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Report on current shield tunnelling methods in Japan

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SYNOPSIS: This report summarizes the present trend of shield tunneling technology in Japan. The report contains the relationship between a shield tunneling method and ground conditions, the relationship between a designing method and soil properties, the relationship between a ground deformation prediction method and soil properties as well as the relationship between a shield tunneling method and a monitoring method.

1 INTRODUCTION

Most Japanese major cities developed in fluvial plains are located on the weak ground with a higher groundwater level. Shield tunneling has developed as an appropriate tunneling method in such cities due to the following factors:

1. Japan is behind European countries in introduction of infrastructures.
2. With a rapid development of motorization, employing a cut and cover tunneling method in construction of water supply/sewerage systems and subways is becoming difficult.

In view of the above, this report will summarize the latest shield tunneling technology in Japan.

2 THE APPLICABILITY OF A SHIELD TUNNELING METHOD

The applicability of a shield tunneling method will be described based on the survey results of constructions, completed, in their proceedings or contracted during the period from 1987 to 1992, conducted by Japan Society of Civil Engineers (JSCE). The results obtained from this survey, which has not yet been publicized, will be presented in this report with a consent of JSCE.

2.1 The relationship between a shield tunneling method and ground conditions

A shield tunneling method is determined based on the synthetic consideration of soil conditions, execution conditions and environmental conditions in the surrounding area. The relationship between a shield tunneling method and ground conditions based on the aforementioned survey results will be described here.

Fig. 1 shows the percentage of employed methods during the period from 1987 to 1992 obtained from the results of the survey conducted by JSCE. As apparent from the figure, a closed face-type shied amounts to well over 85% of all types, in which an earth pressure-type and a slurry-type accounts for 62.9% and 23.3% respectively.

As for the relationship between a shield tunneling method and ground conditions, Fig. 2 presents the relationship between a shield tunneling method and typical soil of the cutting face which show the results obtained from the survey conducted by JSCE.

Fig. 2 shows that more closed face-type shields are employed for soils ranging from cohesive to soft rock. From the above it can be said that in Japan, a closed face-type shield is used under a broad range of ground conditions, except for some exceptional execution conditions.

2.2 The relationship between the primary lining and ground conditions

In selecting an appropriate segment type, such elements as loads that act on lining including earth pressure and water pressure, ductility, durability, workability and economy should be taken into account. A description of the primary lining, based on the results of the survey conducted by JSCE, will be presented below.

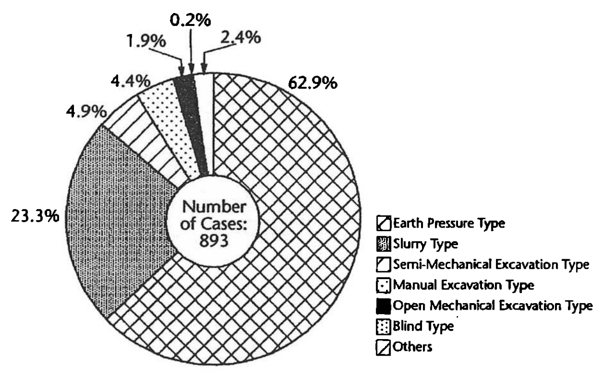

Figure 1. Percentage of application of each shield tunneling methods (1987 to 1992)

Fig. 3 shows the percentage of the employed segment type, in which a steel segment and a reinforced concrete (RC) segment accounts for 75% and 22% of all types respectively.

Fig. 4 illustrates the steel segment applications by their outer diameters. As can be seen in the figure, they are more frequently used for shields with a smaller diameter mainly required for sewerage system construction.

Fig. 5 illustrates the RC segment applications by their outer diameters, in which, more frequent use can be observed for shields with a medium to large diameter mainly required for sewerage and railway system construction.

As apparent from the figures 3 to 5, steel segments are usually used for shields with a small or medium diameter, whereas RC segments are used for that with a medium to large diameter. The correlativity between segments and typical soil is low.

