1. INTRODUCTION

The multi-circular face shield tunnelling (MFS) is a tunnel-cutting method utilizing plural circular faces partially overlapped at the each side. Fig. 1 shows comparison in some features of MFS (horizontal type) for double track railway to a traditional circular face shield (hereafter called CFS).

As shown in Fig. 1, MFS has smaller cutting area, and therefore is economical (cf. Table 1). MFS was applied to Kyobashi shield tunnel of Keiyo Metropolitan Line owned by East Japan Railway Co., Ltd.

The vertical MFS would be extensively applied in the future in the region of strictly limited land use because of its merit of less land area requirement. On the other hand, as the cross sections of these MFS methods are quite different from that of the CFS, many technical problems are caused, and shield design and maneuverability for example, are not established yet.

This study analyzes tunnelling characteristics of the horizontal and vertical MFS along with the traditional CFS based on our model test and especialy gives consideration to MFS.

2. OUTLINE OF THE EXPERIMENT

(1) Purpose of The Experiment

In addition the shape of MFS which rotates plural cutters is more complicated than that of CFS, mutual inter-ference of cutters may be caused. Furthermore, the increase of loosening pressure, cutter torque, thrust force, and unbalance may occur. Table 2 indicates problems to be solved about multi-circular face shield, which our experiment was aiming at. Thus model test was conducted to find out the differences of problems between MFS and CFS when applied to the double track railway tunnelling under various conditions of operation and ground, and eventually to realize practical use of MFS. The model test covered the single circular shield and multi-circular face shield of both horizontal and vertical types.

(2) The Model Test Equipment **(cf. Fig. 2)**

The shields, supported on the mobile supports driven by the hydraulic cylinder, proceed straight ahead. The sheet plate type cutters were adopted considering slurry shield, but a screw-conveyer was used to discharge soil because of difficulty of construction of slurry discharge system. Being driven by each hydraulic motor, two cutters on the MFS can rotate independently to either direction and at any speed.

The dimension of the model followed exactly the same reduced scale of the actual shield for the double track railway. But, the height of the cutter bit, opening ratio of the sheet plate, bit arrangement and the chamber shape were decided assuming that the model was a small shield. Concerning the question which cutter of the vertical MFS should go ahead of the other, the numerical analysis on the cutting face stability did not indicate much difference

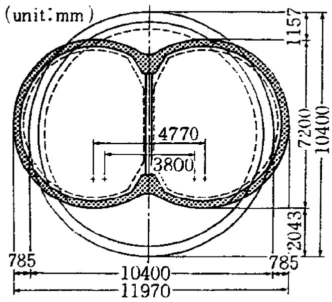


Fig 1 Comparison of Cross Section

Table 1 Comparison of Construction Quantities

Item	unit	CFS (A)	MFS (B)	Ratio (B/A)
Outside diameter of cross section (vertical)	m	10.40	7.20	0.69
Oustide diameter of cross section (horizontal)	m	10.40	11.97	1.15
Excavated cross section	m²	87.9	76.1	0.87
Primary lining	m³	12.6	10.3	0.82
Secondary lining	m³	6.3	5.6	0.89
Backfiling work	m³	4.4	5.5	1.25
Invert concrete	m³	9.7	1.8	0.19

Table 2 Problems to be solved about MFS

Difference from CFS	Problems at Practical Work
Horizontal MFS Reduction of ground arch action Concentration of pressure	Stearing control; Act of unsymmetrical pressure Snake action caused by unbalanced acting force
Rear Cutter / Leading Cutter Excavates loosened ground Leading excavation loosens ground	Stability of cutting face; Intaking excess soil caused by collapse of part Spread of loosened zone
Upper Cutter Leading Vertical MFS Reduction of ground arch action Concentreion of pressure	Stearing Control; Enlargement of pitching Falling sideward
Center of garvity is high Leading Upper Cutter / Rear Lower Cutter Leading excavation loosens ground Excavates loosened ground Width is smaller than height	Stability of cutting face; Intaking excess soil caused by collapse of part
Lower Cutter Leading Vertical MFS Excavates loosened ground	Stearing Control; Enlargement of pitching Falling sideward
Rear Upper Cutter / Leading Lower Cutter Leading excavation loosens ground Width is smaller than height	Stability of cutting face; Spread of loosened zone

