# MECHANISM OF EARTH PRESSURE CHANGE ON A SERIES OF FIVE CONTINUOUS SHIELDS

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## *RINGKASAN*

*"Multi-Micro Shield Tunnelling (MMST)" adalah sebuah metoda baru untuk penggalian terowongan yang akan digunakan di daerah kota dengan tingkat jumlah populasi dan struktur bangunan yang tinggi. Riset ini dilaksanakan dengan model laboratorium. Sejumlah terowongan berbentuk empat persegi panjang berukuran mikro dengan jarak antar terowongan yang sangat dekat, dimodelkan dengan sejumlah pintu jebak yang dikenal dengan "trap door". Massa tanah di lokasi terowongan-terowongan akan dibor, diwakilkan oleh batang-batang aluminium berdiameter kecil. Sasaran dari penelitian ini dikelompokkan menjadi dua. Pertama adalah menyelidiki setiap perubahan besarnya desakan tanah (tekanan tanah) di atas atap terowongan-terowongan empat persegi panjang berukuran mikro, pada setiap tahap penggalian terowongan. Kedua adalah mendapatkan pengertian yang baik mengenai pengaruh dari setiap perubahan urutan penggalian terowongan-terowongan terhadap besarnya desakan tanah (tekanan tanah), baik sebelum dan sesudah setiap terowongan mikro dibor. Penurunan permukaan tanah yang terjadi selama berlangsungnya penggalian juga diamati. Dari hasil-hasil pegujian dapat dilihat bahwa:*

*(1) bermacam variasi dari urutan penggalian untuk membangun terowongan persegi panjang berukuran mikro menghasilkan besarnya desakan tanah (tekanan tanah) yang berbeda yang menekan atap terowongan-terowongan tersebut;*

*(2) pola penurunan permukaan tanah adalah serupa untuk setiap perbedaan urutan penggalian;*

*(3) besarnya desakan tanah (tekanan tanah) akhir (final) harus dihitung dengan mengkombinasikan setiap pertambahan perubahan desakan tanah (tekanan tanah) dimana urutan penggalian juga harus dipertimbangkan.*

## *SUMMARY*

*The Multi-Micro Shield Tunnelling method (MMST) will be employed as a new technology to construct tunnels in densely populated areas. The study is carried out using a laboratory model. A multi-trap door is used for simulating the tunnels and aluminium rods are used for simulating the ground. The objectives of this research are to investigate the change in the earth pressure on the roof of multi-micro rectangular shield tunnel after each construction phase is completely and to determine the influence of the construction sequence on the earth pressure before and after each consecutive micro-shield is bored. The surface subsidence pattern created in each stage of the excavation was also observed. The results showed that:*

*(1) the various sequence of the excavation in order to construct micro rectangular shield will result in different values of earth pressure acting on the roofs of each shield;*

*(2) the pattern of surface subsidence are similar for different sequences of excavation stage;*

*(3) the magnitude of the final earth pressure should be estimated by superimposing each increment of the earth pressure taking into consideration the sequence of excavations.*


## I. INTRODUCTION

It is clear that in large cities the requirement for roads is increasing while the available space for road constructions is decreasing. However, environmental issues and securing land are becoming more important points to consider in locating roads under the ground. In order to build tunnels that will accommodate large traffic flows within narrow underground space, the rectangular-shaped tunnels will be given priority as a solution. This shape is strongly recommended for road tunnel systems in big cities because it is more economic than using circular-shaped tunnels. For constructing tunnels, various well known construction methods are used. For example, the cut and cover method, the shield method and NATM (New Austrian Tunnelling Method). The particular method used depend on the ground condition.

It is not a surprise that in large cities the density of civil engineering structures on the surface have been rapidly increasing, and at the same time the availability of excavation machinery to build these tunnels is becoming more and more limited. Of course, the stability of structures located on the surface is an important consideration when boring the ground. With regard to characteristics of big cities, attention should be paid to the traffic flow on the surface roads, as well as the environmental conditions of the surface. The



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ground water level should also be taken into account during and post-construction process. It is recommended to use a no-open cut method, therefore the shield method is widely used.

Accordingly so, a new no-open cut method of tunnel construction is being studied, which minimises the underground space required. Using micro-shield machines, the ground can be bored to create only the outer perimeter of a large rectangular tunnel lining. This perimeter forms a frame for the tunnel. After the perimeter is formed, the ground is excavated by normal diggers. Determining the number of micro-shields required is related to the final size of the tunnel cross-section. This method is called Multi-Micro Shield Tunnelling (MMST). This name was introduced by Metropolitan Expressway Public Corporation-Japan.

