First Korea-Japan Joint Geotechnical Seminar
October 18-20, Seoul, Korea

TUNNELLING IN SOFT GROUND IN URBAN AREAS

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SUMMARY

Most tunnels in soft soils in urban areas are constructed by shield tunnelling method for environmental reasons. Ground surface settlements are caused by shield tunnelling so that auxiliary measures are often required. Simple methods to predict ground surface settlement are given. The use of the slurry or the earth pressure balance shield machine and the application of new methods of grouting with computer aided operation control systems decreases the ground surface settlement to 3 mm. The construction cost of tunnels is almost identical whichever type of shield machine is employed according to a statistical investigation.

INTRODUCTION

Tunnels in urban areas are employed for underground transportation, mass transit, fresh water supply, sewerage, public utilities, etc., in order to organize the functions of the area efficiently. The cut-and-cover method and the shield tunnelling method have been widely employed for the construction of tunnels in soft soils in urban areas where buildings and structures are densely located.

Use of the shield tunnelling method has been increasing gradually, because the geotechnical and environmental problems associated with this type of tunnel construction are usually less than for the cut-and-cover method. About 500 shield machines are manufactured every year and are used for tunnelling in Japan, which is about 95 % of the world total. Development in techniques of shield tunnelling in the last several years in Japan has resulted in drastic savings in the construction cost of tunnels as well as in assuring the quality of tunnels and avoiding damage to adjacent buildings and structures.

GENERAL ASPECTS OF SHIELD TUNNELLING

The shield is usually cylindrical and is placed horizontally at the tunnel heading in order to prevent the excavated ground from collapsing and to provide space for the excavation and the erection of the segments for the lining of the tunnel.

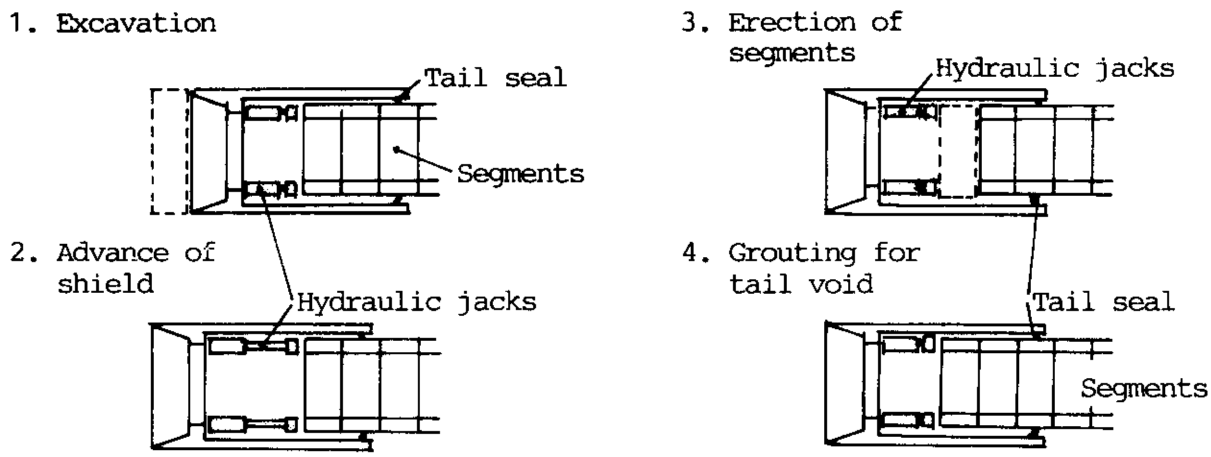


Figure 1. Construction sequence of shield tunnelling.

A typical construction sequence for shield tunnelling is illustrated in Figure 1 with simplified longitudinal sections of a conventional shield machine, and the work proceeds as follows.
1. Excavate ahead for a distance euquivalent to the length of one lining segment. Support the tunnel face if necessary with jacks and sheathing or other measure.
2. Advance the shield one ring length forward by jacks, thrusting against the lining already built.
3. After retracting the jacks, install the segments of one ring length in the shield.
4. Fill the tail void which is developed between the segments and the ground, by grouting.

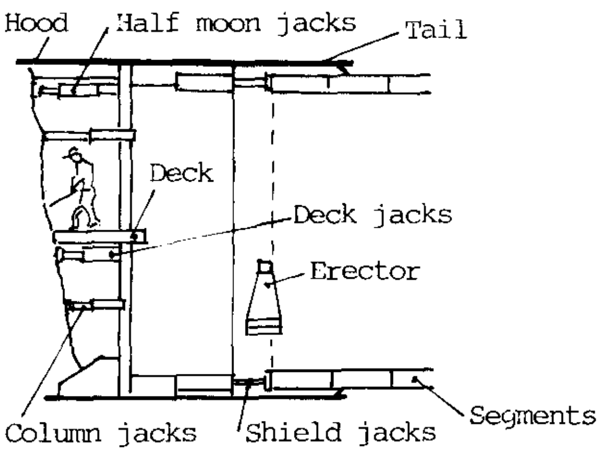
Problems or troubles may arise in every sequence of shield tunnelling. Especially at the first and the fourth phases, the ground will move in towards the tunnel and this may induce collapsing of the face and cause ground surface settlement which would damage adjacent buildings or structures.

In order to prevent or minimize these problems or troubles, advanced types of shield machines have been developed and various auxiliary or additional measures such as chemical injection, dewatering, compressed air, ground improvement, freezing etc., have been applied before and during shield tunnelling. However, auxiliary or additional measures usually induce ground settlement or movement.

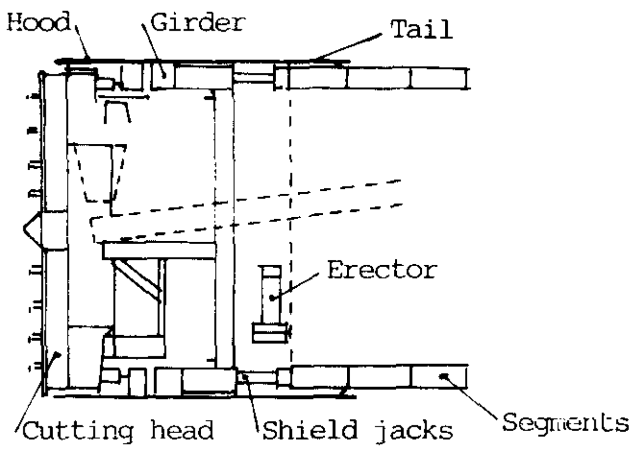
TYPES AND CLASSIFICATION OF SHIELD MACHINES

Research and development have been undertaken widely with the aim of improving the shield machine to increase the rate of advance of tunnelling, to save construction costs and to make tunnelling possible without applying expensive auxiliary measures.