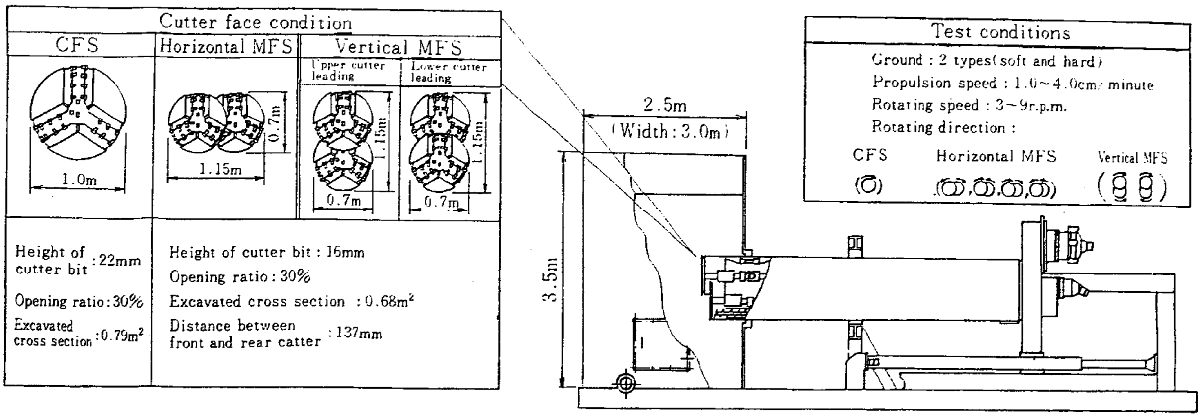


Fig 2 Model Test Equipment

Table 3 Ground Condition

Item \ Type		Soft	Hard
Wet Density	γt (gf/cm³)	1.56~1.61	1.68~1.77
Dry Density	γd (gf/cm³)	1.42~1.46	1.56~1.60
Water Content	w (%)	10.0~11.2	7.7~10.9
Void Ratio	e	0.80~0.86	0.65~0.71
Degree of Saturation	Sr (%)	31.1~35.9	29.2~44.0
Cone Index at the center of the soile tank	qc (kgf/cm³)	10~30	100~130

(These data were measured at the top of the shield)

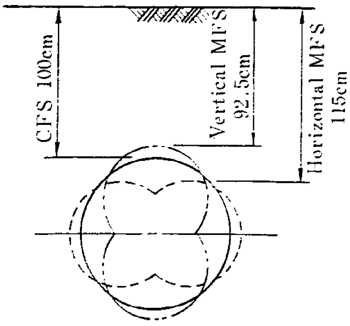


Fig 3 Depth of Overburden

and definite evaluation was impossible, so the test was conducted on both cases of an upper cutter leading type and a lower cutter leading type.

(3) Test Conditions

Two ground conditions indicated in Table 3 were adopted to study the effect of the ground strength on the test results. Concerning the depth of overburden for each cases, as shown in Fig. 3, it was 100cm (= 1D: D is the shield diameter) for CFS, and the center depth of MFS was same with that of CFS.

Rotating speed of cutters and propulsion speed were taken up as the important items of the test, and the range of their test values was decided referring to the average peripheral cutter speed and propulsion speed of actual shield. Rotating directions were also considered important and combinations shown in Fig.-2 were adopted.

(4) Evaluation Method of The Test Results

It is very difficult to observe the strict similarity rules in a model test of a ground-mechanical relation system. The test results were then evaluated as shown in Fig. 4; first, the test was justified by comparison of cutter torque values from the model test to those obtained from actual construction, and next, the characteristics of the MFS were evaluated by calculating ratios of cutter torque, thrust force and etc. of MFS to those of CFS(MF index) based on the test results.

3. TEST RESULTS

(1) Acting Force Characteristics

a) Cutter torque

Cutter torque was measured by reading oil pressure of the cutter driving motors. Fig. 5 and 6 show torque values for each shield in soft and hard ground. The torque T in the Figures is sum of each torque (total cutter troque) of the front and rear cutter.

