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Analysis on ground movements during shield tunneling – A survey on Japanese shield tunneling

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1. INTRODUCTION

This paper is prepared as a part of the study related to a survey on Japanese Shield Tunneling, which was carried out by the Japanese Society of Soil Mechanics and Foundation Engineering — Committee on "Underground Construction in Soft Ground" (JSSMFE TC-28).

The prediction of ground displacement associated with shield tunneling is important when selecting the appropriate shield and measures to prevent the adverse effects of shield tunneling, thereby preventing undesirable impacts on the neighbouring ground due to ground displacement causes by the shield tunneling. There have been many reports in Japan on ground displacement prediction techniques. Among others, the FEM analysis has established itself as the mainstream analysis method to predict ground displacement (Fig. 1).

The mainstream shield tunneling methods have been shifting from such open-type shield tunneling methods as semi-mechanical or manual digging to such closed-type shield tunneling methods as the earth-pressure-balanced-type or slurry-type and the scope of applicable ground has accordingly widened from hard ground to include alluvial soft ground. Ground displacement prediction techniques have developed in line with the improvement of shield tunneling technologies and changes in the ground conditions. In this paper, the focus is placed on the FEM analysis, which has become the mainstream analysis method, in order to study the chronological changes of ground displacement analysis techniques and remaining tasks for ground displacement analysis.

2. CHRONOLOGICAL CHANGES OF GROUND DISPLACEMENT ANALYSIS

The chronological changes of the FEM analysis can be divided into the following 4 stages.

(1) FEM Analysis of Unsupported Tunnel

It was around 1970 when FEM began to be used for the analysis of ground displacement. As most shield tunneling at that time consisted of open-type shield tunneling on diluvial ground, the main causes of settlement were compaction and consolidation settlement due to the lowering of the groundwater level, release of stress at the face and delayed back-filling. Under these circumstances, the FEM analysis of unsupported tunnel was attempted.

Hanya et al. (1969) argued that the settlement phenomenon without ground collapse at the front of the face could be explained by elastic and plastic settlements based on the FEM analysis of unsupported tunnel. Kawamoto et al. (1972) proposed the analytical method where the settlement caused by loosening (descending floor) was added to the elastic settlement based on the FEM method to achieve better correspondence between the actual measurement and the theoretical settlement. They also explained that correspondence could be improved by taking the non-linear characteristics of the ground into consideration.

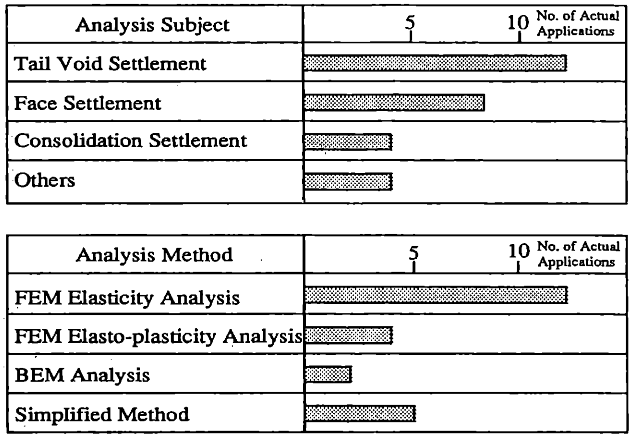


Fig. 1 Analysis methods used in existing studies (based on main Japanese research documents in last 10 years)

(2) Analysis of Consolidation Settlement Following Ground Disturbance

At the next stage, the development of the blind or closed-type shield tunneling method paved the way for the application of the shield tunneling method to alluvial cohesive soil ground for which the application of the previous open-type shield had been difficult. With this type of work, it was discovered that large settlement took place despite control of the theoretical soil discharge volume to nearly the 100% level and grouting of a large quantity of back-filling materials to the tune of several times more than the size of the tail void (Mori et al. (1977)). Mori et al. (1979) explained this to be consolidated settlement following ground disturbance caused by the shield tunneling and proposed a formula to calculate the magnitude of consolidation settlement. According to the method of Mori et al., ground disturbance is caused by shear deformation due to the release of stress. Consequently, the distribution of shear distortion in the ground is established by the FEM elasticity analysis and the consolidation settlement is calculated.

