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Three-dimensional numerical analysis of stress and deformation of surrounding soil in safety construction of metro station

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Abstract. Utilizing underground spaces synthetically has become an important task in urban planning and civil engineering in this century. Due to the complexity and uncertainty of technical issues in underground construction and soil engineering, construction safety arouses a great concern in underground construction industry. This paper focused on construction of an underground metro station, numerical analyses are carried out to estimate the possible stresses and deformations of surrounding soil and underground structures under the worse loading conditions to assess the structural design and construction safety. Influences of pit excavation on existing tunnel and surrounding spaces are discussed and the stability of main structure of metro station will be analyzed.

1. Introduction
In rapid development of economy, increase of population and improvement of people’s living standard, a series of urbanized problems are brought forth. In most cities, there is an enormous demand of spaces in busy central urban area or any congested area in different uses.

In reaction to the increasingly urgent situation, underground spaces have been developed rapidly in recent years. On one hand, exploration of more underground spaces is an effective way to maximize city space. Underground emporium, subway station and underground parking etc. demonstrate multiformity and diversity of underground spaces. On the other hand, the usage of underground spaces

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for setting modern synthetical traffic system might have large advantages and be an attractive alternative. Subway and subsided roadway can provide new forms for vehicle diverging.

Nevertheless, due to complexity of underground projects, uncertainty of rock mass characteristics and multiplicity of structure designing, higher demands for safety, reliability and economy of engineering designs are put forward. Since 1863 the first subway was built in London (Wolmar 2004), it develops quickly in recent one and a half centuries. However, failure in underground construction happens from time to time. In January 1995, Daikai Station in Kobe, Japan completely collapsed during the Great Hanshin earthquake (Wang et al. 1998, Huo et al. 2005). In June 1996, the uncontrolled deformation of certain weak sections in the Tymfristos tunnel (Greece) propagated and produced chain effect, which ultimately led to failure of the tunnel (Kontogianni et al. 2004). In November 1999, Turkey earthquake caused severe damage of the Bolu highway tunnel which was under construction (Huo et al. 2005). In July 2003, continual seepage caused collapse of tunnel of subway line 4 in Shanghai, China. All of the cases above indicate that it is necessary to make a safety evaluation from structural aspect before construction of a subway/metro station to analyze stress state and deformation mechanism of surrounding soil masses and structures.

2. Description of project
Shuangta Station is selected to demonstrate the numerical evaluation for developing underground spaces. It is located at the central subsided square of Pearl River New City, Guangzhou as shown in figure 1. As a double-layer metro station, its longitudinal direction is from north to south. The railway’s direction of Shuangta Station decussates with a subsided roadway and an interzone tunnel, around which large-scale underground space will be built. Shuangta Station is an underground double detached island station. Its central station location is YAK1+548, with station length about 40m. Surrounding Shuangta Station, a treble-layer underground space will be built together with underground emporium, walking street, underground railway, subsided roadway, subsided greenbelts and underground parking etc.

Soil and rock profile in the range of station and underground space consist of plain fill (Q₄₉₄₅), marine silt, organic soil (Q₄₉₄₆), proluvial and alluvial placer (Q₃₉₄₇+₉₈), residual soil (Q₄₉₄₈), siltstone and conglomerate etc, as shown in Table 1. Underground water mainly includes quaternary pore water and fissure water in base rock. The water level is from 0.3m to 5.1m, which is mainly replenished by atmosphere precipitation and the Pearl River. As shown in water-quality survey material of Shuangta Station, underground water will not cause corrosion on reinforced concrete in the soil.

3. Description of numerical model
To synthetically evaluate feasibility of construction of Shuangta Station and get a proper reference state before excavation (Marta 2001), FLAC³D is used to build 3-D finite difference model to simulate the whole constructing process. In consideration of symmetry of station, a quarter of station from its central position and its surrounding underground space are built in the model. The length, width and depth of the model are 290m, 164m and 90m respectively (figure 1, 2). The whole model contains 113, 453 zones and 143, 036 grid points altogether. The top boundary in this model is a free surface, while the side boundaries and bottom boundary are fixed. Material model of Mohr-Coulomb plasticity is adopted to simulate deformation, strength and failure behaviours in this study. Based on in-situ geotechnical inspection and results of lab for rock and soil, the mechanical parameters are shown in table 1.

Because of widen constructing field and no disturbance existing between the field and surrounding traffic, open-cut and bottom-up method will be adopted to build the station and its surrounding underground space. The process of simulation can be divided into 3 stages: (1) stage of pit excavating, (2) stage of structure constructing and (3) stage of station operating. Each stage is simulated according to specific constructing process, as described below.
Figure 1. General layout planning of Shuangta Station.

Figure 2. Model of synthetical underground space.

Table 1. Rock and soil properties.

