature, but the monitoring technology for high-rise or super high-rise buildings is still at the stage of technological research. The biggest technical problem is the formulation of the deformation control indicators and standard of the ground buildings.

Judging from the current academic research and construction practice in China, there is no systematic evaluation standard for the deformation control and prevention of adjacent buildings in underground engineering constructions. For example, in Beijing, Shenzhen, Shanghai and other places, it is generally stipulated that the surface settlement caused by underground excavation is +1 cm (uplift) to -3 cm (settlement), and it is considered that it does not exceed the interval limit. The limit value range is mainly based on expert experience and has no relevant theoretical basis. It is a temporary construction control value. From the actual construction effects, it is often too simplistic to use the ground subsidence as the only control indicator for the ground building, and sometimes it fails to meet the protection requirements of buildings, and many problems and accidents have also occurred.

Different types of building foundation types and superstructures have different resistance to deformation of underground engineering constructions. General buildings are not sensitive to uniform ground settlement. Generally, various ground displacements and deformations should be specified according to the protection level requirements of the threshold of protected objects (vertical displacement,
horizontal displacement, ground tilt, curvature and horizontal deformation, etc).

2 Interaction Mechanisms between Underground Projects and Ground Buildings

2.1 Influences of Tunnel Excavation on the Deformation of Upper Buildings

The deformation of the building caused by tunnel excavation is mainly reflected in the effects of the subsidence caused by the excavation on the superstructure. These deformation parameters include: vertical displacement (settlement) of the foundation soil; differential settlement of the two corners of the foundation; horizontal displacement; compressive strain; tensile strain; the radius of curvature of the settlement curve, the slope.

When the foundation of the building is deformed by the soil, corresponding deformation and internal force changes will occur in the beams, columns and foundations inside the structure. These deformation parameters have different effects on the structure. For masonry and other structures, settlement, horizontal displacement and tensile strain are the main damage factors, while for structures of certain sizes, the effects of curvature is the main one. For reinforced concrete structures, differential settlement is sometimes the biggest damage factor. The destruction of the superstructure is characterized by the occurrence and development of cracks, and the position and form of the cracks are related to the position of the settlement trough. Shear failures such as those of masonry structures generally include regular ‘8’-shaped damage and reverse ‘8’-shaped damage. The failure of the foundation beams and plates is bending failure and shear failure, and sometimes it is the coupling effects of bending and shear, which requires different treatment.

2.2 Building Resistance to Deformation

When the building is subjected to deformation caused by tunnel excavation, the structure itself has different responses under different conditions, including: the stiffness of the foundation; the stiffness of the superstructure; the position of the settlement trough where the structure is located; the width of the foundation. Different structural parameters such as size and form may be critical to resist deformation. The overall rigidity of box foundation and raft foundation is obviously better than that of independent foundation and strip foundation, so it can resist the various forms of foundation soil deformation such as settlement, differential settlement, horizontal displacement, tension and compression strain. The independent foundation is relatively weak in resisting tensile and compressive strains and differential settlements. As a result, large displacements are generated during the construction of the tunnel, which leads to the loss of normal functions.

Therefore, there should be different deformation control indicators and standards for buildings with different foundation types, structural forms, and heights to facilitate the operation for on-site monitoring personnel.

3 Building Deformation Control Standard and Damage Level

3.1 Building Deformation Control Standard

The Foundation Pit Engineering Handbook (1997) compiled by Academician Liu Jianhang gives the response of the building under various differential settlement, as shown in Table 1. It can be seen that for different types of building structures, the relative differential settlement limit of the foundation should generally be less than 1/150, otherwise the building will be severely deformed or have many cracks.

"Geotechnical Engineering Handbook" (1994) gives the permissible deformation values of buildings in some countries, as shown in Table 2. The table shows that the deformation control of buildings should be comprehensively considered from multiple indicators such as compression, extension, tilt, and radius of curvature.
The Coal Mining Regulations (1985) issued by the former Ministry of Coal Industry of China provides the protection and damage levels of masonry structures shown in Table 3. This table was formulated in the 1960s with reference to the relevant regulations of the former Soviet Russia, Poland, Germany and the United Kingdom, and formulated China's earliest protection object classification standard for underground mining and ground buildings. The code can also be used as a reference for the evaluation of the impacts on surrounding ground buildings caused by the surface deformation due to urban tunnel constructions.