(3) FEM Analysis Taking Shield Work Conditions into Consideration

With the growing popularity of closed-type shield tunneling methods, such as the slurry shield and E.P.B. shield, the face stability in closed-type shield tunneling greatly improved and back-filling technologies also showed much improvement. One consequence of such improvement was that the actual measurement value of the settlement often became smaller than the theoretical value given by the FEM analysis of unsupported tunnel, making it essential to take the actual shield work conditions into consideration as part of the FEM analysis.

① Analysis Taking Tail Void Size into Consideration

Yamada et al. (1979) proposed a model (Fig. 2) to explain the release of stress by the tail void taking the tail void size and segment rigidity into consideration. This model limits the ground displacement to the size of the tail void in the FEM analysis of unsupported tunnel and the final displacement is achieved as the sum of the above ground displacement and displacement originating from segment deformation. It is also argued that a fairly realistic ground settlement analysis can be conducted by setting the scope of ground loosening and the deformation coefficient in view of the ground disturbance caused by the advancement of the shield (Makata et al. 1980).

② Analysis Using Rate of Stress Release

Furuyama et al. (1980) proposed a method to reduce the driving equivalent external force by introducing an appropriate rate of stress release based on the soil intake volume and tail void volume, etc. This rate of stress release is often empirically determined based on the results of past work or by means of the back analysis of the actual measurement data.

③ Analysis Taking External Force into Consideration

Nakamura et al. (1986) and Nakayama et al. (1988) argued that the release of stress at the face is negligible in the case of slurry shield tunneling with hard ground and that settlement can be mainly explained by the elastic deformation of the tail void. According to this method, the slurry pressure is believed to control the tail void deformation (Fig. 3) and the digging equivalent external force is calculated by the following equation.

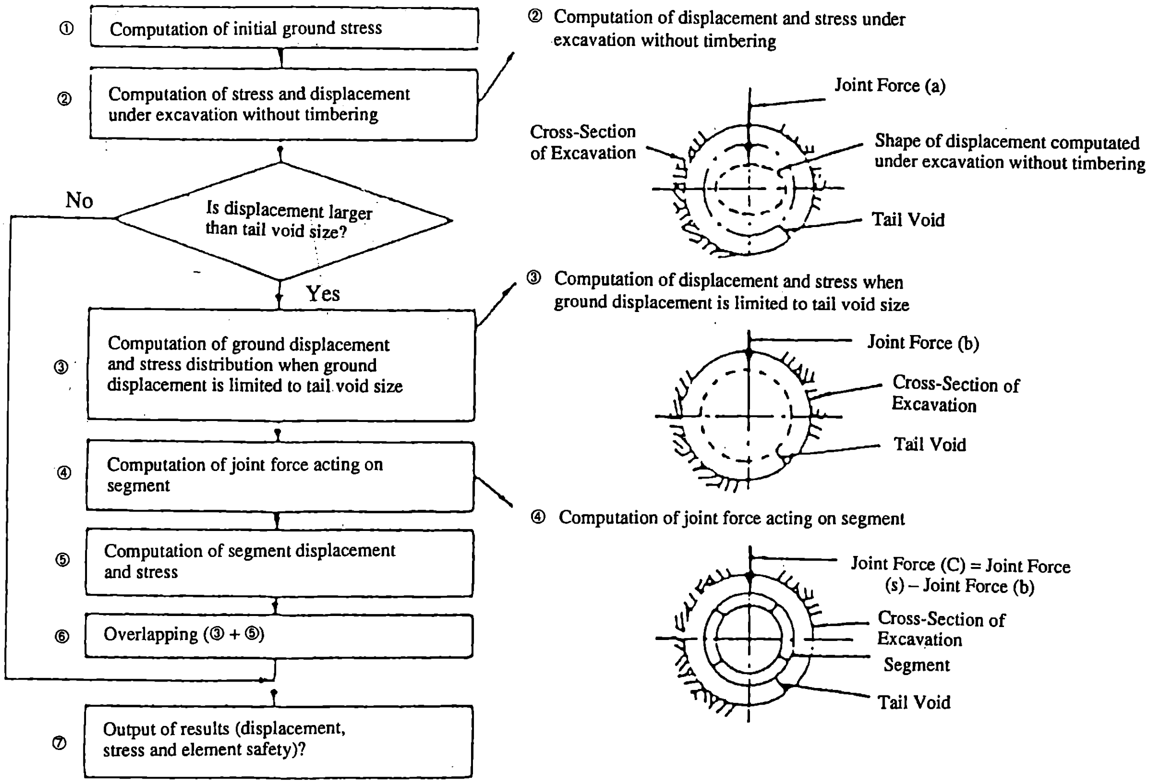
$$p_E = \alpha (p_I - p_S) \quad \cdots\cdots (1)$$