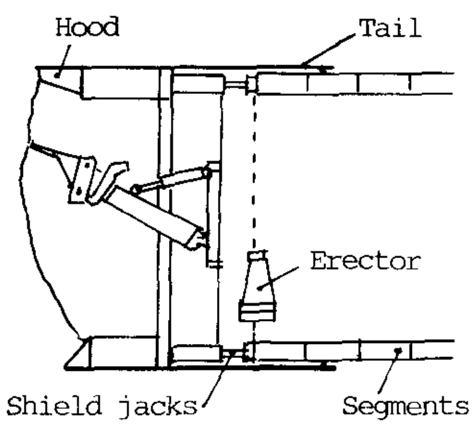
Figure 2(a) shows a typical longitudinal section of a conventional open face type shield, which requires manpower for excavation, so it is called a "hand mining" shield. This shield is applied where the ground condition is favourable. Sometimes, the face is supported by face jacks and sheathing to prevent collapse.



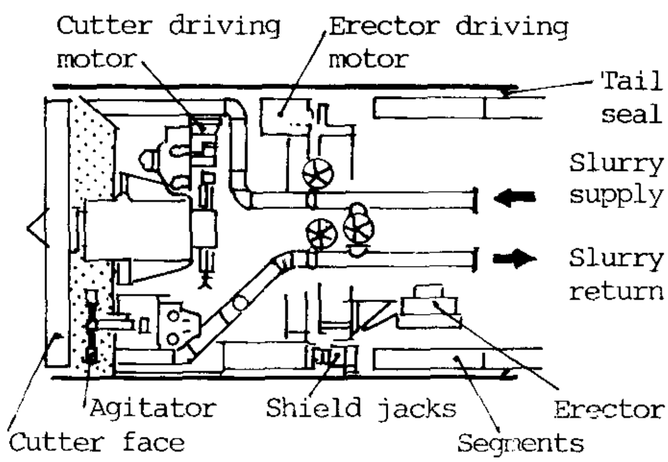
(a) Hand mining shield machine.



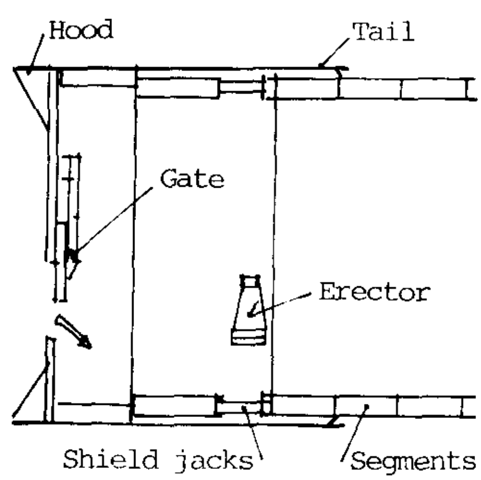
(d) Mechanical shield machine.



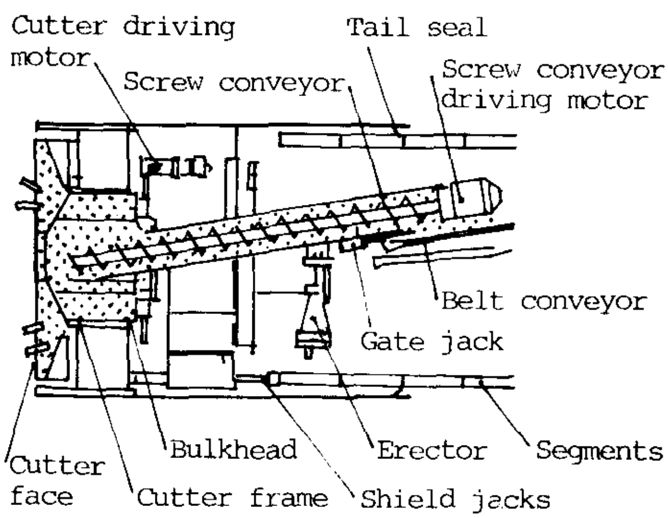
(b) Excavator shield machine.



(e) Slurry shield machine.



(c) Blind shield machine.



(f) Earth pressure balance shield machine.

Figure 2. Various types of shield machine.

Shown in Figure 2(b) is a modification of the hand mining type, replacing manpower with a backhoe excavator to increase the rate of excavation, but it requires better ground conditions. I would like to call it the "excavator" shield, while it is known as the semi-mechanical type in Japan.

The shield machine shown in Figure 2(c) is an example of one equipped with a rotating disc cutter at the front, and is known as the "mechanical" type in Japan. The soil at the face is excavated mechanically by means of bits or edges attached to the disc cutter and taken into the shield through openings or slits provided in the cutting head. The soil becomes free of pressure inside the openings of the cutting head.

The "blind" type shield machine shown in Figure 2(d) is closed at the front except for the small openings which are provided for taking soil into the shield when the shield is pushed forward, so it can be used only for a very soft clay stratum. With this machine, the amount of soil excavated is usually less than the tunnel section and that causes a larger ground movement and a higher excess pore water pressure which induces a larger ground settlement.

Figure 2(e) shows the slurry type shield machine. A chamber is provided between the cutting head and the bulkhead which is filled with the soil excavated by the cutting head and bentonite or other type of slurry. The excavated soil is mixed with slurry in order to transport it out of the tunnel by pumping through a pipe line to the separation plant. The pressure inside the chamber should be kept high enough to oppose the ground water pressure. The bentonite and other small particles in the slurry penetrate into the soil around the face, so that the collapse of the face may be prevented.

An earth pressure balance shield machine is shown in Figure 2(f). The soil is excavated by the rotation of the cutter disc or spoke and is taken into the chamber. Water, slurry, foam or other material is added and mixed to the soil in the chamber for lubrication, so that it can be easily taken out of the chamber by a screw conveyor. The screw conveyor dischanges soil equivalent to the volume of the shield advance continuously, so balancing the pressure of the soil inside the chamber with the earth pressure and the water pressure acting on the face. The pressure inside the chamber is relieved through the long passage over the screw conveyor which is free from pressure at the gate. The shield should be advanced and operated in such a way as to maintain the balance properly.

From the viewpoint of face stability, the shield machines can be classified into three types, i.e. the open face, the semi-open face and the closed face types.

SELECTION OF SHIELD MACHINE

In selecting a shield machine to be used for tunnelling, it must be a type that maintains the stability of the tunnel face and keeps the ground surface settlement or ground movement to a minimum as well as being able to achieve economical construction of the tunnel.

