A Tunneling-induced Stratum Settlement Assessment and Prediction System: STEAD-RISK

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ABSTRACT: Stratum environmental damage induced by urban tunnel construction is almost inevitable, which makes structures, roads and underground pipelines work improperly. This paper described the formula and details of development of a computer system. A prediction and control system for environmental damage induced by tunnel construction, named STEAD-RISK, was developed and introduced in this paper. This system had been developed in Delphi programming environment, by classical predict formulations, numerical analysis and three-dimensional imagery technology, prediction results and engineering field data was saved in database of this system, and then transfer was changed to visual three-dimensional maps. The main emphasis in this study was placed in developing calculation method and conversion between database from the system and points on the map. A newly computing package was developed in this program, which could predict settlement in construction site. By three-dimensional simulation, this code could transform predicted and monitored data into visual three-dimensional maps, in which the influence caused by construction to the stratum environment could be simulated veritably, so it's helpful for damage predictions and safe precautions. Finally, the paper presents a case application of the new system (Chinese version) in Beijing subway project.
Keywords: Urban tunnel construction, Stratum environmental damage, Settlement prediction, Three-dimension settlement graph

1. INTRODUCTION

With the industrialization process and the acceleration of economic development, the construction of urban underground has been paid more attention. Currently, shield method is conventionally used on the international plane, which has superiority to traditional methods (e.g. the method of shallow excavation) in construction quality, safety and risk management. However, ground deformation and subsidence will be caused inevitably by rapid constructing, the regularity of stratum environmental damage, control device and management with information technology in rapid construction are the most pressing concern in tunnel construction. Consequently, a forecasting and control system is necessary to be built up for these problems.

In response to increased problems on the tunneling induced stratum environmental damage, several attempts have been made to develop the assessment systems or methods for urban tunneling constructions, however, most of them are based on two dimensional settlement forecasts, which means the consideration is only one single angle from horizontal or vertical. In this context, the way how to bringing three-dimensional and settlement evaluation into the previously developed system STEAD and providing users with fully interactive accurate and visual data is the ultimate goal of this effort.

2. SETTLEMENT PRINCIPLE INDUCED BY SHIELD CONSTRUCTION AND PREDICT METHODS

2.1 The settlement principle induced by shield construction

Ground movement and deformation can be effected by sorts of factors, which include the depth of the tunnel, rock and groundwater conditions, the size of digging section and construction method, etc. The stratum deformation caused by tunneling occurs along the tunnel axis and varies according with the propel location of shield, consequently, as a dynamic process, tunnel construction contains five steps as follows: pre-settlement, settlement (or rise) in front of shield cut, settlement while tunnel going through, settlement caused by interstices of construction and lag settlement, etc.

Stratum damage is the difference volumes between the time actual soil excavation in tunnel construction and the tunnel completed, and the volumes of tunnel completed also contain the impressed slurry which wrap around tunnel. Stratum damage could be induced by a variety of factors, which commonly contains shield overbreak or underbreak, interspaces between shield and segments, damage induced by lining deformation, and shield propulsion in varied direction, etc. In these factors, settlement in front of the excavated surface, settlement while tunnel going through, and settlement caused by interstices of construction are substantial ones, and the most one is settlement caused by interstices of construction. Under condition of ignore consolidation, the volume of surface settlement trough caused by tunnel excavation should be equal to the volume of ground loss. The stratum damage is distributed in a fairly equal manner at the length of the whole tunnel construction, in which assumptions, elasto-plastic theory, Peck formula and stochastic medium theory could be applied theoretically on the analysis of surface subsidence.