where,

p_E : Digging equivalent external force,
α : Correction factor,
p_I : Initial ground stress,
p_S : Slurry pressure.

(4) Consideration of Three-Dimensional Effects of Ground

Most of the analyses so far rely on the two-dimensional distortion model. There have been many attempts to express more realistic ground behaviour by analyzing the three-dimensional effects of an advancing shield on the ground.



(a) Flow Chart (b) Joint Force Acting on Segment

Fig. 2 Release model of tail void stress

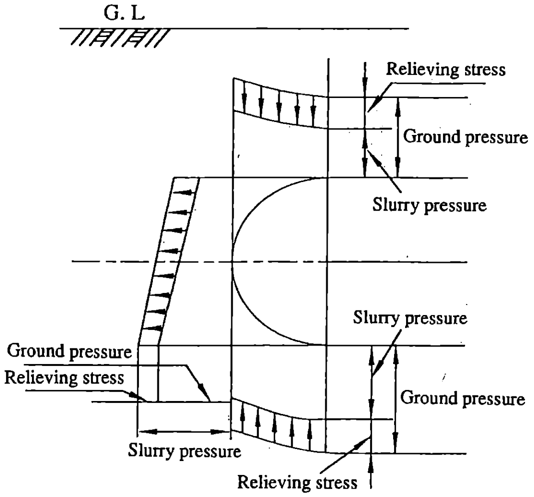


Fig. 3 Relation between ground stress and slurry pressure

Hisatake et al. (1988) proposed a surface settlement amount estimation method which takes the construction processes, face location and digging speed, etc. into consideration using a dimensionless settlement curve of the shield profile ground surface given by the three-dimensional boundary element method and FEM two-dimensional traverse model. In contrast, Ohta et al. (1985) proposed a method to express the three-dimensional effects of the ground by obtaining the characteristic curve of settlement based on an axial symmetry model and then by gradually introducing the forced displacement equivalent of the tail void size to the tunneling surface of the two-dimensional model in accordance with the characteristic curve.

3. TASKS OF GROUND DISPLACEMENT ANALYSIS

As seen so far, many proposals have been made to forecast ground displacement by the FEM analysis following the development of shield tunneling methods. At the same time, it has become obvious that there are still many tasks to be solved. These tasks are examined below.

(1) Modelling of Ground

As it is apparent that the modulus of elasticity of the ground material has a significant impact on the FEM analysis results, this aspect of the ground must be carefully examined in any attempt to create model ground. Hanya et al. (1969) suggested that the modulus of elasticity should be determined based on a number of soil test results and recommend that the deformation characteristics of the ground vis-a-vis the short-term load should be taken into consideration.

Table 1 gives examples of modulus of elasticity used in past studies, indicating the fact that the various analysis methods discussed earlier rely on different assumptions of the modulus of elasticity. The use of a uniform modulus of elasticity in future studies is highly desirable to avoid confusion in ground displacement prediction for practical purposes.