Cutter torque was affected by operative conditions,i.e. propulsion speed V and number of cutter rotations f and linear corelation between T and V/f was observed which was remarkable in the hard ground. The torque values in soft and hard ground did not indicate much difference. Total cutter torque of MFS was less than 50% of CFS torque, and that of vertical MFS was 40-60% of the corresponding value of the horizontal MFS. This small tor-

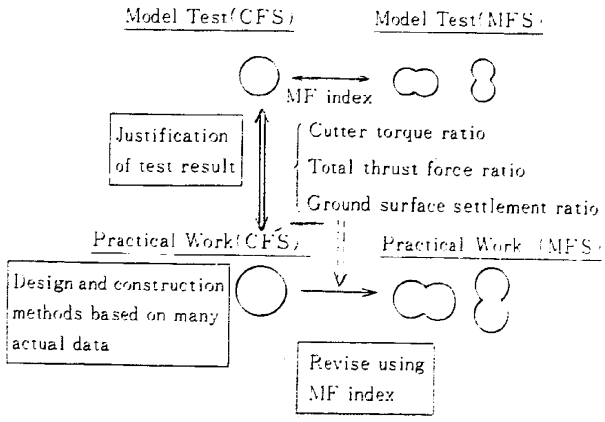


Fig 4 Evaluation Method of Test Result

que value of vertical MFS might be attributed to easy intake low density soil in the upper chamber, perhaps caused by lack of partition between upper and lower chamber. To estimate the cutter torque of the vertical MFS with a partition between two chambers, the torque of the lower cutter, which had the same cutting area as the upper cutter, was taken as that of the upper cutter. As the result of calculation, the total torque of the vertical MFS proved to be 80-90% of that of the horizontal MFS.

Fig. 7 and 8 indicate front (leading) cutter torque T_F and rear cutter torque T_R.

In these Figures, the test results for various rotating directions of the cutters were plotted using the same mark, but the plotted points were not scattered irregularly; linear correlation was observed between T_F, T_R and V/f. Even if the rotation number of the front and rear cutter, f_F and f_R are not the same ($f_F/f_R = 0.33 - 3.0$), this correlation was maintained. Thus it was proved that both cutters of the MFS have their own characteristics, regardless of the rotation number and rotating directions of the other cutter.

b) Thrust Force of the Equipment

The main resistant forces against the shield propulsion are the resistant force F_t at the cutting face and that of friction F_f at the cylindrical face.

F_t was measured as the cutter axial force by strain gauges. In Fig. 9, relation between F_t and V/f is indicated. F_t of both horizontal and vertical MFS is 50-60% of that of CFS. All the data of MFS were used to indicate linear regression equation as shown in Fig. 9, because meaningful difference among MFS types was not observed.

Friction force F_f was calculated as indicated in the Table 4; at first, increasing rate of the thrust force F (measured by the oil pressure of the thrust jack) per propulsion distance L was calculated, $\Delta F/\Delta L$ thus obtained is the friction force on the cylindrical face of unit length of the test equipment. Next, cylindrical friction force per unit area of the skin plate F_f/A was calculated from $\Delta F/\Delta L$ devided by circumferential length of the skin plate, finally, F_f was obtained from F_f/A multiplied by skin plate area, where the length of the shield body was assumed to be 85cm.

Each F_f value for various types of the shield are arranged as follows—circular shield > horizontal MFS > veretical MFS, and so for the vertical MFS, F_f of the lower cutter leading type was larger than that of the other.

(2) Stability of Cutting Face

a) Ground Surface Settlement

Fig. 10 shows typical value of lateral directional ground surface settlement distribution on a soft ground caused by each type of shield. Absolute settlement values and range of influence in lateral direction for each cases are as follows;