The problem of soil mechanics, particularly the earth pressure acting on a tunnel lining of a single tunnel can be directly solved using Terzaghi's formula (the formula for earth pressure in yielding sand), which is easily applied in current practise. This formula can also be used for situations involving two tunnels that are bored close together but at a distance greater than the diameter of the tunnels, because there is less interaction between the two tunnels. If the space between the tunnels is less than one diameter, the change of earth pressure due to the excavation process of the second tunnel will affect the lining of the first.

The problem becomes more complex when the number of tunnels to be excavated increases. The phenomenon of load transfer in earth pressure due to the excavation of one tunnel after another is not clearly understood, hence, the magnitude of the earth pressure acting on upper parts of the tunnel is also important factor to consider in assessing tunnel stability. Greater understanding of the distribution of the earth pressure above the tunnel's roof when the tunnel excavation takes place in multi-stage by adjacent multiple shield or by adjacent multiple drift method by the NATM is desired.

Earth pressure studies involving the conditions mentioned above, were performed with a two dimensional model using multi-trap door equipment. The tests were based on Terzaghi's single trap-door test set beneath a model ground, which used aluminium rods.

Focusing attention on the distribution of earth pressure only on the upper part of a large rectangular tunnel, we modelled roofs of five adjacent shields with rigid panels. The aluminium rods were used for simulating sandy soil, the ground condition of which is not conservative compared with clayey soil.

The purposes of this research are shown below :

(1) to estimate the mechanism of earth pressure change on five continuous trap-door relating to various tunnel excavation sequences, and
(2) to study the subsidence surface pattern above the multi-trap door.

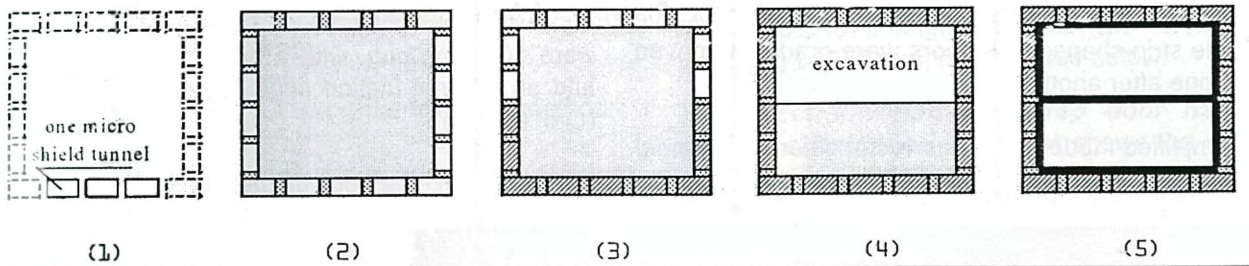
Therefore, the first section of this paper is devoted to describing the principles of the Multi-Micro Shield Tunnelling method. Experimental investigation is presented in later sections, then a detailed discussion of the results is included. The last part of the paper presents details of the conclusion to assist in understanding the changes in earth pressure as a result of multi-shield tunnelling process.

## II. MULTI-MICRO SHIELD TUNNELLING METHOD

The Multi-Micro Shield Tunnelling method is a construction method, which uses small size shield tunnel machines with rectangular cross-section type to obtain one large rectangular cross-section tunnel. Generally the procedure of MMST can be explained as follows (see Figure 1) :

(1) each machine bores the ground to construct a multi-micro shield, providing a portion of the outer lining of one large tunnel. Steel shells are incorporated around each of the micro shields;
(2) after the adjacent micro-shields have been completed, the ground between the micro-shields is grouted then excavated;
(3) the reinforcing bars are installed to connect each micro shield;
(4) the MMST body is constructed by filling inside each micro-shield with concrete and steel plates forming the frame of one large rectangular tunnel;
(5) using a normal digger, the ground inside the frame is then excavated;
(6) linings inside the frame are installed, then slabs and barrier walls are built appropriately.