Table 1 Modulus of elasticity used in FEM analysis

	Sandy Soil	Cohesive Soil
Kawamoto et al. (1972)	Plate bearing test or 7N (kgf/cm^2)	
Nakayama et al. (1988)	25N (kgf/cm^2)	210 c_u (kgf/cm^2)
Hisatake et al. (1988)	5N + 70 (kgf/cm^2)	210 c_u (kgf/cm^2)

N: SPT N-value
c_u: undrained shear strength (kgf/cm^2)

In the case of stress-strain modelling, the elasticity model shown in Fig. 1 is frequently used. Taking into consideration the significant decrease of ground settlement in recent years due to the efficient control of face stability through the extensive use of computers and the development of excellent back-filling materials with superior filling performance, it may be sufficient to rely on the FEM elasticity model. Nevertheless, it is rather risky to assume sandy ground liable to collapse as an elastic continuous mass. It is important to adopt a stress-strain model which is appropriate for the specific ground conditions. The inclusion of joint elements in a ground model should also be considered.

(2) Improvement of Construction Technologies and Rationalization of Ground Displacement Prediction

The existing ground displacement analysis methods are well aware of the close relationship between ground displacement and such construction elements as face stability and back-filling. At the actual construction stage, the monitoring of the causal relationship between ground displacement and face pressure, back-filling quantity and back-filling pressure, etc. are identified to improve the construction method, has been established to minimize ground displacement. At the planning and design stages, however, these causal relationships are not often referred to and, instead, the ground displacement forecast with a large safety margin is emphasised to select appropriate measures to minimize ground displacement.

One reason for this is the fact that the state of ground stress is not yet fully understood. While it is difficult to measure the earth pressure without disturbing the ground, the optimal face pressure for each soil condition to be established by the monitored construction method can be taken as the earth pressure at rest. Another problem appears to be that construction control is conducted through the pressure control on the discharge pump despite awareness of the importance of back-filling. For quantitative evaluation of the relationship between back-filling and ground displacement, the distribution of the back-filling pressure inside the tail void and the filling rate of the back-filling materials must be understood at all times.

Further advancement of the research and development of construction technologies will make it possible to analyze ground displacement with detailed consideration of the actual construction conditions at the design stage, subsequently achieving further rationalization of shield tunneling.

4. APPLICATION OF ANALYTICAL RESULTS TO WORK CONTROL

To reduce ground displacement caused by shield tunneling work, the monitoring method for construction control have been proposed and used.

In this context, Hirata et al. (1983) monitored ground behaviour in detail in the case of E.P.B. shield tunneling work against a soft cohesive soil formation (N = 0 – 4) in the light of the work conditions and fed the monitoring results back to the actual construction work. Automatic simultaneous back-filling operation was employed, which was linked to the progress of digging, through grouting pipes mounted on the shield to minimize ground displacement, particularly at the tail section.

Fig. 4 shows the hourly changes of both the vertical and lateral displacements of the ground for shield progress immediately above it when digging was conducted with the internal pressure of the chamber being approximated to the earth pressure at rest. Fig. 5 shows the lateral displacement along the transection. The vertical displacement of the ground in front of the face is not more than 5mm throughout the area between the top of the shield and the ground surface. Upheaval caused by back-filling can be observed near the shield when the tail passes but the ground surface is little affected. Lateral displacement in the form of minor inward movement occurs near the shield tunneling machine when the face reaches a measuring point. When the tail passes, minor outward movement of some 20mm caused by back-filling is observed near the shield but again the ground surface is little affected, indicating the successful containment of ground displacement with a soft cohesive soil formation (Hirata et al. 1983).

Moreover, shield tunneling control combining on-site measurement data and ground displacement analysis methods to minimize ground displacement has been gaining popularity in recent works.

Makata et al. (1980) proposed a construction control method using dynamic monitoring as a comprehensive construction control method to contain ground displacement as shown in Fig. 6. This method consists of preliminary prediction, initial detailed monitoring and ordinary monitoring control. Prelimi-