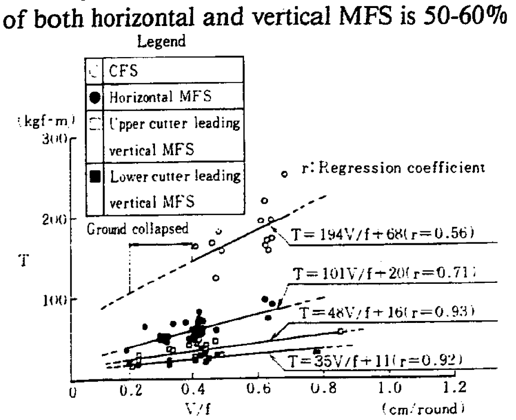


Fig 5 Total Cutter Torque in Soft Ground

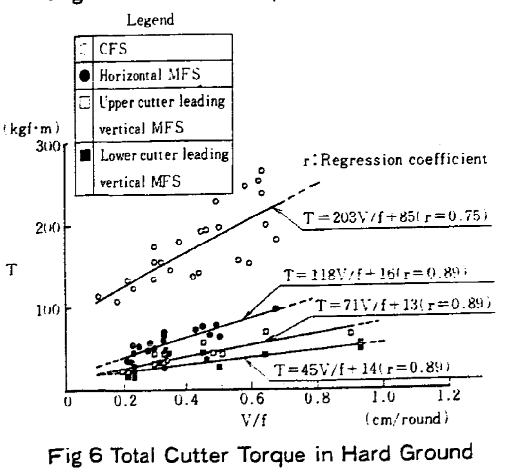


Fig 6 Total Cutter Torque in Hard Ground

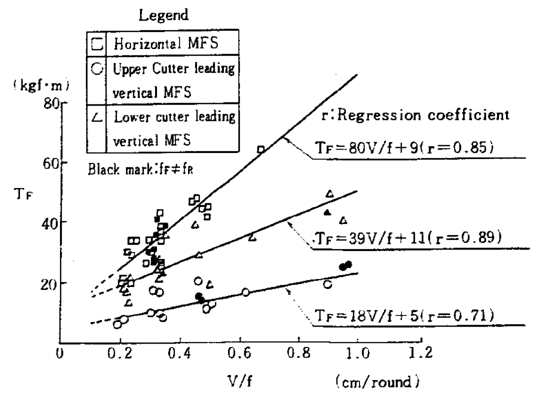


Fig 7 Front Cutter Torque of MFS

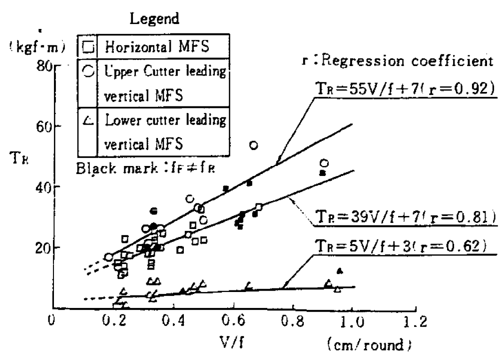


Fig 8 Rear Cutter Torque of MFS

CFS > horizontal MFS > vertical MFS, and as for two types of the vertical MFS, almost any difference was not observed. On the other hand, almost any ground surface settlement did not occurred on a hard ground.

b) Ground Slack

Fig. 11 shows study results of decreasing situation of ground cone index before and after tunnelling. For any shield type, the height of decreased cone index is 50-60cm, and decreasing degree of MFS is smaller than that of CFS.

Fig. 12 shows a range of decreasing cone index of nearby ground for two types of vertical MFS, which does not indicate much difference.

To examine any ground collapse around constructed part of MFS, tracers (pieces of 1cm long rubber tubes) were set at 10cm intervals. Test results proved that there was no ground collapse around that area, as no tracer was discharged regardless of ground conditions, any shield types or rotating direction. It was proved as well that the amount of discharged soil was equal to the amount derived from cutting area.

Based on these test results, we can say that influence of MFS to nearby ground is the same or less than that of the circular shield.

4. STUDY

After calculation of the MF index based on the test results, characteristics of MFS were studied by comparison with CFS concerning acting force characteristics and cutting face stability.

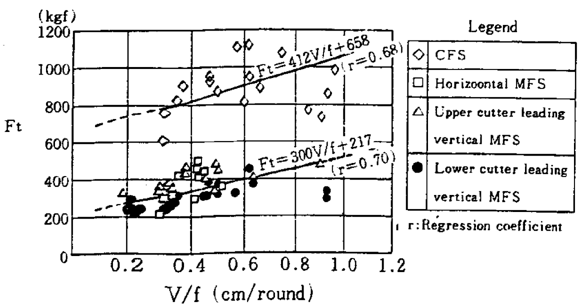


Fig 9 Resistant Force of Cutting Face

Table 4 Calculation of Friction Force of Cylindrical Face

Item \ Type	CFS	Horizontal MFS	Vertical MFS: Upper cutter leading	Vertical MFS: Lower cutter leading	Notice
Thrust force per unit distance ΔF/ΔL(kgf/cm)	24.9	23.3	17.6	19.3	
Circumferential length of skin plate (cm)	314	318	318	318	
Friction force per unit area Ft/A (kgf/cm²)	0.079	0.073	0.055	0.061	L: Shield body lenght of MFS
Friction force Ft (kgf)	2120	1880	1420	1560	