2.2 Peck formula for stratum damage prediction (Empirical prediction method)

A mount of measured data of ground settlement and engineering data were analyzed by R.B. Peck (1969), who proposed approximate normal distribution curve of the surface settlement trough and the width of settlement trough subsequently, and a dimensionless relation between different types of strata, the tunnel diameter and depth were also introduced. The sorts of equations was improved by Cording and Hansmire (1970) in succession, and the concept of “Negative ground loss” was introduced by

Academician Liu and Hou (1991), which is one of the basis calculation method of this developed system, the vertical and horizontal displacements on a deforming ground are predicted using Eqs. (1) - (3).

$$S(x)=\frac{V_l}{\sqrt{2\pi}i}\exp\left[-\frac{x^2}{2i^2}\right],\quad i=\frac{H}{\sqrt{2\pi}\tan\left(45^\circ-\overline{\varphi}/2\right)} \tag{1}$$

$$S(y)=\frac{V_{L1}}{\sqrt{2\pi}\cdot i}[\Phi(\frac{y-y_i}{i})-\Phi(\frac{y-y_l}{i})]+\frac{V_{L2}}{\sqrt{2\pi}\cdot i}[\Phi(\frac{y-y_i'}{i})-\Phi(\frac{y-y_l'}{i})] \tag{2}$$

$$S_x'=\frac{dS_x}{dx}=\frac{-V_l\cdot x}{\sqrt{2\pi}\cdot i^3}\cdot\exp(-\frac{x^2}{2i^2}) \tag{3}$$

$$x=x'\cos\alpha-y'\sin\alpha+x_0$$
$$y=x'\sin\alpha+y'\cos\alpha+y_0 \tag{4}$$

In the above equations, V_l is stratum loss induced by tunneling, i is the settlement trough span coefficient, taken the distance between the surface settlement curve inflection point and the origin point, y is the distance from settlement point to the origin of the coordinate axis, y_i is the distance from shield excavation face at the starting point of shield promoting to the origin of the coordinate axis.

By introducing the two-dimensional Cartesian coordinate translation equations (Eqs.(4)), the vertical and horizontal displacements at any point on the field could be predicted. Transform coordinate of assess point into the given relative coordinate system, which use the shield head as the origin and the heading direction as the longitudinal direction of Y-axis.

2.3 Stochastic medium theory for stratum damage prediction

Stochastic medium theory was firstly introduced by Polish scholar J. Litwiniszyn (1957), and then was improved by Chinese scholars Liu and Liao (2002), now this theory gradually matured. As a kind of near-surface excavation, urban tunneling construction is suitable with the properties of stochastic medium, therefore the ground displacement and deformation induced by tunneling construction is appropriately predicted by stochastic medium. Correspondingly, the soil in subway construction is affected and damaged frequently by surface impact and human activity, for this reason, its primary structure is disturbed and become discontinuous obviously. Accordingly, the soil in subway construction is suitable for the medium definition in stochastic medium theory. According to stochastic medium theory, as a stochastic medium, the soil layer is a moving process as a stochastic process subject to statistical laws, and the way with this view to research the rock and ground movement shall probability integration method. The transverse and longitudinal settlements predicte equations are Eqs. (5) and (6).

$$
\begin{aligned}
W_{\Gamma}(x,H) = & \int_{H-a}^{H+a}\int_{-\sqrt{a^2-(H-\eta)^2}}^{\sqrt{a^2-(H-\eta)^2}} \frac{\tan\beta}{\eta}\exp[\frac{-\pi\tan\beta^2}{\eta^2}(x-\xi)^2]d\xi d\eta \\
& -\int_{H-b}^{H+b}\int_{-\sqrt{b^2-(H-\eta)^2}}^{\sqrt{b^2-(H-\eta)^2}} \frac{\tan\beta}{\eta}\exp[\frac{-\pi\tan\beta^2}{\eta^2}(x-\xi)^2]d\xi d\eta
\end{aligned} \tag{5}
$$

$$
\begin{aligned}
W_L(y,H) = & \frac{1}{2}W_L(0,H) + \int_{H-a}^{H+a}\int_{-\sqrt{a^2-(H-\eta)^2}}^{\sqrt{a^2-(H-\eta)^2}}\int_{-\frac{\sqrt{\pi}y\tan\beta}{\sqrt{\pi}\eta}}^{0} \frac{\tan\beta}{\eta}\exp\left(\frac{-\pi\tan\beta^2}{\eta^2}\xi^2\right)d\varphi d\xi d\eta \\
& -\int_{H-b}^{H+b}\int_{-\sqrt{b^2-(H-\eta)^2}}^{\sqrt{a^2-(H-\eta)^2}}\int_{-\frac{\sqrt{\pi}y\tan\beta}{\eta}}^{0} \frac{\tan\beta}{\sqrt{\pi}\eta}\exp\left(\frac{-\pi\tan\beta^2}{\eta^2}\xi^2\right)d\varphi d\xi d\eta
\end{aligned} \tag{6}
$$

