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Statistical Analysis of Surface Settlements Laws Induced by Construction of Subway Shallow Tunnel

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Abstract: It's inevitable to disturb strata, leading to strata deformation in different degree, in the urban metro shallow tunnel excavation. It can influence the safety of subway construction and environment. In the paper, based on the analysis of the temporal-spatial effects of surface settlement and its mechanism caused by the construction of the shallow tunnel, analyze the 1400 ground surface settlements of 24 running tunnels in Beijing subway Line 5 and Line 10 with the fuzzy cluster analysis method. The general distinction of ground surface settlement and its distribution during construction of shallow tunnel is represented. What's more, ground settlement trough width parameter inflexion point distance is represented, too. Stratum loss ratio of is gained. The relation between ground settlement slot width parameter inflexion point distance and equivalence axial burial depth has been set up.

Keywords: subway engineering; tunnel engineering; ground settlement; temporal- spatial effects;

It's inevitable to disturb strata, leading to strata deformation in different degree, in the urban metro tunnel excavation. And, it can influence the safety of subway construction and environment. Therefore, the laws of ground deformation and control methods influenced by the construction of urban tunnels are hot issues in engineering in recent years[1-3].

The author, based on the Beijing Metro Line 5, Line 10 as the engineering background, studies the general characteristics of the surface settlement caused by the shallow tunnels construction in Beijing, including the largest value of surface settlement, the surface settlement trough width parameter and equivalence axial depth of burial, etc. At the same time, the author, collecting, selecting and making systematic analysis of the indicators, proposes the control standards of surface settlement caused the shallow tunnel construction, which make it to be safe, economical, reasonable and feasible.

1 Temporal-spatial effects of surface settlement

Although the tunnel geological conditions, structure, excavation methods, supporting different timing and stiffness are different, and the extent of the disturbance of the strata is also different, the surface settlement caused by the tunnel excavation has similar characteristics. Its law is developing with the change of the location and mobile process of the tunnel excavation surface, which shows clear temporal- spatial effects. The interaction of time and space reflects the general characteristics of surface settlement caused by the tunnel construction.

1.1 Time effect of surface settlement

After the shallow tunnel excavation, surface settlement is not a moment to reach the final value but gradually accumulated over time, and the stratum settlement has obvious time-effect. The process of a single surface settlement has three stages: first settlement, construction settlement and follow-up settlement. The first settlement means that the settlement arose before the tunnel excavation face reaches the measuring point, which is due to the excavation face earth pressure imbalance, lack of supporting forces, as well as lowering the water table. In the tunnel construction phase, excavation leads to the surrounding strata moving towards to the tunnel. And, as the tunnel support time, supporting strength and stiffness lag, as well as the lack of the density of sprayed concrete leading to formation gaps, this phase often results in greater surface settlement, usually a month or so. Follow-up settlement means that the settlement caused by the ground secondary consolidation and creep.

1.2 Spatial effect of the surface settlement

1.2.1 Horizontal surface settlement law

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Peck makes the horizontal surface settlement curve caused by the construction of the shallow tunnel approximately normal distribution curve, such as the equation (1) ~ (3) as shown.

$$S_x = \frac{V_l}{\sqrt{2\pi}i}\exp(-\frac{x^2}{2i^2}) \quad (1)$$

$$S_{\max} = \frac{V_l}{\sqrt{2\pi}i} \approx \frac{V_l}{2.5i} \quad (2)$$

$$i = \frac{H}{\sqrt{2\pi}\tan(45° - \frac{\varphi}{2})} \quad (3)$$

S_x is the ground point settlement on the cross-section whose distance away the tunnel axis is x; V_l is the is amount of soil loss caused by the tunnel excavation; $S_{\max}$ is the maximum amount of ground settlement, which is located at the tunnel centerline; i is the sedimentation coefficient of slot width, which is the distance between the surface settlement curve inflection point and the origin; H is the thickness of cover layer; φ is the internal friction angle of stratum.