The cost of a shield machine is comparatively high and the machine is not usually reused. Generally, in the case of good ground conditions or when few obstacles exist in the ground, an open type shield machine, which is the cheapest, is selected. Where the ground condition is poor, especially if the ground water level is high, a closed type of shield machine, which is the most expensive, is suitable.

For designing the structure of a shield machine, the construction period, the length, depth, area of cross section, radius of curvature of the tunnel and the nature of the surrounding structures are included in the factors to be considered as well as the ground conditions such as the ground water level, soil properties, composition of strata, size and amount of gravel and boulders, existence of obstacles, explosive gas or deoxidizing materials and amount of inflow water.

Various types of auxiliary, additional or supplementary measures are applied before and during the shield tunnelling, in order to maintain the face stability, to decrease the inflow water, to improve the soil characteristics and to decrease the ground surface settlement etc.. These measures are very expensive and the need for these measures is comparative high, when the open type or semi-open type shield machine is employed in tunnelling. In order to minimize the construction cost of tunnel, these factors should be accounted for. A proposed method for selecting the type of shield machine is shown in Table 1.

Table 1. Selection of type of shield machine.

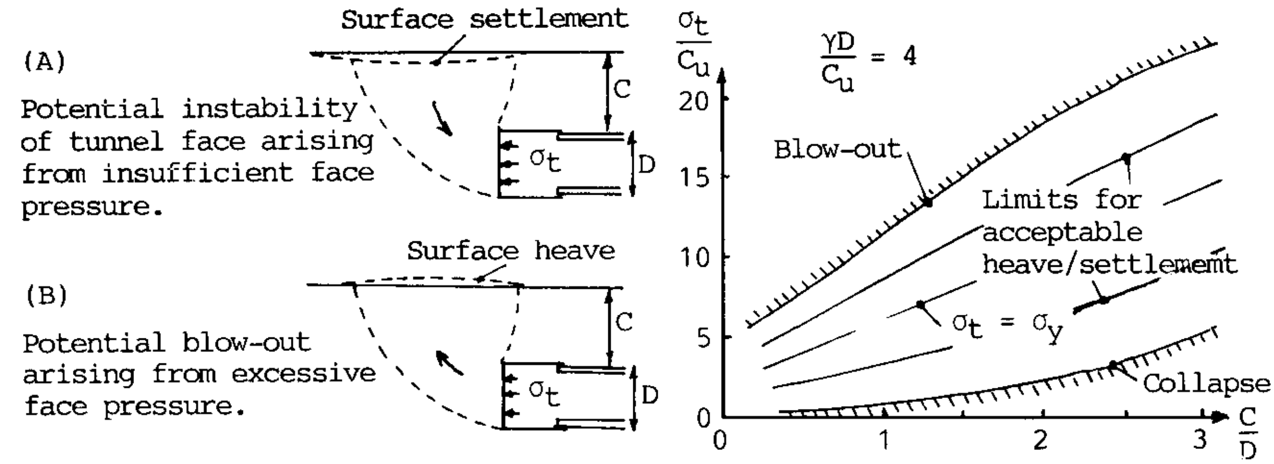
Soil Conditions	Types of shield machine					
	Hand	Exca.	Blind	Mech.	Slurry	Earth
Clay soft	Δ	x	o	x	o	o
Clay stiff	o	o	x	o	Δ	o
Sand loose	Δ	Δ	x	Δ	o	Δ
Sand dense	o	o	x	o	Δ	o
Gravel loose	Δ	Δ	x	Δ	o	Δ
Gravel dense	o	o	x	o	Δ	o
Boulders	o	o	x	Δ	Δ	x
Soft rock	o	o	x	o	Δ	x

Notes: o: Generally suitable to the conditions.
Δ: Considerable study is required prior to selection.
x: Unsuitable.

PROBLEMS ASSOCIATED WITH SHIELD TUNNELLING AND FACE STABILITY

The major geotechnical problems associated with shield tunnelling are the stability of the tunnel face, the ground movement and the ground surface settlement, which may cause damage to the adjacent buildings and structures. Regarding the stability of the face, Mair [1] proposed the idea shown in Figure 3, which was derived from the results of centrifugal model tests carried out by Kimura and Mair. The effects of tunnel face pressure on the face stability and ground movement are illustrated in Figure 3(a).

Figure 3(b) gives the extreme conditions of the tunnel face pressure which cause the collapse of the face or the blow-out of compressed air to the ground



(a) Effect of tunnel face pressure on stability and ground movements.

(b) Face pressures required for stability and for control of ground movements.

Figure 3. Tunnel face pressure and ground movements (Mair - 1987).

surface. A relatively small increase or decrease of face pressure will cause an unacceptable heave or settlement at the ground surface. If ground movements are to be minimized, the face pressure should be as close to the overburden pressure as possible.

The undrained shear strength is assumed to be equal throughout the ground in Figure 3, whereas, it usually increases with depth in practice. However, Mair's proposal should be very useful, not only for determining the air pressure to be given to the tunnel face, but also in assessing the pressure to be maintained or controlled in the chamber of a slurry shield or earth pressure balance shield, to minimize the ground movement or other problems which may occur.

A CASE OF GROUND MOVEMENTS CAUSED BY SHIELD TUNNELLING

Figure 4 shows a cross-section of shield driven parallel tunnels for underground transportation in Osaka and the vertical settlements of the ground caused by the tunnelling. Two tunnels each having an outside diameter of 6.93 m, 15 m apart on centers, and 15 m in depth at the center of the tunnel were constructed by employing earth pressure balance shield machines and were completed in 1982 [2].

The ground consisted of alluvial clay and sand strata and diluvial strata lay 20 m below the ground surface where the tunnels were to be driven. A sand layer was found in about the lower quarter of the tunnel and the water table was about 1 m below the ground surface. The maximum settlement caused by the shield tunnelling was observed to be about 27 mm, and occurred 2 months after the first tunnel and 1 month after the second tunnel were driven.

Shown in Figure 5 is a longitudinal section of the same tunnel and the ground movements before and after the passing of the shield machine. The ground heaving started before the arrival of the shield, the maximum heaving at the elevation of the tunnel crown was recorded as 40 mm, while it was about 3 mm at the ground surface.