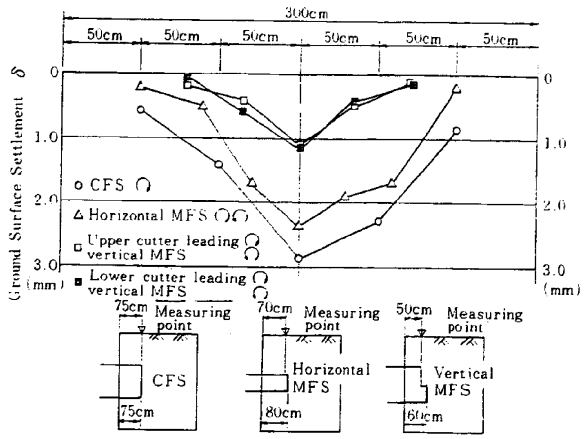
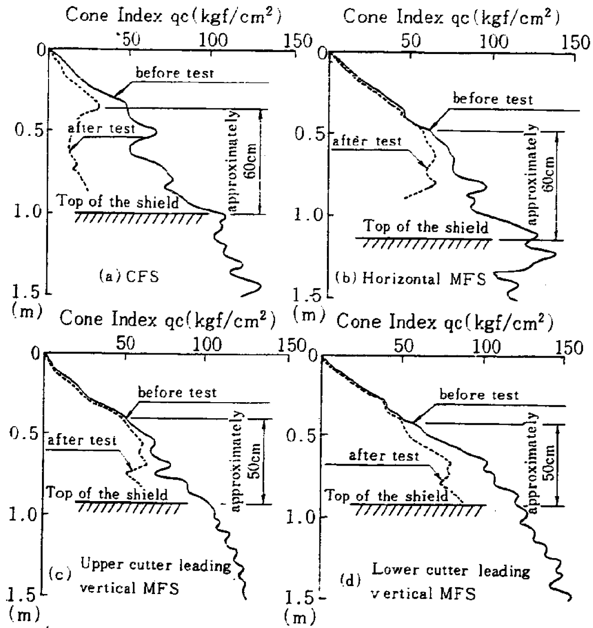


Fig 10 Lateral Direction Ground Surface Settlement (Soft Ground)



(point of cone penetration test : Center of soil tank)

Fig 11 Decreasing Situation of Ground Cone Index

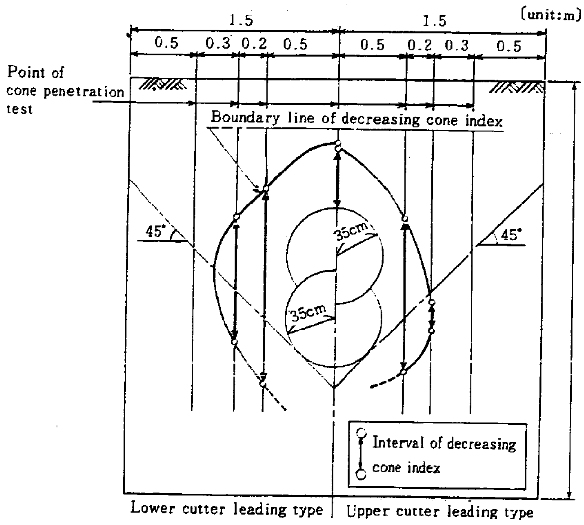


Fig 12 Comparison of Decreasing Cone Index between Two Types of Vertical MFS

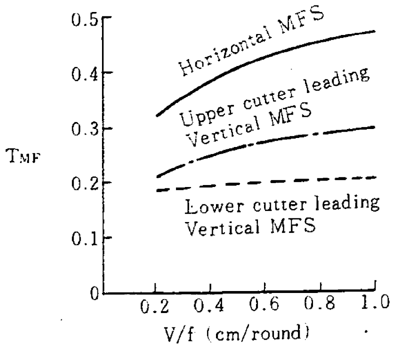


Fig 13 MF Index of Cutter Torque

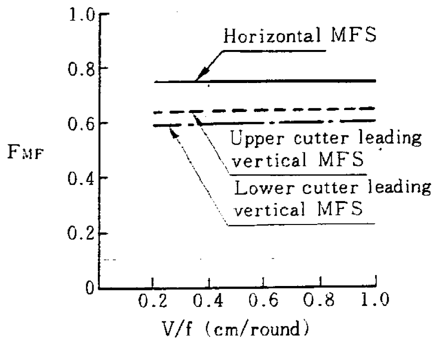


Fig 14 MF Index of Total Thrust Force

(1) Acting Force Characteristics

Fig. 13 shows MF index of cutter torque which was calculated from the linear regression equation about cutter torque and V/f indicated in Fig. 6.