In Eqs. (5) and (6), $W_{\Gamma}(x,H)$ and $W_L(y\ ,H)$ are the transverse and longitudinal surface settlement; a and b are the initial radius of the tunnel excavation and convergence radius after the effective support; H represents the tunnel depth; β is the angle of main influence sphere.

2.4 Numerical simulation analysis

This system uses the famous Itasca FLAC^{3D} engineering simulation software for the numerical analysis, by using node displacement continuity conditions; the analysis of large deformation of continuous medium could be achieved. Since many support structure models it build-in, FLAC^{3D} could commendably simulate the tunnel lining (segment), anchor, backbone, and other support units, consequently it is suitable for tunnel excavation problems.

3. DEVELOPMENT OF STEAD-RISK

This chapter is focus on the basic structure of STEAD-RISK; achieve the theoretical programming and numerical analysis for the prediction of surface movement and deformation in Delphi7 environment; and the principles of methods of data storage, processing and output display which source from the system.

3.1 System structure

STEAD-RISK was programmed in an object-oriented development environment using the Borland Delphi7.0. And currently Chinese is the only supported language of the operate interface. Accurate computation, user-friendly GUI and convenient data sharing are the substance of this system. Four modules are contained by STEAD-RISK (Fig.2~4): (1) Input module. In this module, an authorized user could input tunneling-related data and information in a user-friendly window-based GUI. The required input data contain location of monitoring points, geo-information, tunnel alignment, boring information, and load information, etc. All of the data are severed in a database built in the system, and are utilized later in computing the magnitude and distribution of ground movements. (2) Ground movement predict module. The function of this module is read off data from the internal database, then predict surface deformation by various predict methods which mentioned in last chapter. (3) Data storage and display module. Combined with module2, the two modules are foundation core of this system. Through BDE controls integrated in Delphi7.0, The predicted data from module2 and field monitoring data are stored into the system database with three-dimensional coordinates (x, y, and z). These data could be directly operated through Microsoft Excel for graphics output and risk assessment. (4) Risk assessment module. Take Visual C++ Programming Language as a tool, this module is developed independently on the basis of risk assessment criteria enact by national and related industries. And the result of risk assessment could be displayed visually in three-dimensional map with the cross-linked database. Each module could be operated independent, but is highly interfaced with other modules. Fig.1 shows the structure of STEAD-RISK.

Noteworthiness, in order to ensure the accuracy and authenticity of the output three-dimensional maps, it is recommend that user input the prescriptive coordinates of the predict points, which be used in CAD engineering draws, or the definite relative coordinates on the basis of CAD draws.