Table 1. The Response of Buildings under Various Differential Settlement

| Building Structure Type                                                                 | δ/L (L is the length of building, δ is the differential settlement) | Building Responses                                                                 |
|----------------------------------------------------------------------------------------|------------------------------------------------------------------|----------------------------------------------------------------------------------|
| General brick wall load-bearing structures, including structures with inner frames, with | Up to 1/150                                                      | There are quite a lot of cracks in the partition wall and load-bearing brick wall, which may cause structural damage |
| a length-to-height ratio of less than 10; ring beams; natural foundations               |                                                                  |                                                                                  |
| General reinforced concrete frame structures                                            | Up to 1/150                                                      | Severe deformations occur                                                        |
| High-rise rigid buildings (box foundation, pile foundation)                            | Up to 1/500                                                      | Cracks started to appear                                                         |
| The natural foundation or pile foundation of factory buildings with a single-story bent | Up to 1/250                                                      | The tilt of buildings can be observed                                             |
| frame structure with bridge driving                                                    |                                                                  |                                                                                  |
| Frame structure with diagonal bracing                                                  | Up to 1/600                                                      | Bridge driving is difficult to operate, it is difficult to operate without adjusting the level of the rail surface, and the partition wall is cracked |
| Machine foundations that are generally sensitive to differential settlement.            | Up to 1/850                                                      | At the safety limit                                                              |
|                                                                                       |                                                                  | Difficulties may arise in the use of the machine, and it is at the limit of operation |

Table 2. Permissible Deformation Values of Buildings in Some Countries

| Country        | Compression (mm/m) | Stretch (mm/m) | Tilt (mm/m) | Radius of Curvature (km) | Notes                  |
|----------------|--------------------|----------------|-------------|--------------------------|------------------------|
| China          | 2                  | 3              | 5           |                          |                        |
| UK (for buildings 30m tall)                | 1                  | 0.5            | 1-2         | 0.5                      | Mechanical foundation |
| France         | 0.6                | 0.6            | 1-2         | 0.5                      |                        |
| Poland         | 1.5                | 1.5            | 2.5         | 20                       |                        |
| Japan          | 0.5                | 0.5            | 1           |                          | Concrete foundation    |
|                | 1                  | 1              | 5           |                          | Wooden house           |
|                | 2                  | 2              | 4           | 20                       | Cesspool               |
| Soviet Russia  | 2                  | 2              | 6           | 3                        | Donbass                |
| USA            | 4                  | 4              | 6           | 3                        | Karayuda               |

Table 3. Damage Levels of Masonry Structures (Protection Levels)

| Damage Level | The Level of Damage the Buildings Can Reach                                            | Ground Deformation Value | Handling Methods                |
|--------------|---------------------------------------------------------------------------------------|--------------------------|---------------------------------|
| I            | No or a few small cracks with a width less than 4mm on the wall                      | ≤3.0                     | ≤0.2                            | ≤2.0 | Do not repair                                       |
|              | There are no 4~15mm wide cracks on the wall, the doors and windows are slightly slanted, the wall skin is partially peeled off, and the beam support is slightly abnormal |                         |                                 |      |                                                  |
| II           | ≤6.0                     | ≤0.4                     | ≤4.0 | Minor Repair                   |
|              | There are no 16~30mm wide cracks on the wall, the doors and windows are seriously deformed, the wall is tilted, the beam head has twitch marks, and the indoor floor is cracked or bulging |                         |                                 |      |                                                  |
| III          | ≤10.0                    | ≤0.6                     | ≤6 | Medium Repair                  |
|              | The wall is severely tilted. Dislocation. Outer drum or inner concave, the beam head twitches greatly, the roof and wall are squeezed out, and there is a serious risk of collapse |                         |                                 |      |                                                  |
| IV           | >10.0                    | >0.6                     | >6 | Major repair, rebuild, demolish |                          |
The Chinese Code for Design of Building Foundation (GB50007-2011) is a national standard, in which the foundation deformation of various types of building structures is specified in Table 4. The table gives the limit values of various types of more sensitive deformation indicators. For example, high-rise structures are mainly tilted, high-rise buildings are mainly tilted as a whole, masonry structures are mainly partially tilted, and frame structures have differential settlement.