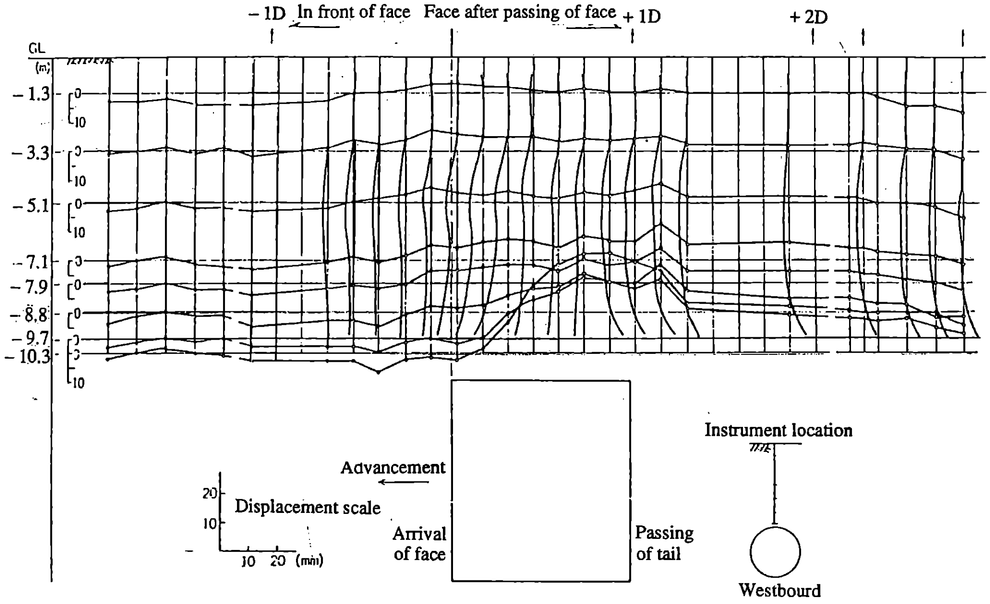


Fig. 4 Vertical and lateral displacements of the ground immediatery above shield machine

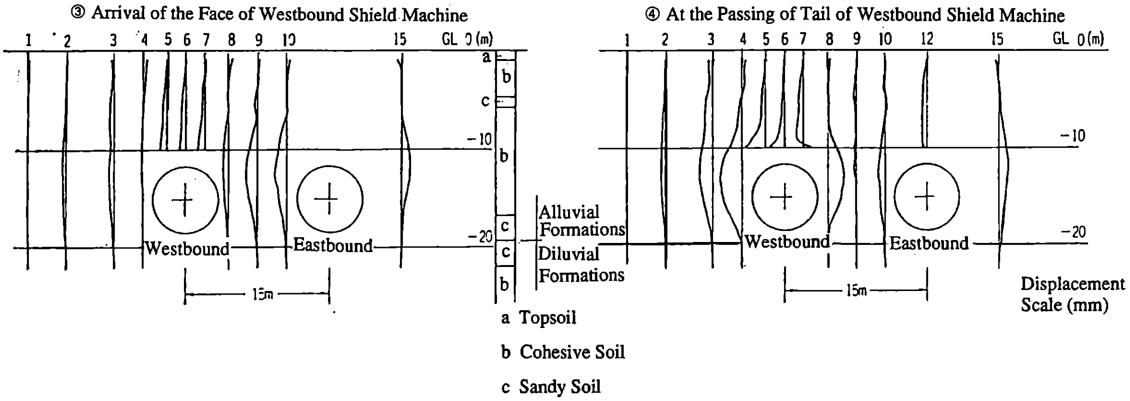


Fig. 5 Lateral displacement across shield

nary prediction means the establishment of the ground settlement and their distribution through numerical analysis and then the prediction of the likely impact on the surrounding environment based on the distribution of the various ground settlements. Initial detailed monitoring means the detailed monitoring of ground surface settlement, underground vertical displacement, change of groundwater level, subsidence of utilities and subsidence of house foundations, etc. at the early construction stage to obtain basic data to be used for subsequent construction control. Ordinary monitoring control mainly means the monitoring of the surface settlement along the central axis of the shield to judge the work quality and to identify the causes of increased or decreased settlement wherever it occurs so that the obtained data can be fed back to the actual construction work.

With the accumulation of experience of adopting comprehensive construction control, it is highly likely that ground displacement caused by shield tunneling will be further reduced.