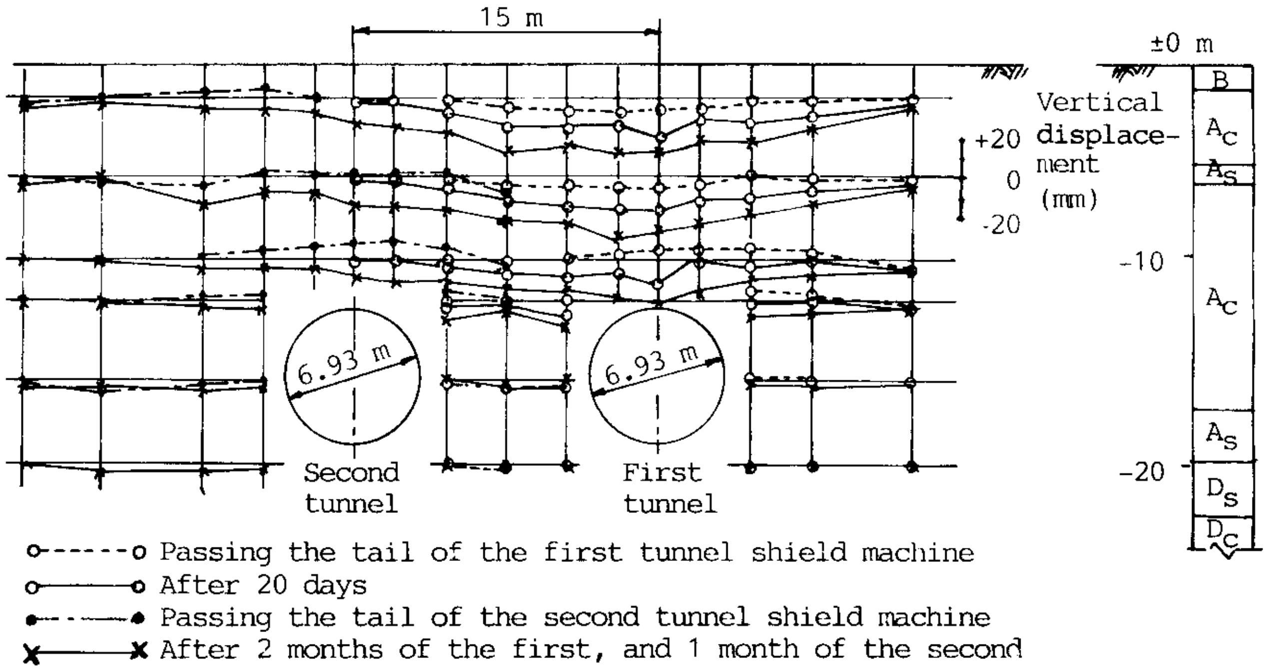


Figure 4. Example of ground settlements caused by shield tunnelling (Hirata et al. - 1983).

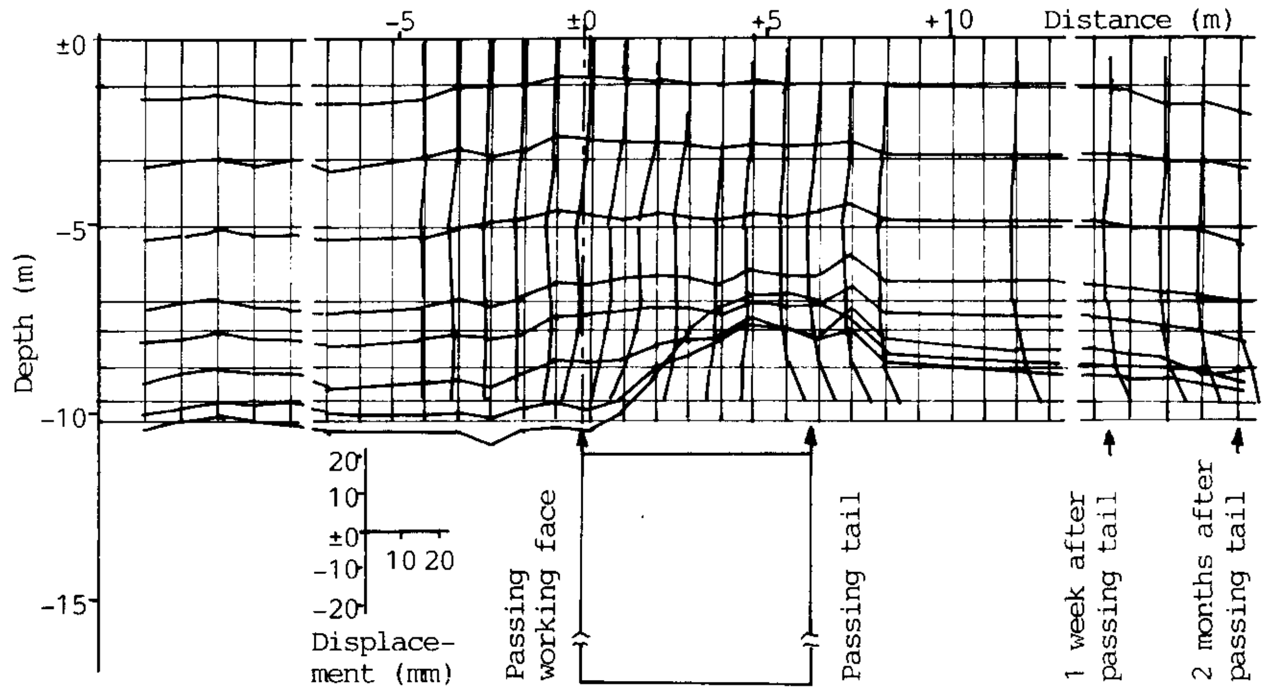


Figure 5. Ground movements before and after passing of a shield machine (Hirata et al. - 1983).

SETTLEMENT OF GROUND SURFACE

The ground surface settlement caused by shield tunnelling is generally about 30 mm to 300 mm along the center line of tunnel. Prediction of the magnitude and the extent of the ground surface settlement are necessary when planning auxiliary measures or underpinning to be provided for the adjacent buildings, structures and public utilities before the construction of the tunnel. So, various methods for the prediction of the ground surface settlement based on theoretical procedures have been proposed. They were generally proved to correspond well with the observed settlements of some case studies. However, the magnitude of the settlement no only depends upon the subsurface conditions but also on the type of shield machine, the workmanship and the performance of the tunnelling operation, so that one method is not applicable to all cases.

The ground surface settlement is caused by over excavation, the tail void, instability of the tunnel face and consolidation of surrounding ground. The tail void is produced between the lining segments and the outside of the shield at the time of advancing the shield machine, and is about several centimetres thick. The tail void should be filled completely with cement grouting before the surrounding ground collapses. However, the operation of grouting is apt to be delayed because the working space inside the shield machine is limited. When a higher pressure is required for grouting because the surrounding ground has collapsed, it will induce further problems such as instability of the tunnel face, consolidation settlement of ground, etc..