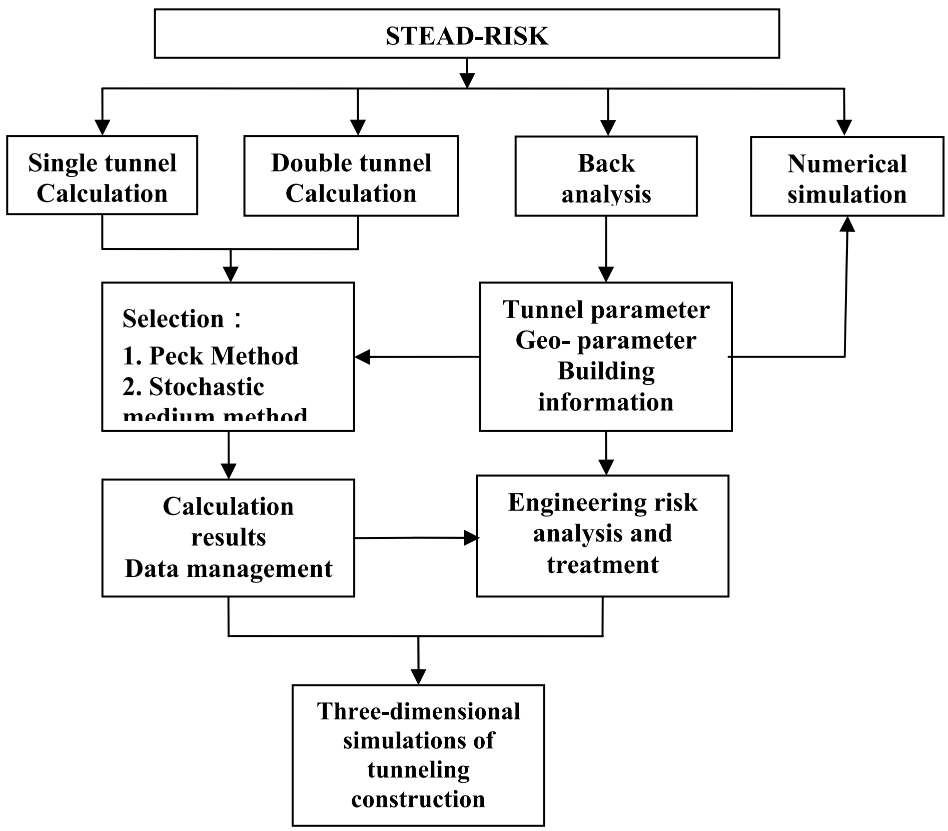


FIG. 1 System structure of STEAD-RISK

4. IMPLEMENTATION OF STEAD-RISK

This developed system was applied to Beijing subway Line 10 construction site. This 1989.5m length single tunnel section constructed under densely populated and skyscrapers area as seen in Fig.5. The ground at the site consists of clay, silt, sand soil, and gravel soil, with thick gravel layer and abundant ground moisture. To verify the predict ability, a typical tunnel section is selected, which located under a 12th floor building. The closest distance is 3.715m, the depth is 10m, and the tunnel diameter is 6000mm, thick lining 300mm. As mentioned, the prediction requires stratum loss induced by tunneling V_l, and the settlement trough span coefficient i, from the equations, the range of the former coefficient is 0.53m^3~0.56m^3, and the range of i is 6.74m~6.91m.

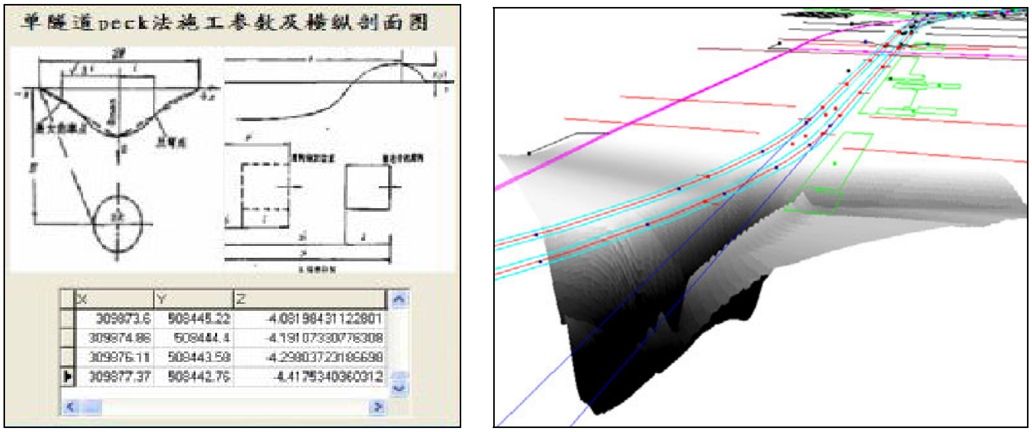
Through various methods, the predict results are displayed in the 3D map. The predict result shows that some buildings nearby the tunnel would be affected seriously (settlement more than 30cm) without any strengthening support measures. For the sake of avoiding the occurrence of excessive settlement, steel support was used timely to reinforce the tunnel structure. Comparing with the measured data selected from field monitoring point, the scientificity and feasibility of this system was verified. The result and comparison is presented in Fig.6.