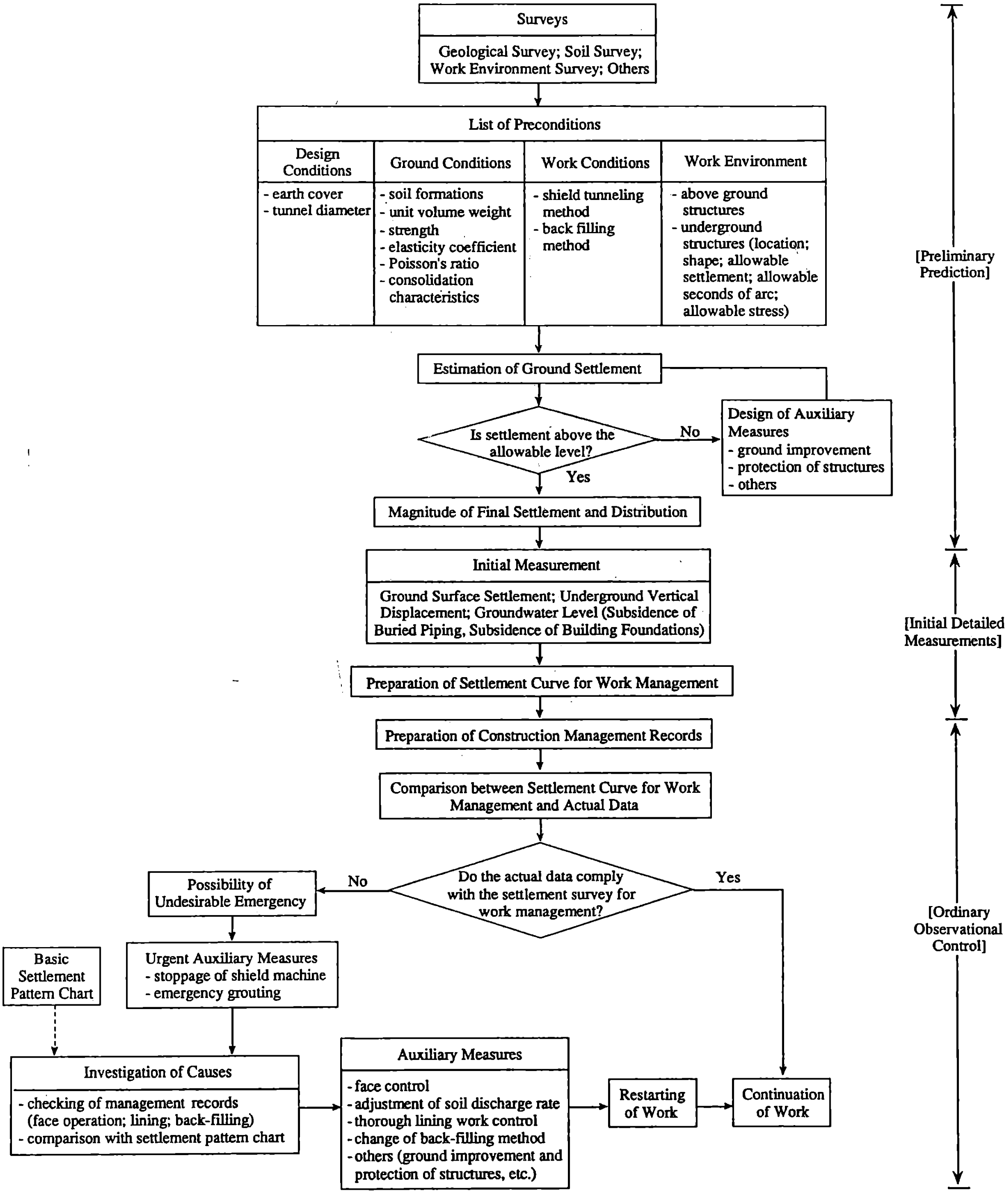


Fig. 6 Flow chart of construction control using dynamic monitoring

5. CONCLUDING REMARKS

The important requirements of shield tunneling work are to ascertain a high quality completed tunnel in terms of durability and other aspects and to suppress advance impacts on the surrounding ground and structures in the vicinity below the permissible level. The estimation and suppression of ground displacement are, therefore, major tasks for shield tunneling work to meet such strict requirements. Ground displacement estimation methods, developed as a result of the advancement of computer technologies designed to make analysis of ground excavation easier and more accurate, have been discussed in this paper.

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