3 EARTH PRESSURE AND WATER PRESSURE ACTING ON LINING

Designing methods of segment rings proposed in Japan have the concept of earth/water pressure in common. The concept of earth/water pressure as well as structure designing methods will be described below.

3.1 The concept of earth pressure and water pressure

The earth pressure acting on the segment ring as well as determination of water pressure are presented in Fig. 6.

There are two different ways of thinking in computing earth pressure. In one way, water pressure is computed as part of earth pressure. Whereas in the other, water pressure is computed independently. The former is generally employed for cohesive soil, while the latter for sandy soil.

The former allows computation of water pressure by assuming uniformly distributed load in a vertical direction and trapezoidal load in a lateral direction, based on hydrostatic pressure. Meanwhile in the latter, setting water pressure is not necessary as water is considered as an inclusive element of earth. To achieve reliable design, water pressure must be determined allowing for ground water level fluctuations during and after construction.

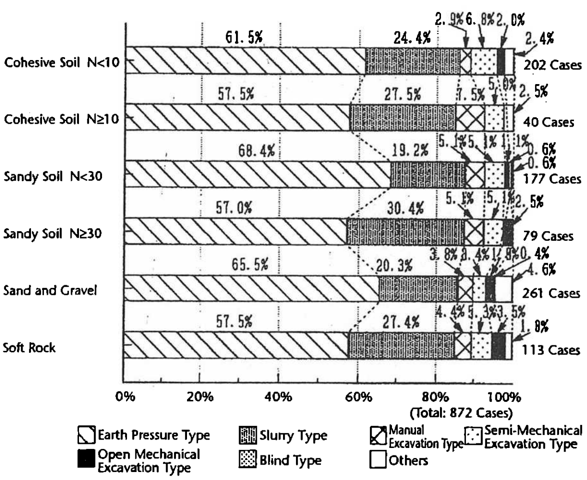

Figure 2. Relationship between shield tunneling methods and typical soil conditions at cutting face

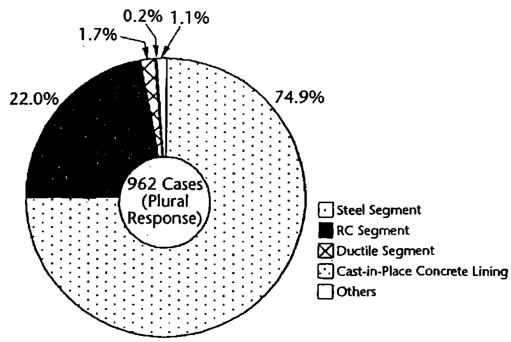

Figure 3. Percentage of application of each segment type (1987 to 1992)