1.2.2 Vertical surface settlement law

According to the different distance away the excavation face, the vertical surface settlement caused by the shallow tunnel construction, is divided into small deformation zone, dramatically increased zone, slow deformation zone and steady deformation zone. Small deformation zone, whose settlement is about 10% to 20% of the total settlement amount, refers to the zone 1 ~ 1.5 times diameter before the tunnel excavation surface. And it is caused by the stress release and dehydration consolidation of the stratum, which is lead by the tunnel excavation. Dramatically increased zone, whose settlement is about 50% to 60% of the total settlement amount, refers to the zone 1 time diameter before and 3 times diameter after the tunnel excavation surface. At the zone, the surface settlement rate of acceleration increases, and the deformation increases sharply. The deformation is mainly due to the boundary condition change, the disturbance of soil cover and the re-distribution of the stress, which caused by the tunnel excavation. Slow deformation zone, whose settlement is about 10% to 15% of the total settlement amount, refers to the zone 3~5 times diameter after the tunnel excavation surface. At the zone, the surface settlement rate slows down, the amount of deformation slowly increases, and settlement curve begins to converge. Steady deformation zone, whose settlement is about 5% to 10% of the total settlement amount, refers to the zone 5 times larger than the diameter after the tunnel excavation surface. At the zone, the surface settlement increases slowly and the stratum is stabilized-like.

2 Statistics and Analysis

2.1 The principle of selecting points

Subway Line 5 and Line 10 are the two important lines in Beijing mass transit network planning. Based on the engineering geological conditions and characteristics of the surrounding environment, 24 running tunnels are built with shallow tunneling method in the two lines, in which the interval section excavation span ranges from 5.80m to 14.60m, and the excavation method covers bench method, CD method, CRD method, as well as the double side drift method. The ground conditions, influenced by the construction, are relatively similar, mainly fine sand, medium coarse sand, silt, silt clay, clay and pebble gravel, etc. As the ‘phase change’ of the geological sedimentary layer in Beijing is clear, the sand clay stratum and sticky sand stratum are unique.

According to the principles that the selected points can reflect the maximum surface settlement (at the top of the centerline between the left and right structures) and can reflect the accumulated sedimentation value caused by the whole process of subway construction, excluding outliers, and the large section (including the return routes and transit lines, etc.) point in the statistical process of the effective measuring points, there are 1497 valid surface settlement measurement points totally in the 24 interval tunnels built with shallow tunneling method.

2.2 Statistic analysis of surface settlement

2.2.1 Analysis of surface settlement

By statistical analysis of the surface settlement values of the 1400 measuring points, the largest settlement value is 77.88mm, the minimum settlement value 0.06mm, and the mean is 31.6mm. And the points with settlement values less than 30 mm account for 46%, and those with settlement values less than 40mm account for 70%. If we exclude the points with settlement value less than 5mm, we can get the mean 33.4mm. And the points with settlement values less than 30 mm account for 42%, and those with settlement values less than 40mm account for 67%. If we exclude the points with settlement value less than 10mm, we can get the mean 35.6mm. And the points with settlement values less than 30 mm account for 39%, and those with settlement values less than 40mm account for 66%.

Nearly half (47.56%) of the measuring points' settlement values are range from 25mm to 45mm. There is a inflection point near the settlement of 40mm, showing that the point corresponds to 40mm settlement peak should exist probability density in the probability density distribution map.

2.2.2 The analysis of settlement trough width parameter and stratum loss rate

The inflexion point distance i reflects the scope of the lateral impact of the tunnel surface settlement trough, and the stratum loss rate V_1 reflects the extent of the disturbance to stratum caused by excavation, Such as (4), (5) showing. These two parameters reflect the general characteristics of the transverse surface settlement trough.

$$V_s = \int_{-\infty}^{\infty} S dy = \sqrt{2\pi} i S_{\max} \approx 2.5 i S_{\max} \quad (4)$$

$$V_1 = \frac{4V_s}{\pi D^2} \quad (5)$$

From the equations we can know that settlement trough volume unit distance on the tunneling direction (stratum loss). The stratum loss rate is the settlement trough volume each unit distance percentage of total volume of tunnel excavation. V_1 is the stratum loss rate and D is the equivalent diameter of the tunnel.

