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Research Article

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 -3cm (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.

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 a length-to-height ratio of less than 10; ring beams; natural foundations	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
General reinforced concrete frame structures	Up to 1/150	Severe deformations occur
	Up to 1/500	Cracks started to appear
High-rise rigid buildings (box foundation, pile foundation)	Up to 1/250	The tilt of buildings can be observed
The natural foundation or pile foundation of factory buildings with a single-story bent frame structure with bridge driving	Up to 1/300	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
Frame structure with diagonal bracing	Up to 1/600	At the safety limit
Machine foundations that are generally sensitive to differential settlement.	Up to 1/850	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	1(for buildings 30m tall)				
France	1-2	0.5			Pipeline
Germany	0.6	0.6	1-2 0.5		Mechanical foundation
Poland	1.5	1.5	2.5	20	
Japan	0.5 1 5	0.5 1 5			Concrete foundation Wooden house Cesspool
Soviet Russia	2 4	2 4	4 6	20 3	Donbass Karayuda
USA	0.8	0.4	3.3		

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 3. Damage Levels of Masonry Structures (Protection Levels)

Damage Level	The Level of Damage the Buildings Can Reach	Ground Deformation Value			Handling Methods
		Tilt (mm/m)	Curvature (10^{-3}/m)	Horizontal Deformation (mm/m)	
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
Ⅱ	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	≤6.0	≤0.4	≤4.0	Minor Repair
Ⅲ	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	≤10.0	≤0.6	≤6	Medium repair
Ⅳ	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	>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	Foundation Soil Type	
	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		
(1) Frame Structure	0.002l	0.003l
(2) Side-row Piles Filled with Masonry Walls	0.0007l	0.001l
(3) Structures that Do Not Generate Additional Stress when the Foundation Settles Unevenly	0.005l	0.005l
Overall Tilt of Multi-story and High-rise Buildings		
$H_g \le 24$	0.004	
$24 < H_g \le 60$	0.003	
$60 < H_g \le 100$	0.0025	
$H_g > 100$	0.002	
Average Settlement of a Simple High-rise Building Foundation (mm)	200	
Tilt of High-rise Structure Foundation		
$H_g \le 20$	0.008	
$20 < H_g \le 50$	0.006	
$50 < H_g \le 100$	0.005	
$100 < H_g \le 150$	0.004	
$150 < H_g \le 200$	0.003	
$200 < H_g \le 250$	0.002	
Settlement of High-rise Structure Foundation (mm)		
$H_g \le 100$	400	
$100 < H_g \le 200$	300	
$200 < H_g \le 250$	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 3cm (6cm at the station), the daily average settlement was 2mm/d and the maximum was 5mm/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.

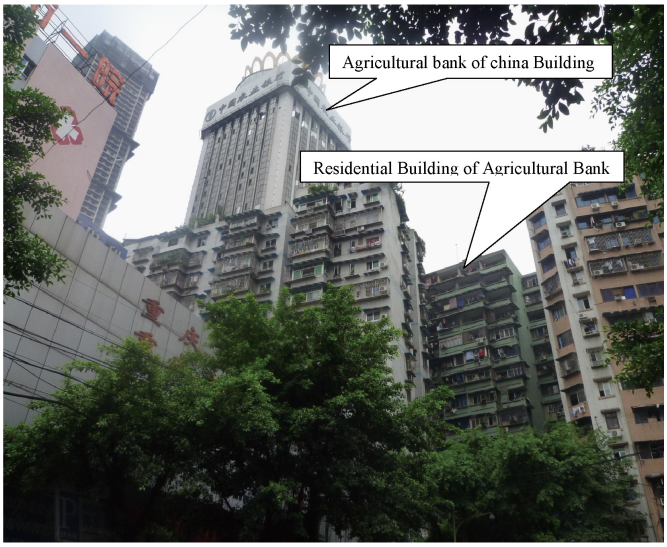

Figure 1. On-site Photos of Agricultural Bank

Table 5. Relationship between Main Buildings and Yuzhong Tunnel

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	K13+985~K14+008 Tunnel top	Top: 223.97~222.97	3F (Podium) 28F (Main Building)	Independent columnar foundation	249.00	~ 26m
Residential Building of Agricultural Bank of China Chongqing Branch	K13+988~K14+010 Tunnel top	Top: 223.81~223.01	12F	Strip 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	249.65	~ 19m
Huaxia Bank (Seven Days Inn Hotel Chain)	K14+332~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	10mm 1/500	Compulsory
				③ Tilt ④ Horizontal Displacement	3‰ 0.5mm/m	Optional
Residential Building of Agricultural Bank of China Chongqing Branch	12F	Strip foundation		① Settlement ② Differential Settlement	10mm 1/500	Compulsory
				③ Tilt ④ Radius of Curvature	3‰ 2mm/m	Optional
Chopsticks Street 65#	11F	Pile foundation Independent columnar foundation	Completely located at the top of the tunnel	① Settlement ② Differential Settlement ③ Tilt	10mm 1/500 3‰	Compulsory
				④裂缝宽度	2mm	Optional
Luohan Temple	6 F	Pile foundation		① Settlement ② Differential Settlement	8mm 1/500	Compulsory
				③ Tilt ④ Horizontal Displacement ⑤ 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.

References

[1] Chou WG. Research on the mechanics principle and countermeasures of the close construction of underground engineering [D].2003.

[2] Cao RL, He SH, Li ZF. Analysis of Strata Deformation And Structure Impact Due To Large Section Water-Abundant Soft Rock Shallow Tunnel Under Unsymmetrical Pressure Passing Through Existing Structure [J]. Chinese Journal of Rock Mechanics and Engineering, 2012, 31(5).

[3] Guo HB. Study on the Influence Zone of Adjacent Construction of over Crossing Tunnels [D].2008.

[4] Feng XH. Numerical simulation of the influence of underground structure construction on neighboring buildings [D].2012.

[5] Li WJ, Zhu YQ, Liu ZC. Study on the effect and plan of the close construction of rock tunnel [A].2007 Seminar on Hot Issues of Rock and Geomechanics in Surface and Underground Engineering [C].2007.

[6] Yu XF, Wang J. Research Status and Thinking of the Interaction of Approaching Excavation in Subway Tunnel [J]. Journal of Beijing Institute of Civil Engineering and Architecture, 2008, 24(3).

[7] Chongqing Transportation Research and Design Institute. JTG D70—2004 Code for Design of Road Tunnel [S]. Beijing: China Communications Press, 2004.

[8] China Academy of Building Research. GB 50007—2011 Code for design of builiding foundation [S]. Beijing: China Architecture and Building Press, 2011.

[9] Geotechnical Engineering Handbook Compilation Committee. Geotechnical Engineering Handbook [M]. Beijing: China Architecture and Building Press, 1994.