<table>
<thead>
<tr>
<th>Layers</th>
<th>Names</th>
<th>Epoch and genesis</th>
<th>Density (kg/m³)</th>
<th>Cohesion (KPa)</th>
<th>Internal friction angle (°)</th>
<th>Elastic modulus (MPa)</th>
<th>Poisson's ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;1&gt;</td>
<td>plain fill</td>
<td>Q₄mil</td>
<td>1500</td>
<td>10</td>
<td>10</td>
<td>5.1</td>
<td>0.2</td>
</tr>
<tr>
<td>&lt;3-2&gt;</td>
<td>coarse sand</td>
<td>Q₃silt</td>
<td>1300</td>
<td>25</td>
<td>23</td>
<td>9.5</td>
<td>0.38</td>
</tr>
<tr>
<td>&lt;4-1&gt;</td>
<td>clayey soil and silty soil</td>
<td>Q₂silt</td>
<td>1840</td>
<td>28</td>
<td>22</td>
<td>4.7</td>
<td>0.32</td>
</tr>
<tr>
<td>&lt;5-1&gt;</td>
<td>residual soil</td>
<td>Q₁silt</td>
<td>1990</td>
<td>35</td>
<td>25</td>
<td>3</td>
<td>0.33</td>
</tr>
<tr>
<td>&lt;6&gt;</td>
<td>completely weathered siltstone</td>
<td>k₅co</td>
<td>2020</td>
<td>60</td>
<td>28</td>
<td>6140</td>
<td>0.28</td>
</tr>
<tr>
<td>&lt;7&gt;</td>
<td>highly weathered siltstone</td>
<td>k₅co</td>
<td>2500</td>
<td>1200</td>
<td>28</td>
<td>8890</td>
<td>0.24</td>
</tr>
<tr>
<td>&lt;8&gt;</td>
<td>moderately weathered siltstone</td>
<td>k₅co</td>
<td>2540</td>
<td>1600</td>
<td>38</td>
<td>11.7</td>
<td>0.3</td>
</tr>
<tr>
<td>&lt;9&gt;</td>
<td>weakly weathered conglomerate</td>
<td>k₅co</td>
<td>2500</td>
<td>1200</td>
<td>38</td>
<td>6140</td>
<td>0.28</td>
</tr>
</tbody>
</table>

4. Influence of Pit Excavation on Existing Tunnel

Pit is excavated to the depth of 2.2m, 5.8m, 10.1m, 15.7m and 20.5m by layers. To control settlements of earth surface outside the pit, deep mixing cement-soil pile is applied as retaining structure on the sides of pit, with designing depth of 25m, to make weakly weathered conglomerate as temporary earth retaining structure.

Generally speaking, during excavation of pit, lateral earth pressure will cause horizontal displacements on lateral support system. Because of a large amount of research about it, the lateral support system is out of scope in this paper. In condition of synchronous construction, soil inside and outside of the station is excavated at the same time, which makes a favorable stress environment for retaining structure of the station. In consideration of interaction between the soil and structures, pit is recommended to be excavated by layers and blocks within a specified time period and in a symmetrical and equilibrating way (Fan et al.).

Excavating large pit above the existing tunnel will lead to unloading effect, which demonstrates as uplift of the bottom of pit and existing tunnel as shown in figure 3 and figure 4. Many factors can influence the uplift value of existing tunnel, such as soil properties, depth of excavation, range of excavation and exposure time etc. Obviously the maximum displacement of crest in the existing tunnel is roughly 2.2 cm, which is less than desired controlling value of 3 cm in Chinese Code for Design of Subway (GB 50157–92). Moreover, at certain position of station whose stratum contains silty soil, under the disturbance of excavation, the soil is extremely easy to liquefy, which may cause local failure of existing tunnel. Accordingly, a series of measures should be taken to ensure the construction, such as: (a) adopt mixing cement pile to reinforce the bottom of pit; (b) set sheltering pile at the
outboard of tunnel; and (c) grout in the crest of tunnel (Kuang 2000). Through these measures, strength of the soil mass can be improved, liquefying of soil mass can be avoided, the undesirable displacements of tunnel can be controlled in the range of tolerance.

Figure 3. Principal stress of existing tunnel after pit excavation (unit: MPa).

Figure 4. Displacement of crest of existing tunnel after pit excavation.

5. Analysis of stability of station’s main structure
The constructing process of metro station’s main structures is also simulated in this numerical model. Construction of metro station’s main structure can be regarded as process of successive load as shown in figure 5 and 6. The change of stress distribution can be observed, accompanied with construction of walls, slabs and columns.

During stage of construction, unified dead load (4KN/m²) is applied on slabs to simulate the crowd load. Obviously load acting on slabs gradually transfers to columns. As shown by vertical stress contour of slab in figure 7, the central position of slab accommodates the maximum stress, so it is worse for axial load for mid-column in figure 6. Supported on side walls, central position of slabs deforms largest as shown in figure 8. Therefore central column in metro station is always designed with highest strength in consideration of safety. Taking 1995 Hanshin (Japan) earthquake for example, the mid-column of Daikai station damaged badly (Wang et al. 1998, Huo et al. 2005).

Figure 5. Principal stress distribution of station under-construction (unit: MPa).