(a) Peck method

(b) Stochastic medium method

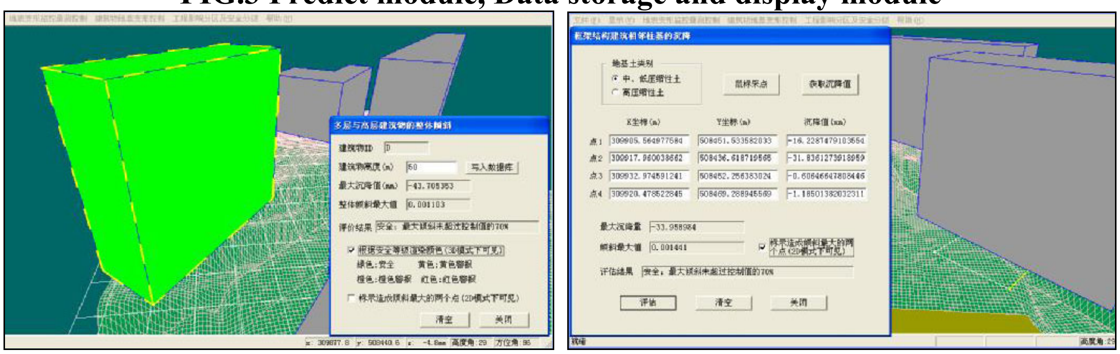
(c) Numerical simulation

FIG.2 Input module



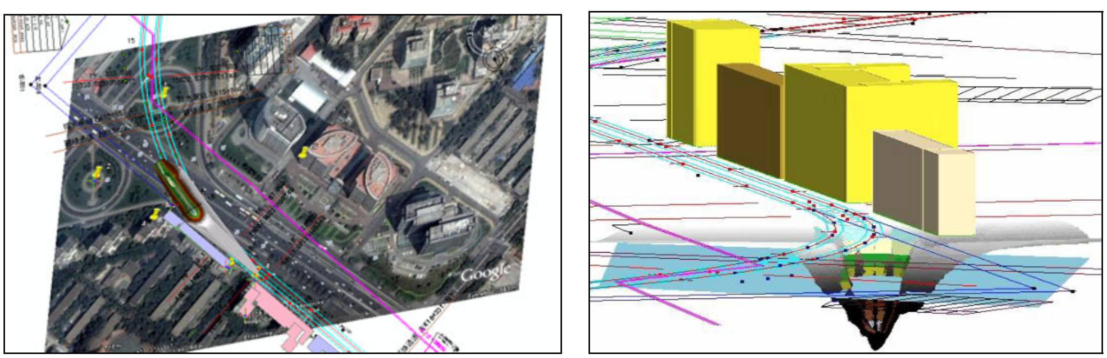
(a) Predict data stored in module 2 (b) 3D display of the predict settlement

FIG.3 Predict module, Data storage and display module



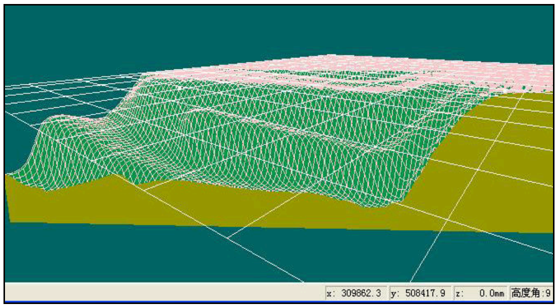
(a) Building overall tilt risk assessment (b) Local settlement risk assessment