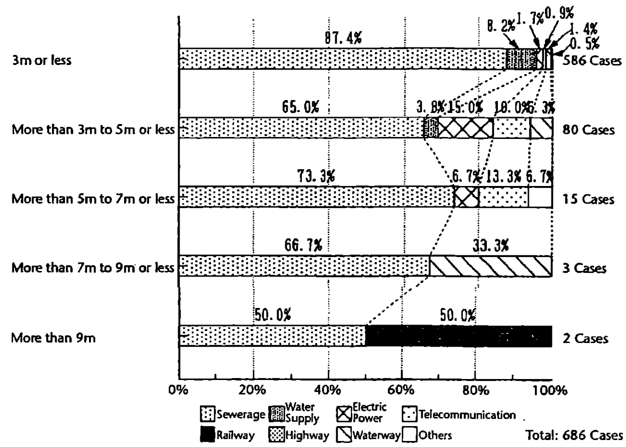

Figure 4. Tunnel usage classified by outer diameter of steel segment

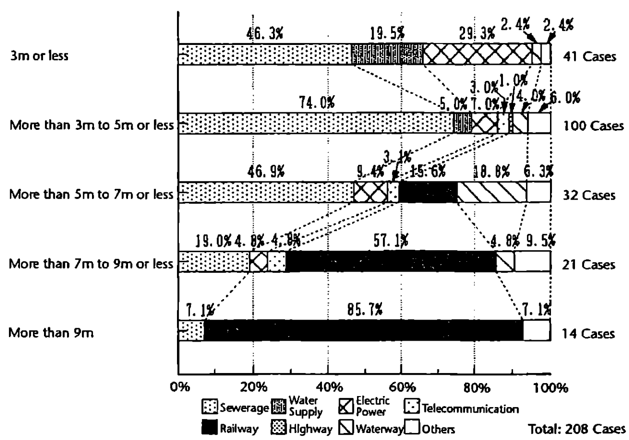

Figure 5. Tunnel usage classified by outer diameter of RC segment

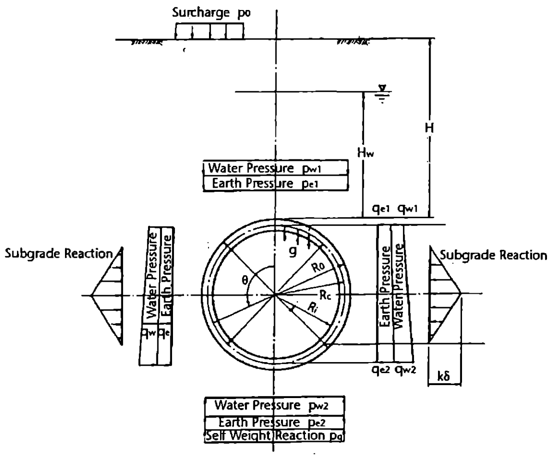

Figure 6. Example of design earth and water pressures acting on segment ring

Table 1 Lateral pressure coefficient (λ) and modulus of subgrade reaction

(k-value: kg/cm^3)

Types of Soils	λ	k	Criterion with N-value
Compacted Sandy Soil	0.35~0.45	3.0~5.0	N≥30
Consolidated Cohesive Soil			N≥25
Compacted Sandy Soil	0.45~0.55	1.0~3.0	15≤N<30
Hard Cohesive Soil			8≤N<25
Medium Cohesive Soil		0.5~1.0	4≤N<8
Loosen Sandy Soil	0.50~0.60	0~1.0	N<15
Soft Cohesive Soil	0.55~0.65	0~0.5	2≤N<4
Very Soft Cohesive Soil	0.65~0.75	0	N<2

a) Vertical earth pressure

Vertical earth pressure is usually considered as uniformly distributed load that acts on the top of lining, and is determined based on earth covering and an outer diameter of a tunnel as well as ground conditions, in which, either total earth covering pressure or loosening earth pressure is used. Loosening earth pressure is generally employed for sandy soil of good quality (example: N≥10) and consolidated cohesive soil (example: N≥8) where earth covering is one to two times the dimension of an outer diameter of a tunnel. Earth covering is often determined as twice the dimension of an outer diameter of a tunnel with a smaller outer diameter.

To ensure structural safety, the lower limit is often set to loosening earth pressure when employed as vertical earth pressure, allowing for load fluctuations during and after construction.

b) Lateral earth pressure

The lateral earth pressure acting on the sides of lining is determined as trapezoidal load obtained through multiplication of vertical earth pressure computed in a) by side earth pressure coefficient (earth covering pressure acting on the top of lining is taken into account). Side earth pressure coefficient (λ) is generally determined in correlation with soil classification, N-value and subgrade reaction coefficient (κ). A list of set values obtained from the standard specifications of the tunnel (Shield) (Japan Society of Civil Engineers 1986) is presented in Table 1.

3.2 Structure computation

The following three designing methods are proposed according to the concept of decrease in flexural rigidity of a segment ring due to the use of joint, as well as subgrade reaction.

a) A method in which a segment ring is assumed to have an uniform flexural rigidity (Conventional designing method and Modified conventional designing method)

b) A method in which a segment ring is assumed to be a multiple hinge ring (multiple hinge ring analytical method)

c) A method in which a segment ring is assumed to have rotating blades (Beam/spring model analytical method)

Of the above three methods, "Conventional designing method" is most commonly used. The method allowing easy computation and resultant reliable design is widely used for the cross sections with a medium diameter and smaller. Whereas for the cross sections with a larger diameter, "Modified conventional method" and "Beam/Spring model analytical method" that take into account the decrease in rigidity due to the use of joints as well as joint effects due to staggered joint, are used. Only a limited number of use of "Multiple hinge ring analytical method" are confirmed.