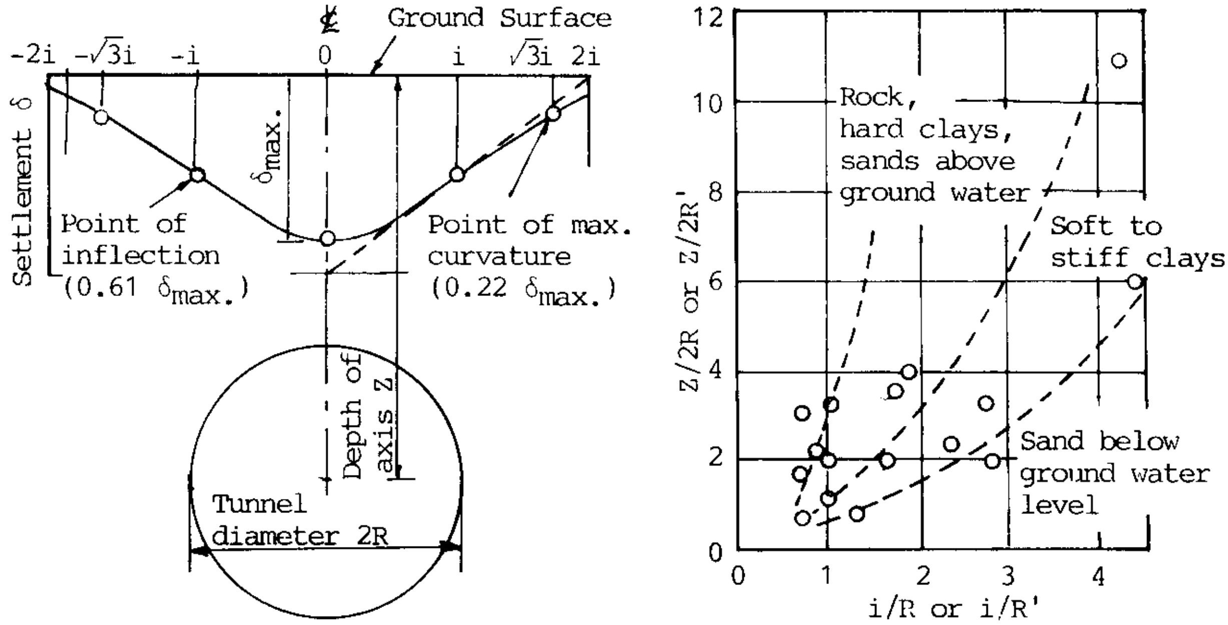
When the tunnelling is carried out in cohesive soil ground and the ground water level is lowered, a consolidation settlement will occured around the tunnel. The advancement of the shield, especially if not in a straight line, induces excess pore water pressure due to the ground movements and this also causes consolidation settlement. The magnitude of the consolidation settlement is estimated or observed to be more than 50 percent of the total ground surface settlement. In the case of employing compressed air for maintaining the face stability and minimizing the inflow of water, a consolidation settlement occurs rapidly at the time of the decompression.

The cross section of the ground surface settlement has the form of a trough so that it is called the settlement trough. Peck [3] contributed a concept in which the cross section of the settlement trough over a single tunnel caused by conventional mining and shield tunnelling can be represented approximately by the error function or normal probability curve as shown in Figure 6(a). Figure 6(b) was also prepared by Peck, by assembling the available reliable settlement data. It shows that it is possible to separate the results according to three types of ground condition.

Fujita [4] prepared Figure 7, using observed data available from 43 cases reported in Japan, and the results were generally similar to Peck's plot shown in Figure 6(b). However, the data from the tunnels driven by the slurry or the earth pressure balance shield machine, which were developed after Peck's study, are plotted in the zones with better ground conditions. A small number of them were operated unskillfully at that time.

Recent advances in shield tunnelling techniques, especially the use of slurry or earth pressure balance shield machines, together with a combination of immediate grouting and simultaneous grouting as well as the use of computer aided operational control systems developed in Japan, have resulted in decreasing the surface settlement to a minimum, i.e. about 3 mm. Consequently this has no longer been a problem in shield tunnelling since 1985 [5].

However, in cases of shield tunnelling which employ conventional shield machines, it is necessary to estimate the ground surface settlement by a simple method for construction planning purposes.



Ratio i/R is a function of Z/2R and soil conditions.
Volume of trough = $2.5\, i\, \delta_{max}$.

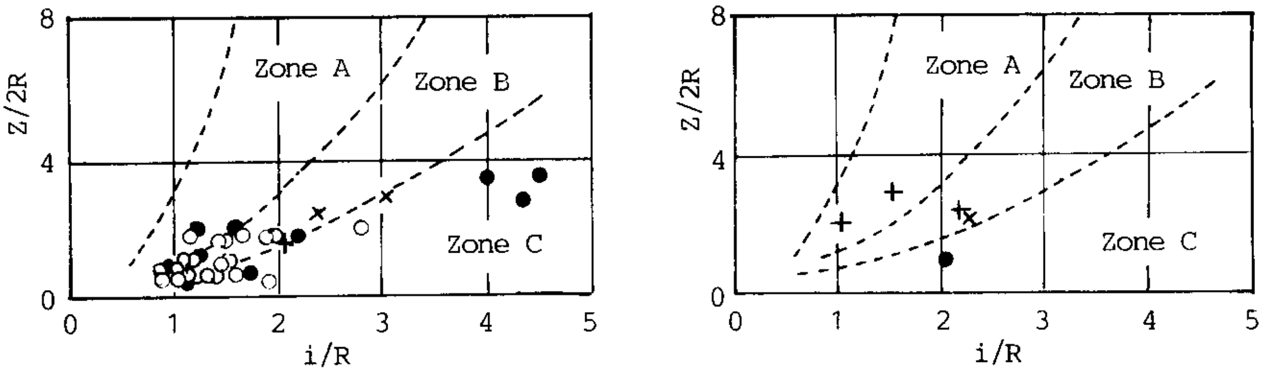
(a) Settlement trough above tunnel.

(b) Relation between width of settlement trough and depth of tunnel for various tunnels in different materials.

Figure 6. Shape of settlement trough and relation between width of settlement trough and depth of tunnel (Peck - 1969).

Zones proposed by Peck
Zone A: Rock, hard clays, sands above groundwater level
Zone B: Soft to stiff clays
Zone C: Sands below groundwater level

Types of shiels machine
○ :Hand mining type
● :Blind type
× :Slurry type
+ :Earth pressure balance type



Z: Depth of tunnel axis, 2R: Diameter of tunnel
i: Point of inflection of settlement

(a) Clays

(b) Sands below groundwater level

Figure 7. Width of settlement trough vs. depth of tunnel axis relationship for driven tunnels by applying various types of shield machine (Fujita - 1981)

ESTIMATION OF GROUND SURFACE SETTLEMENT

Hanya proposed Table 2 for the maximum ground surface settlements to be expected under different ground conditions, based on many data observed during shield tunnelling for metro lines in Japan.