FIG.4 Risk assessment module

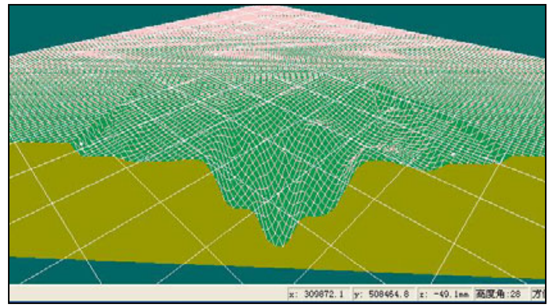


(a) Plane drawing in satellite map (b) Settlement displayed in 3D map

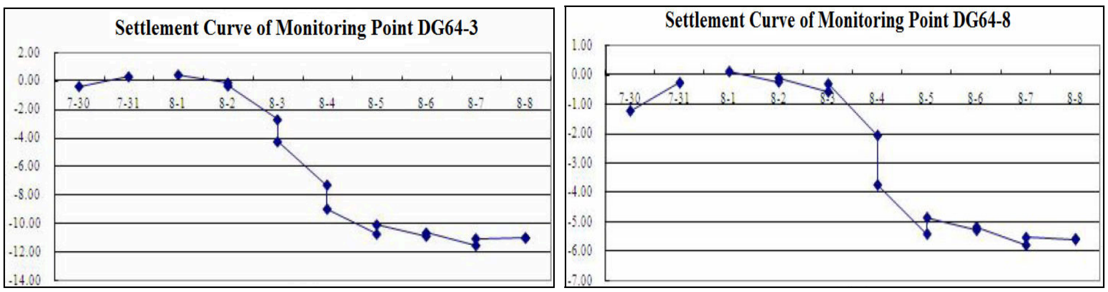
FIG.5 Plane and 3D map view of the site



(a) Transverse settlement profile



(b) Longitudinal settlement profile



(c) Time curves of settlement and time at monitoring point No.3 and No.8

FIG.6 Predict result and comparison

5. CONCLUSIONS

An assessment and prediction system for environmental settlement and damage induced by tunnel construction (STEAD-RISK) was developed in this study. This system improved classic Peck method and stochastic medium methods prediction equations, coded the assessment program with Pascal language, which could estimate the settlement at any point of the site. By three-dimensional data processing, this system could transform the predicted and field-monitored data into visual three-dimensional maps, in which the influence caused by construction to the stratum environment could be simulated veritably.

The developed system was successfully applied to Beijing Subway Line 10 project of section tunnel between Sanlihe and Liangmaqiao, the predicted results had been compared with the measured data, which verified the rationality and applicability of the prediction and assessment methods proposed by STEAD-RISK.

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A Case History of the Excavation of deep Foundation Pit Adjacent to Railway

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ABSTRACT: Minzhi station foundation pit in Shenzhen subway is adjacent to Pingnan railway. There is obvious unsymmetrical loading above the pit, and the pit is affected by the dynamic load from train. Therefore, the impact of pit excavation on the railway and the safety of the pit itself must be paid close attention to. The main technical measures adopted in the design and construction of deep foundation pit adjacent to railway is introduced. The measures include using steel pipe piles and prestressed anchor cables to reinforce the railway embankment, using diaphragm wall in the building envelope, setting strand prestressed cables in the middle of the diaphragm wall, using sleeve valve pipe grouting to reinforce the soil, and so on. The settlement of the railway embankment and track, as well as the horizontal displacement of the diaphragm wall, is monitored. Monitoring results show that these technical measures can ensure the normal operation of the railway and the safety of the pit itself.

INTRODUCTION

With urban development, there are more and more deep foundation pits. The safety of deep foundation itself and the environment is more and more paid attention to. As the technical, economic and management reasons, during the construction of deep foundation pit, there are many incidents. The analysis on domestic deep excavation accident shows that, the most direct factor which affects the safety of the project is the stability of the supporting structure, and the main reason which results in the accident such as foundation pit instability is the design and construction. Therefore, how to ensure safety and reliability of deep excavation with economic rationality, under the complex environment conditions in the cities, as far as possible to reduce the accidents and losses in deep foundation pit, has become an urgent need to focus on.