### Table 4. Permissible Values of Foundation Deformation of Buildings

| Deformation Characteristics | Medium and Low Compressibility Soil | High Compressibility Soil |
|-----------------------------|-------------------------------------|---------------------------|
| Partial Tilt of Foundation of Masonry Bearing Structure | 0.002 | 0.003 |
| The Differential Settlement between Adjacent Pile Foundations of Industrial and Civil Buildings | 0.0021 | 0.0031 |
| (1) Frame Structure | 0.00071 | 0.0011 |
| (2) Side-row Piles Filled with Masonry Walls | 0.0051 | 0.0051 |
| (3) Structures that Do Not Generate Additional Stress when the Foundation Settles Unevenly | 0.002 | 0.002 |
| Overall Tilt of Multi-story and High-rise Buildings | | |
| $H_1 \leq 24$ | 0.004 |
| $24 < H_1 \leq 60$ | 0.003 |
| $60 < H_1 \leq 100$ | 0.0025 |
| $H_1 > 100$ | 0.002 |
| Average Settlement of a Simple High-rise Building Foundation (mm) | | |
| | 200 |
| Tilt of High-rise Structure Foundation | | |
| $H_1 \leq 20$ | 0.008 |
| $20 < H_1 \leq 50$ | 0.006 |
| $50 < H_1 \leq 100$ | 0.005 |
| $100 < H_1 \leq 150$ | 0.004 |
| $150 < H_1 \leq 200$ | 0.003 |
| $200 < H_1 \leq 250$ | 0.002 |
| Settlement of High-rise Structure Foundation (mm) | | |
| $H_1 \leq 100$ | 400 |
| $100 < H_1 \leq 200$ | 300 |
| $200 < H_1 \leq 250$ | 200 |

#### 3.2 Experience Standards of Chinese Urban Underground Projects

Beijing and Guangzhou also put forward the settlement limit value standards for the sections and stations where the subway adopts shield tunneling and undercutting methods in the city according to their respective conditions. Since the subway is located in a large city, the limit value standard basically takes into account the impacts of neighboring buildings (structures).

It can be seen that the total amount of ground and vault control deformation of the Beijing urban shield construction was controlled at 2 cm, and the daily average settlement was controlled at 1 to 3 mm/d; shallow buried and concealed excavation was slightly larger, and the total amount of surface settlement caused by the tunnel construction was controlled at 3 cm (6 cm at the station), the daily average settlement was 2 mm/d and the maximum was 5 mm/d. The total ground deformation of various surrounding rocks during the construction of the Guangzhou Metro was controlled to be less than 3 cm, with an average daily settlement of 3 to 5 mm/d, and a standard of 3‰ of building tilt was specifically proposed.

#### 4 Deformation Control Indicators for Constructions Adjacent to Buildings

Through carefully sorting out the interaction mechanisms between underground projects and surface buildings and relevant domestic and foreign codes and standards, it can be found that when the local project is constructed close to buildings, the foundation bearing capacity and exerted forces of the buildings are mainly affected by the three-way deformation due to the settlement trough produced. Its impact indicators are mainly reflected in the following aspects: vertical displacement (settlement); horizontal displacement; compressive strain; tensile strain; the radius of curvature of the settlement curve.

Through these indicators, combined with domestic and foreign technical standards and codes, the main deformation control indicators of buildings adjacent
to tunnels can be given: foundation settlement; foundation differential settlement; horizontal displacement; overall tilt; deflection or deflection ratio, relative deflection; rotation angle or torsion angle

5 Real Cases of Application

5.1 Project Background

The Yuzhong connecting tunnel of the Chongqing Liangjiang Bridge project passes through the Yuzhong Peninsula and is connected to the Jiefangbei underground ring road and underground parking system. Among them, the Yuzhong Tunnel passes through the side or is directly under many high-rise or super high-rise buildings such as the Chongqing Branch of Agricultural Bank of China, Huaxia Bank, and Chopsticks Street 65#. The construction phase faces severe deformation control problems. For the relationship between the main buildings and the Yuzhong Tunnel, see Table 5.

![On-site Photos of Agricultural Bank](image)

Figure 1. On-site Photos of Agricultural Bank

| Building (Structure) | Position in Relation to the Tunnel | The Elevation of the Bottom or Top of the Proposed Tunnel | Building Floors | Foundation type | Base Elevation (m) | Distance from Top to Bottom |
|----------------------|----------------------------------|--------------------------------------------------------|----------------|-----------------|-------------------|--------------------------|
| Jinhe Lido           | K13+819 Right 0m Bottom: 224.043 | 31F                                                    |                | Pile anchor retaining wall | 221.10 (Retaining Wall Base) | -2.94m                   |
| Agricultural Bank of China Chongqing Branch Office Building Residential Building of Agricultural Bank of China Chongqing Branch | K13+985–K14+008 Tunnel top Top: 223.97–222.97 3F (Podium) 28F (Main Building) | 12F Strip foundation |                | Independent columnar foundation | 231.00 | ~ 8m               |
| Chopsticks Street 65# | K14+055–K14+103 Tunnel top Top: 221.68–221.74 | 11F |                | Pile foundation Independent columnar foundation | 241.07 | ~ 19m            |
| Luohan Temple        | K14+205–K14+224 Tunnel top Top: 227.26–228.82 | 6 F |                | Pile foundation Independent columnar foundation | 249.65 | ~ 19m            |
| Huaxia Bank (Seven Days Inn Hotel Chain) | K14+322–K14+381 Tunnel top Top: 230.67–232.55 | 14F |                | Independent columnar foundation | 236.30 | ~ 3.8m          |
| Southwest Securities Group Building | K14+394 Right 0m Top: 233.02 | 28F |                | Pile foundation | 228.20 | -4.8m          |