Fujita prepared Figure 8, summarizing the maximum ground settlement of 94 cases from reports published in Japan. Figure 8 shows that the magnitude of the settlement depends upon the type of shield machine. The settlements caused by slurry and earth pressure balance shield tunnelling are scattered and

Table 2. Relationship between soil condition and settlement (Hanya - 1977)

Soil layer above tunnel	Soil at tunnel face	Settlement (mm)
Alluvial.	Alluvial, Soft cohesive	30 - 100
Diluvial, thinner than tunnel dia.	Diluvial, Cohesionless	50 - 80
Diluvial, thicker than tunnel dia.	Diluvial, Cohesionless	10 - 30
Diluvial / alluvial	Diluvial, Cohesive	- 30

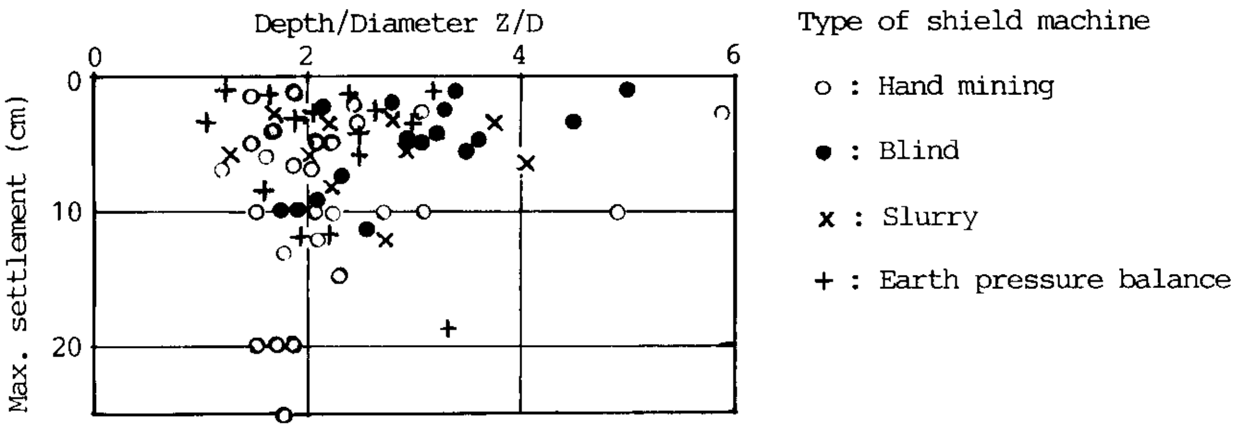


Figure 8. Maximum settlements caused by various types of shield tunnelling methods (Fujita - 1981).

Table 3. Predicted settlement and max. errors. (Fujita - 1982)

Auxiliary measures	Type of soils	Predicted settlements and maximum errors (cm)			
		Hand	Blind	Slurry	Earth
No	Clay*	10 ± 3	4 ± 2	4 ± 1	6 ± 2.5
	Clay**	20 ±	10 ± 2.5	-	15 ± 3.5
	Clay/Sand	10 ± 3	-	9 ± 3	2 ± 1
	Sand	-	-	4 ± 2.5	2 ± 1
Yes	Clay	-	3 ± 2	-	-
	Sand*	4 ± 3	-	-	-
	Sand**	20 ± 5	-	-	-

Note: * For a group with smaller settlements
** For a group with larger settlements

some of them are comparatively large, because there was little experience in operating these shield machines at that time.

Table 3 was prepared by Fujita [6] for the prediction of the maximum ground surface settlement caused by shield tunnelling taking into consideration the types of shield machine and soils as well as the application or not of auxiliary measures.

WIDTH OF THE SETTLEMENT TROUGH

To determine the width or the shape of the settlement trough for the purpose of planning the auxiliary measures especially underpinning of the adjacent buildings and structures, it is useful to estimate the point of inflection i defined in Figure 6(a). There are various methods for the estimation of i.

The relation for estimating the volume of the settlement trough, given by Peck, can be transformed as follows:

$$i = V_s/2.5\delta_{max}$$

where V_s is the volume of the settlement trough and δ_{max} is the maximum settlement. It is necessary to assume values for V_s and δ_{max}. Peck also gave another relationship,

$$i = 0.2(2R+Z)$$

where R is the excavated radius of tunnel and Z is the depth from the ground surface to the tunnel axis. Attewell proposed the following relation,

$$i = K(Z/2R)^n \cdot R$$

where K and n are parameters for the calculation of the settlement. O'Reilly and New gave the following relationship,

$$i = 0.13Z + 1.1 \quad \text{for cohesive soils}$$
$$i = 0.28Z - 0.1 \quad \text{for granular soils}$$

AUXILIARY MEASURES

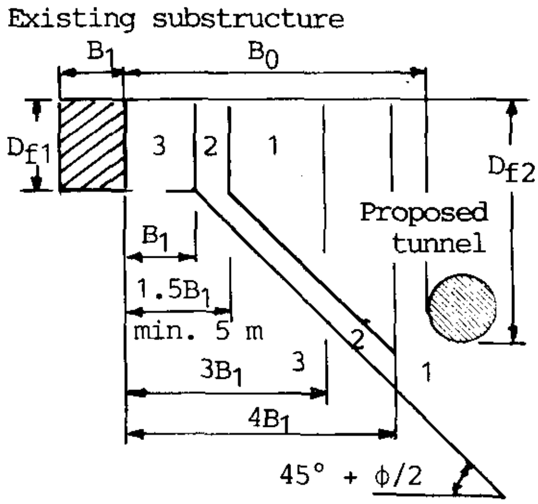
The tunnel is often excavated adjacent to or under existing buildings or other structures and they are deformed or sometimes damaged, if no proper foundations or counter measures are provided. The deformation of the buildings or structures decreases their strength so that they might be damaged or destroyed when they are subjected to external forces such as earthquake, wind, vibration, etc..

Various auxiliary measures have been applied before and during construction of tunnels, in order to minimize the problems associated with shield tunnelling such as collapse of the tunnel face and ground surface settlement. The auxiliary measures often employed are underpinning, intercepting walls, chemical injection, jet grouting, soil stabilization, dewatering, freezing and compressed air.

These auxiliary measures often cause secondary problems, are expensive and are of a temporary nature, so that it is advisable to study the possibility of employing a high grade shield machine which does not require the application of auxiliary measures.