To the inflexion point distance of the settlement trough curve i, there are mainly two calculation forms: linear function and complex exponential function. Influenced by the surrounding complex surface environment, the horizontal range of the running tunnel surface settlement monitoring points is generally small, and it's difficult to consider the influence to the surface settlement trough inflection point. So it is unsatisfactory to fit with complex exponential function, and the equivalent axis cover depth distribution is concentrated. In order to ensure the reliability of analysis results, and make the law more evident, we the simplified linear function equation (6) to fit.

$$i = K z_t \quad (6)$$

i is the distance of the settlement trough inflection point. z_t is the equivalent depth of the tunnel axis. K is the width factor of the settlement trough.

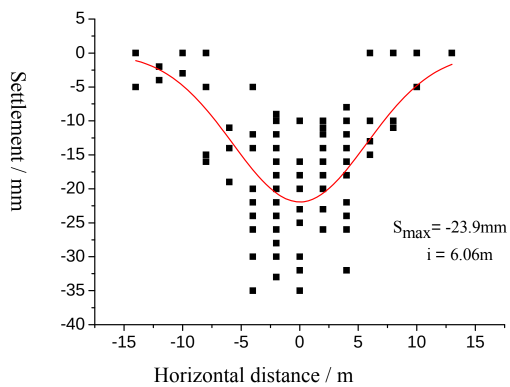

Figure1. Surface settlement trough fitting result of running tunnel

3 Subway Tunnel surface settlement control standards

At present, 30mm of surface settlement is regard as the control standard in construction of tunneling range in Beijing subway, but, we found, by field measurement of 1497 surface settlement measuring points, that the measurement points out of control standard account for 54% of the total measuring points. And the measurement points out of control standard concentrate in the regions of the large span tunnel excavation or simple surface environment, and the influence of their ground surface settlement is not significant. It shows that it is completely done to make the control standard of the surface settlement below 30mm in the current level of construction,

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and it also shows that the standard is not necessary sometimes and this "control standard" is more demanding. The strict control standard is bound to strengthen the relevant auxiliary construction measures and increase construction costs. This makes the standard can't play its "control standard" effect in many cases. Thus, the current control standard and construction technology, formation stability requirements are not well matched, and it should be adjusted appropriately.

According to the statistical analysis of the tunnel surface settlement in Beijing subway Line 5 and Line 10, without considering the environmental requirements of important ground buildings, the surface settlement control standard of Beijing Subway shallow running tunnel using 40mm is a more reasonable and feasible in the current engineering geological conditions and hydro-geological conditions.

According to the request of the shallow tunnel construction process control and variable bit allocation control principle, we should use three classes of control to the surface settlement of running tunnel: early warning, alarm and limit. We use 40mm as the control limit of shallow tunnel surface settlement in Beijing Subway, and use the value 60% of the limit (24mm) as warning value. After the alarm value, the construction party should take effective measures to control surface settlement. We use the value 80% of the limit (32mm) as the alarm value, and after the alarm, the construction party must take further measures, strengthening the support parameters and optimizing the construction program to control surface settlement. If the surface settlement is over the limit, they should immediately stop the construction. Seriously, they should start the emergency contingency plan, and organize the participation parties and experienced experts to discuss the next construction plan. When it is necessary, they should use compensation and rehabilitation measures.

4 CONCLUSIONS

1)The surface settlement of the shallow buried tunnel has clear temporal and spatial effects, and we should understanding the evolution of its development in divided period and divided region.

2) The mechanism of the surface settlement of shallow buried tunnel can be attributed to the settlement of stratum loss, stratum water loss consolidation settlement and secondary consolidation settlement, and we should use the corresponding control technology according to the settlement mechanism in the construction.

3) According to the principle of selecting surface settlement measurement points in this paper, we can get 1497 effective monitoring data of surface settlement of the 24 shallow buried running tunnels in Beijing Subway Line 5 and Line 10. And the Statistical data can reflect the real situation of surface settlement in Beijing Subway.

4) The surface settlement maximum is 78mm, and the mean is 31.6mm.The measuring points with settlement value less than 40mm account 70% of the total points. And there is a inflection point near the settlement of 40mm, showing that the point corresponds to 40mm settlement peak should exist probability density in the probability density distribution map.

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