5.2 Construction Deformation Control Indicators Along the Yuzhong Connecting Tunnel

Depending on the structural form, height and foundation bottom form of the building, as well as the spatial relationship between the building and the tunnel, according to the degree of impacts and considering the sensitivity of the building itself and the convenience of monitoring operations, different deformation monitoring and control indicators are recommended for different buildings. The recommended deformation control indicators and standards are shown in Table 6.
Table 6. Recommended Deformation Monitoring Indicators

| Building (Structure) | Building Floors | Foundation Type | Position in Relation to the Tunnel | Recommended Monitoring Indicators | Deformation Standard | Testing Requirement |
|----------------------|-----------------|-----------------|-----------------------------------|----------------------------------|----------------------|---------------------|
| Jinhe Lido           | 31F             | Pile anchor retaining wall | Only a part of the corner is located outside the tunnel side wall | ① Differential Settlement | 1/500 | Compulsory |
| Agricultural Bank of China Chongqing Branch Office Building | 3F (Podium) 28F (Main Building) | Independent columnar foundation | One side eats into the top of the tunnel and is parallel to the tunnel axis | ① Settlement ② Differential Settlement ③ Tilt ④ Horizontal Displacement ⑤ Settlement | 10mm 1/500 3‰ 0.5mm/m | Compulsory |
| Residential Building of Agricultural Bank of China Chongqing Branch | 12F | Strip foundation | Completely located at the top of the tunnel | ① Settlement ② Differential Settlement ③ Tilt ④ Radius of Curvature | 10mm 1/500 3‰ 2mm/m | Compulsory |
| Chopsticks Street 65# | 11F | Pile foundation Independent columnar foundation | Completely located at the top of the tunnel | ① Settlement ② Differential Settlement ③ Tilt ④裂缝宽度 ⑤ Horizontal Displacement ⑥ Radius of Curvature | 10mm 1/500 3‰ 2mm/m 1.5mm/m 0.05mm/m | Optional |
| Luoan Temple 6 F | Pile foundation | | | ① Settlement ② Differential Settlement ③ Tilt ④裂缝宽度 ⑤ Horizontal Displacement ⑥ Radius of Curvature | 2.5‰ 1.5mm/m 0.05mm/m | Optional |
| Huaxia Bank (Seven Days Inn Hotel Chain) | 14F | Independent columnar foundation | Cross the sideline on the sideways and intersect with the tunnel at a small angle, almost parallel | ① Settlement ② Differential Settlement ③ Tilt | 10mm 1/500 3‰ | Compulsory |
| Southwest Securities Group Building | 28F | Pile foundation | A corner pile of the podium is located at the side wall of the tunnel | ① Differential Settlement | 1/500 | Compulsory |

6 Conclusion

The construction of tunnels adjacent to high-rise buildings is a complex scientific problem, involving the multi-layer relationship of tunnel structure-surrounding rocks-foundation-building structure. Deformation control indicators and standards during construction should be formulated according to the tunnel structure form, building structure form, building height, and the spatial relationship between the building and the tunnel.

(1) Neither the empirical formula method nor the theoretical formula method considers the time factor,

(2) The engineering conditions and environmental conditions of each adjacent construction project are extremely complex and different. Based on extensive experience in similar projects, the corresponding deformation control standards should be formulated through the empirical formula method and theoretical analysis method. The existing research results show that: for tunnels passing through the side of the building, only differential settlement should be monitored; for tunnels passing under the side of the building, two indicators of settlement and differential settlement should be monitored; for tunnels passing directly below the building, three indicators of settlement, differential settlement and tilt should be monitored.

(3) After knowing the deformation value of the building foundation, evaluation of the safety status of building structure is an extremely difficult and urgent problem that needs to be solved. Currently, similar research is not mature enough, and further research and discussions are needed.
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