In cases where existing structures may settle or be displaced due to the ground movements associated with shield tunnelling, which may exceed the acceptable range, ground treatments, construction of intercepting walls and/or underpinning should be taken prior to tunnel excavation in order to reduce the amount of ground movement and settlement and/or to support the existing structures.

For planning the auxiliary measures, detailed investigations must be carried out to examine the strength and acceptable deformations and/or displacements of the existing buildings or structures and to estimate the extent and



Zone 1 : No restriction.
Zone 2 :
As a minimum, tunnelling shall proceed by applying prudently selected method and techniques.
Zone 3 :
Auxiliary measures shall be employed.
Displacements of existing structures shall be predicted and checked for safety.
Observation of displacements to existing structures; Zone 1 : If necessary.
Zone 2 : To be conducted.
Zone 3 : Shall be conducted.
D_{f1}: 3/4 of length of penetration for bearing piles and caissons. No penetration considered for friction piles.

Figure 9. Extent of protection for adjacent substructure of expressway during shield tunnelling (Otogawa - 1983).

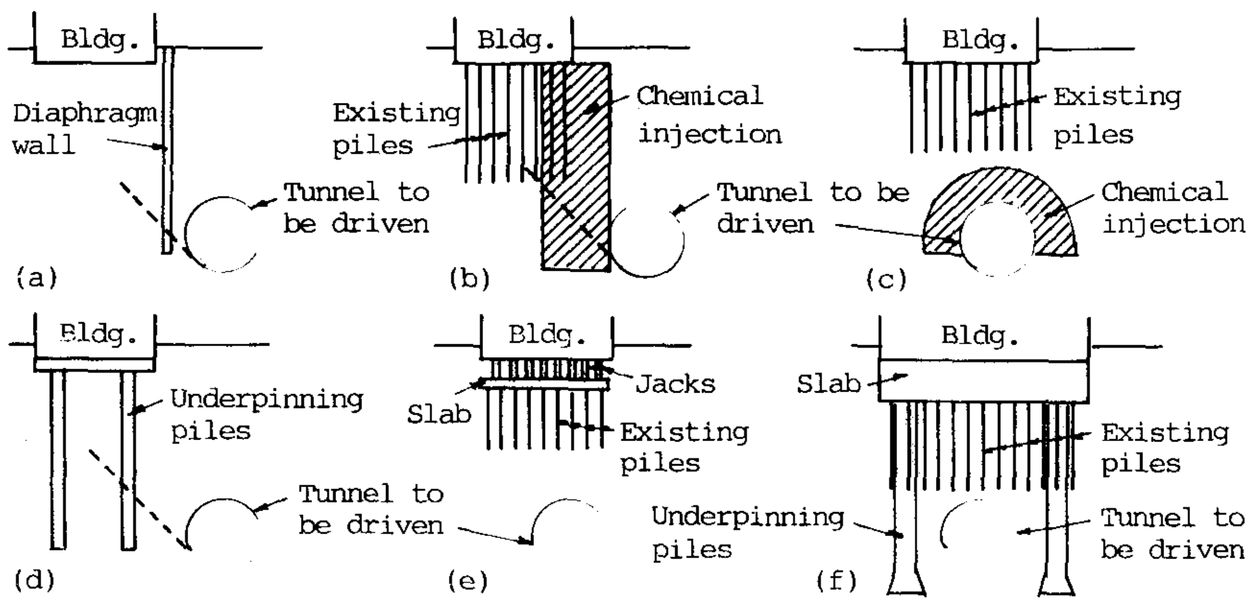


Figure 10. Examples of protective measures for existing buildings.

the magnitude of the ground movements or settlement by analysis or experience.

Some public organizations have established their own regulation or guidelines in order to prevent their structures from damages caused by adjacent construction. The auxiliary measures should conform with their provisions. Shown in Figure 9 is the provisions that should be applied if shield tunnelling is carried out adjacent to the foundations of an expressway in Metropolitan Tokyo.

Figure 10 demonstrates examples of the auxiliary or protective measures for existing buildings. Providing a series of jacks between building and existing foundation or underpinning as shown in Figure 10(e) is very advantageous for adjusting the settlement properly.

LATEST METHOD OF BACK-FILL GROUTING

New techniques of back-fill grouting for the tail void, including simultaneous and immediate groutings and a new type of grout, i.e. non-dehydrating grout were developed around 1985 in Japan, for minimizing the ground surface settlement caused by shield tunnelling.

Use of the slurry or the earth pressure balance shield machine and a combination of simultaneous grouting and immediate grouting together with the non-dehydrating grout and a computer aided control system have reduced the ground surface settlement to a minimum. As a result, the maximum ground surface settlement will be no longer than 3 to 5 mm under normal conditions, which is less than 1/10th of the average settlement caused by conventional shield tunnelling methods.

Remarkable success has been achieved with these techniques, and no problems related to ground movement issues are caused by the shield tunnelling methods introduced here.

For simultaneous grouting, a set of pipes parallel to the tunnel direction is installed in the encasement provided outside the skin plate (see Figure 11) or inside the skin plate around the tail of the shield. Immediate grouting is conducted radially through the holes provided in the segments (see Figure 11) as close as possible to the tail of the shield. Both simultaneous grouting and immediate grouting must be applied during the advance of shield machine.

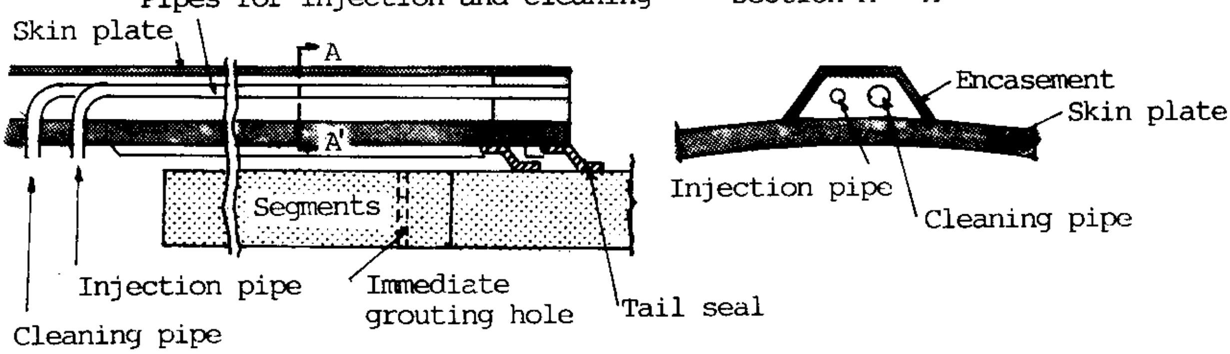


Figure 11. Simultaneous grouting pipe set-up of encased type.