3.3 Soil constants used for designing

Vertical earth pressure (loosening earth pressure or total earth covering pressure), side earth pressure coefficient (λ) and subgrade reaction (κ) are determined on the basis of N-value (see Table 1). Determination of total earth pressure as vertical earth pressure requires such parameters as unit weight (γ) and submerged unit weight (γ'). In addition to the above parameters, cohesion (C_u) and internal friction angle (ϕ) are required for determining loosening earth pressure.

4 GROUND DEFORMATION

4.1 Estimation methods of ground deformation

In Japan, Settlement is mainly estimated through numerical analysis, however, empirical formulas based on settlement data are also employed (Peck 1969, Takeyama 1983 et al.). Of such numerical analysis, the following methods are commonly used. The theory of elasticity (Jeffrey et al.) is used for immediate settlement analysis in which the subjective ground is assumed to be single-layered. The FEM elasticity analysis is used for multiple-layered ground, and consolidation computation (Mori et al. 1979) for consolidation settlement due to disturbance in the ground. As for the FEM elasticity analysis, the analysis of the strain in the shield cross section has been mainly performed using a two-dimensional plane strain model. However, recently, more practical models allowing the evaluation of shield advancement or three-dimensional effects of the ground are proposed by Ohta (1985) et al.

4.2 Soil constants used for ground deformation analysis

Numerical analysis requires such parameters as ground deformation coefficient (E), Poisson's ratio (ν), unit weight (γ) and submerged unit weight (γ'), whereas an empirical formula requires soil classification and ground deformation coefficient (E).

Of the above parameters, E, γ and γ' are generally determined on the basis of the results obtained through soil analysis, however, E is often estimated by the equation below when soil analysis is inadequate.

In case of cohesive soil: $E = 210\ C_u$
In case of sandy soil: $E = 70 + 5N$

where,
C_u: Cohesion of the ground
N: N-value obtained from standard penetration tests

Poisson's ratio of 0.3 to 0.4 is commonly used for sandy soil, meanwhile that of 0.4 to 0.475 for cohesive soil.

5 MONITORING METHODS

Two types of monitoring methods are usually used for shield tunneling work, a monitoring method of ground deformation and that of earth/water pressure acting on lining. Generally the former is more often used for a short-term monitoring, whereas the latter, for a long-term monitoring.

5.1 Ground deformation monitoring methods

Of ground deformations, ground surface settlement is monitored using a level monitoring method, except for that in the special section crossed by rivers.

In case shield tunneling is carried out near to the foundation of a building, in-situ settlement gauges, multi-element inclinometers, in-situ load cells and piezometers are also installed to perform a detailed monitoring of ground deformation.

5.2 Monitoring methods of earth/water pressure acting on lining

Only a limited number of monitoring of loads and stresses acting on tunnel lining have been carried out in a disproportionately large number of lining works.

In-situ monitoring methods of loads and stresses can be roughly divided into the following two types; direct monitoring in which a pressure sensor is installed at the back of a segment, and indirect monitoring in which loads are estimated through monitoring of distortion in a segment. In most cases the above two methods are used simultaneously to confirm the propriety of such monitoring.

5.3 Forward prospecting methods

Geophysical prospecting (including magnetic, electromagnetic, seismic and acoustic prospecting) is carried out as forward prospecting. The aim of such prospecting is to detect obstacles such as steel piles. Prospecting using Rayleigh wave has started to be carried out experimentally.

6 REFERENCE LITERATURES ON SHIELD TUNNELING METHODS

Reference literatures on shield tunneling published by public organizations are as follows: "Standard specifications of the tunnel (Shield) and expository comments" by JSCE; "Typical segments for shield tunneling construction" by Japan Sewerage Works Association (1990); and "A guide to shield tunneling design and construction" by Japan Railway Civil Engineering Association.

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