T_{MF} value was 0.31 – 0.46 for horizontal MFS, and 0.18 – 0.29 for vertical MFS. Although this value increases as V/f does, it is almost convergent in the range of the test. These values are evidently smaller than those calculated by the following equiation for T^*_{MF} using torque calculation formula $T = \alpha D^3$ (where α; torque coefficient, D; shield diameter) which is very often used for shield design in Japan.

$$T^*_{MF} = \text{(front cutter torque of MFS+ rear cutter torque of MFS) / cutter torque of CFS}$$
$$= (\alpha \times 0.7^3 + \alpha \times 0.7^3 \times 0.73) / (\alpha \times 1.0)$$
$$= 0.59$$

(0.73 is a ratio of rear and front cutter, concerning section linear moment around the cutter axis)

MF index of total thrust force F, F_{MF} was calculated from linear regression equation of F_t and V/f in Fig. 9 and F_f in the Table 4 (Fig. 14). F_{MF} value was 0.75 for horizontal MFS and in case of vertical MFS, 0.59 – 0.61 for the upper cutter leading type, and 0.64 – 0.65 for the lower cutter leading type. In reality, total thrust force per cutting area is almost constant, and so F^*_{MF} calculated in relation to the above is equal to 0.86 which is the ratio of cutting area of MFS and CFS. This value is larger than that obtained from the test.

Table 5 MF Index Concerned with Cutting Face Stability

	Horizontal MFS	Upper Cutter leading vertical MFS	Lower Cutter leading vertical MFS
$\delta_{max \cdot MF}$	0.82	0.37	0.40
$\delta_{A \cdot MF}$	0.69	0.21	0.22
h_{MF}	1.00	0.83	0.83

(2) Cutting Face Stability

Table 5 indicates (i) $\delta_{max.MF}$ is MF index concerning maximum amount of ground surface settlement obtained from lateral directional ground surface settlement distribution in Fig. 10, (ii) $\delta_{A \cdot MF}$ is MF index about lateral directional ground settlement area which is also obtained from Fig. 10 and (iii) h_{MF} is MF index about the height of decreased of cone index obtained from Fig. 11. In this study, the value of $\delta_{A \cdot MF}$ was calculated based on the assumption that settlement is 0 at the soil vessel wall surface (at points 1.5m right or left of the shield center).

All values, $\delta_{max.MF}$, $\delta_{A \cdot MF}$, h_{MF} are less than 1.0 regardless of shield types, which means cutting face stability of MFS is better than that of CFS.

Those MF index values for vertical MFS are almost same regardless of the upper cutter leading type of the other, and are less than those of horizontal MFS. From this result, we can see that the shield width rather than the height is more influencial on the cutting face stability.

5. CONCLUSION

Aiming at the analysis on tunnelling characteristics of MF shield, model test was conducted on the shield for the double track railway tunnel, comparing MFS (horizontal and vertical) with a traditional circular shield. Based on data of MFS's acting force characteristics and cutting face stability obtained by our model test, the conclusion of our experiment is outlined as follows in terms of MF index i.e. comparison of MFS to CFS.

(1) The value of MF index about cutter torque, T_{MF} is 0.31 – 0.46 for horizontal MFS, 0.18 – 0.29 for vertical MFS. These values are less than T^*_{MF} value 0.59 which is calculated by applying torque equation $T = \alpha D^3$ to each cutter (α; torque coefficient, D; shield diameter) that is used for shield design at present.

The value of MF index about the thrust force, F_{MF} was 0.75 for horizontal MFS and 0.59 – 0.65 for vertical MFS. These values are less than F^*_{MF} value calculated due to the fact that thrust force per unit cutting area is constant.

From these data, acting force characteristics of MFS is considered superior to those of circular shield.

(2) The value of MF index concerning maximum amount of ground surface settlement, $\delta_{max.MF}$ was 0.82 for horizontal MFS and 0.37 – 0.40 for vertical MFS, and that of lateral directional ground settlement area $\delta_{A \cdot MF}$ was 0.69 for horizontal MFS and 0.21 – 0.22 for vertical MFS. All these values are less than that of circular shield, which indicates that the cutting face stability of MFS is the same or better than that of circular shield.

As described above, many valuable tunnelling characteristics for MFS design and construction were now revealed by the results of our experiment.

ACKNOWLEDGEMENT

Cooperation and suggestions extended by PROFESSOR Yoshiji MATSUMOTO and many other persons are much appreciated.