TYPE OF SHIELD MACHINE AND CONSTRUCTION COST

The shield machine is usually not reused, and its cost is a comparatively high percentage of the total tunnelling cost. In the case of good ground conditions, the open type shield machine is generally selected, because it is simple and the cheapest. However, it is necessary to apply auxiliary measures to minimize the problems induced by the ground surface settlement. Where the ground condition is poor, the closed type of shield machine, i.e. the slurry or the earth pressure balance shield machine is suitable but also the most expensive. However, tunnelling can be carried out without applying any auxiliary measures.

The International Tunnelling Association (ITA) / the Japanese Tunnelling Association (JTA) published a report on "Applicability of the shield method to urban tunnelling" in 1989 [7]. Comparison of the construction cost of tunnels

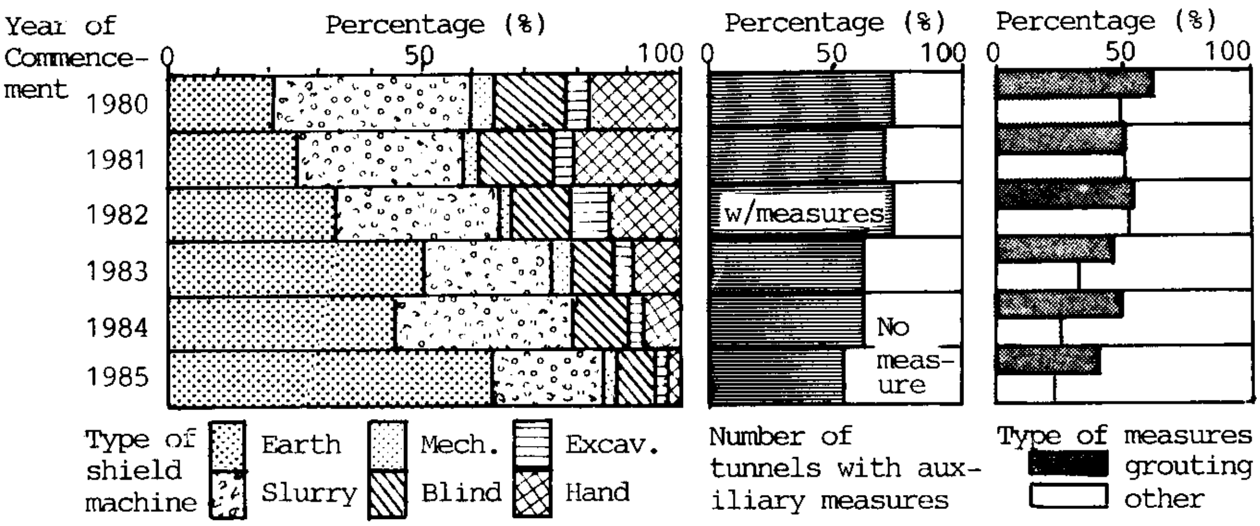


Figure 12. Ratio of types of shield machine and auxiliary measures employed in Japan by year of commencement 1980 to 1985 (ITA/JTA - 1989).

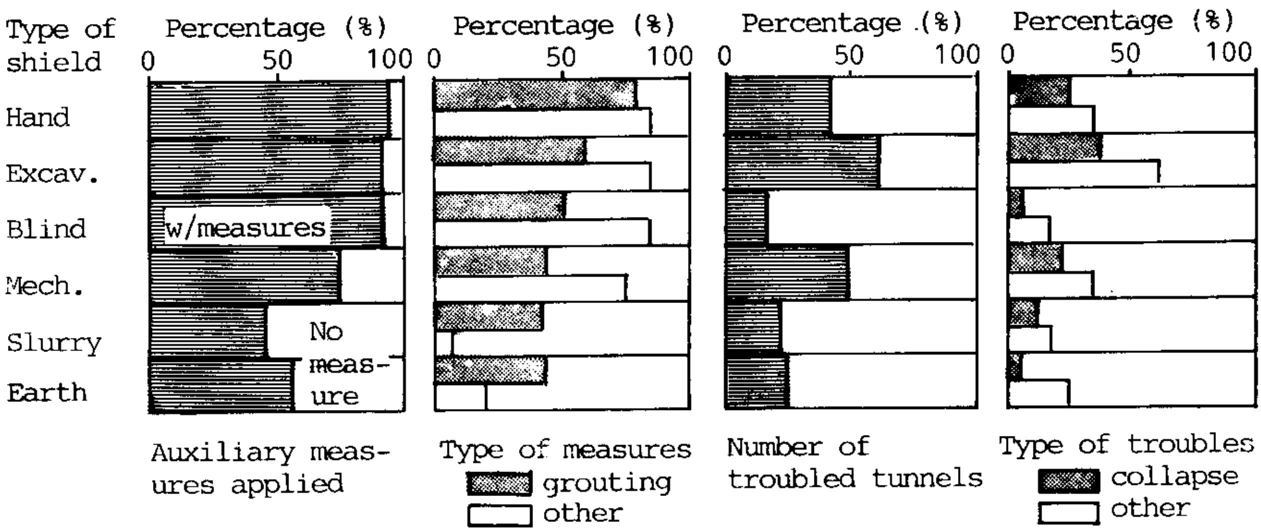


Figure 13. Ratio of auxiliary measures applied and troubles during tunnelling by different types of shield machine employed (ITA/JTA - 1989).

by means of different types of shield machine is an interesting issue, but is very difficult to examine, because the ground conditions, and environmental and various other factors affect the cost. According to the ITA/JTA survey, there were more than 1000 cases in which the construction cost of tunnels could be examined statistically. It was found that the unit cost per cubic meter of excavation was almost identical whichever method was used.

Figure 12 shows the types of shield machine used and ratio of shield tunnelling in which auxiliary measures were applied in Japanese tunnelling projects plotted for the year in which construction started during the period 1980 to 1985. It was found that the use of the earth pressure balance shield machine increased remarkably, and the use of auxiliary measures decreased gradually.

Figure 13 indicates that in the case of employing the slurry or the earth pressure balance shield machine, the proportion of projects applying auxiliary measures and the proportion experiencing troubles were smaller than for other types of shield machine.

CONCLUSION

In conclusion, the recent development of the slurry and the earth pressure shield machines as well as related techniques has been successful in decreasing the need to apply auxiliary measures and in preventing troubles during shield tunnelling. As a result, the unit cost of a tunnel is almost identical with that of conventional simple shield tunnelling. The quality of tunnel construction is also improved and environmental and geotechnical problems are minimized.

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