Figure 6. Principal stress of southern partial columns in the station (Unit: MPa).

Figure 7. Vertical stress of middle slab (unit: MPa).
Then vertical loads transferred to other bearing structures and lead to destruct of top slab and side walls as shown in figure 9. Laminated rubber bearings are widely used for prevention of high frequency ground motions and can be considered as the simplest way for seismic isolation. In order to improve earthquake resistance, construction joints which are made of laminated rubber bearings are always adopted in central columns, girders and top slabs to prevent damage in earthquake.

![Figure 8](image)

**Figure 8.** Displacement in vertical direction of middle slab (unit: m).

![Figure 9](image)

**Figure 9.** Transverse damage sketch of Daikai Station due to 1995 Hanshin Earthquake.

![Figure 10](image)

**Figure 10.** Vertical displacement of subsided roadway’s surface before running (unit: m).

### 6. Influence of Construction on Surrounding Underground Space

Besides relative independent functions of different parts in underground space, their conjunct safety should also be considered. Especially the subsided roadway decusses with the station, so the deformation of roadway’s surface should be estimated when station comes into operating. Moreover, from stage of pit excavating to stage of station operating, the deformation of soil is one of the key factors which may influence the stability of underground equipments and upper buildings. These problems are discussed through analyzing results of numerical simulation. The disturbing loads during operating are simulated according to Chinese Code for Design of Subway (GB 50157–92), including: (a) subway-equipment load and equivalent wallp load, 20KN/m²; (b) over load in earth’s surface, 20KN/m²; (c) roadway-equipment load and equivalent wallp load, 20KN/m²; and (d) crowd load, 4KN/m².

Figure 10 depicts displacement of underground roadway’s surface. A part of underground emporium is under roadway’s surface in zone A, while soil under roadway’s surface in zone B is not excavated. So the roadway’s surface settles in zone A under vehicle load, but in zone B uplifts because of unloaded soil. The maximum settlement and maximum uplift of roadway’s surface are only -0.3cm and 0.5cm respectively, less than controlling value of 5cm under Chinese Code for Design of Road Tunnel (JTGD70–2004).
Under the roadway, four monitoring points are installed at the bottom of pit to monitor uplift of soil, which are located at distances of 20m, 50m, 80m and 100m away from the metro station as shown in figure 10 and figure 11.

In the stage of pit excavating, as the soil unloads largely, soil at the bottom of pit comes into plastic state and uplifts continually. It can be seen clearly the uplift values of soil increase considerably. Because residual soil and completely weathered siltstone at bottom of the pit have the characteristics of high water content and low permeability, excavation of pit will produce negative excess pore water pressure (Li et al. 2005). With dissipation of negative excess pore water pressure, effective stress in soil reduces gradually, which leads to swelling of soil. Therefore even when excavation is finished, the bottom of pit still uplifts because of swelling of soil. As stresses reduce dramatically after previous deformation, the uplift values of soil grow moderately and reach the maximum. Influenced by large range of soil unloading, the greatest uplift value and increasing rate was at monitoring point 1, rising to nearly 2.3cm. At four different monitoring points, it is also can be found the nearer away from the station, the larger the uplift value of soil is.

In the stage of construction, the uplift values of soil reduce steadily, which indicates soil is compressed and consolidated under successive load. Obviously the values reduced with roughly same rate. It can be interpreted from two aspects: (a) soil in different monitoring points has the same modulus of compressibility; and (b) unified dead load is adopted and applied on slabs in this simulation.

When the subsided roadway comes into operating stage, the soil is compressed by the adjunctive load, and the uplift values reduce gradually and tend to remain stable. The maximum of ultimate uplift value is 1.5cm, within the tolerance of 5cm under Chinese Code for Design of Road Tunnel (JTGD70–2004).

![Figure 11. Vertical displacements of different inspecting points during different stage.](image)

7. Conclusion
In this paper, synchronous construction of metro station and large underground space is discussed and analyzed through numerical simulation. Some measures should be adopted as below.

(a) Choose suitable constructing methods to excavate the pit. Excavation of pit is recommended to be done by layers and blocks within a specified time period and in a symmetrical and equilibrating way. Reduce exposing time of pit after excavation. Adopt effective measures to drain off water, improve strength of soil and avoid piping and quicksand.

(b) Adopt effective measures (mixing cement pile, sheltering and grouting etc.) to consolidate surrounding rock and soil of the existing tunnel when necessary. Control displacement of the existing tunnel within related standard.

(c) Install construction joints which are made of laminated rubber bearings in central columns, girders and top slabs to prevent damage in earthquake.

(d) Because construction is complex and uncertain, monitoring points should be set effectively. Construction can be adjusted in time according to feedback of monitor.
Developing underground space, improving utilizing rate of space and harmonizing underground and upper building have become mutual developing orientation of urban planning in the world. Utilizing of underground space will not be limited as a task of civil engineering, but also a mutual task of environmental protection, disaster prevention and mechanical engineering. Development of underground space will bring bran-new vitality to the field of civil engineering in this century.

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