**Figure 1**
**METHOD OF TUNNEL CONSTRUCTION USING MMST**



Moreover, the characteristics of MMST can be described as follows :

(1) the method is appropriate for constructing a large rectangular cross-section tunnel in soft ground under ground water without drawing it;
(2) this method is suitable for the construction of relatively large tunnels with a ground cover of small depth;
(3) the size, shape, and line of the tunnel can be changed easily;
(4) it is easier to construct rectangular tunnels using this method than other no-open cut method. The cut and cover method often apply dewatering by draining to sumps or by ground-water lowering;
(5) the micro-shield machines can be used many times and are economical for excavating short tunnels;
(6) excavating the ground inside the multi-micro shield tunnel is carried out using a normal digger;
(7) because of various excavation stages in constructing the micro-shields, and because the state of the earth pressure at each construction stage is different, proper design at each stage is required;
(8) precise control of the micro-shield machine position is required;
(9) the temporary facilities required for one shield machine are smaller when compared with other methods.

When compared with the use of a large diameter shield machine to excavate all the ground at once, where overburden height is low, the number of influences on the surface and the effects of tunnelling on neighbouring structures is reduced. A reduction in these influences can be obtained because the surface subsidence can be controlled easily. With regard to face stability, controlling the stand-up of the face can be easily maintained with micro-shield machines because they are small enough.

## III. EXPERIMENTAL INVESTIGATION

### 3.1 Scope and Method

As stated above, the main purpose of the experimental investigation was to get a good understanding of the mechanism of earth pressure change on the tunnel roof due to excavating the series of shield tunnels. The aluminium rods material were piled up horizontally on the base of the multi-trap door equipment. The five movable strip-shaped trap-doors were gradually moved down, one after another.

This simplified model of a large rectangular road tunnel in urban areas should agree with the standards for roads, including proper ground conditions and that the slope of tunnel-approachs to the surface is reasonable. Therefore, in this study the large rectangular tunnel was located at a shallow depth, in which assumed that the ground arching extended to the surface of the ground. This was considered in the category of the shallow tunnel model when the span of the excavation was taken as a total width of the five micro-shield tunnels.

The initial vertical pressure acting on the multi-trap door before the trap-door began to be lowered was equal to the depth of the stack of the aluminium rods times it's unit weight

During the tests, the earth pressure on each trap-door was measured and the subsidence pattern of the rod surface was recorded.

### 3.2. Parameter of Tests

The parameters of the tests are, overburden height (H), the order in which the five multi-trap doors were sequentially moved, and the amount of movement downward of each trap-door ($\Delta h$). Various overburden heights have been used, representing the depth of cover according to the category of the shallow tunnel type as mentioned before. The sequences of micro-shield construction have been represented by changing the order of which multi-trap door was moved, where the amount of movement corresponds to the tail clearance of a micro-shield machine, which is related to the allowance value of ground convergence during tunnelling process.

The range of values used for each parameter in these tests were:

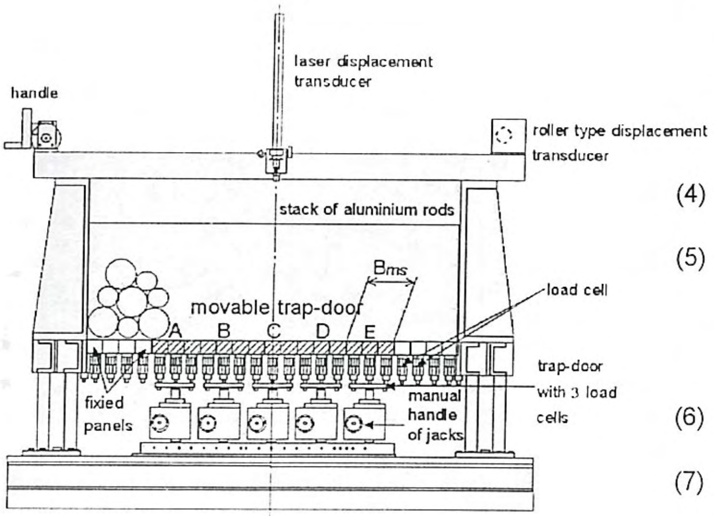
(1) Height of overburden: values used were, 250 mm, 450 mm, 500 mm and 750 mm;
(2) Construction sequence: four different sequences were used: ABCDE, ACEBD, BDCAE and CBDAE where the fivetrap-door were lettered consecutively (see Figure 2);
(3) The effect of tunnel convergence was examined by changing the length that the trap doors were moved downward ($\Delta h$). The lengths used were from 0.5 mm to 2.5 mm, with intervals of 0.5 mm.

### 3.3 Model Material and Apparatus

In the model, the sandy soil was represented by a stack of aluminium rods of two diameters, 1.6 mm and 3.0 mm, with a weight ratio of 3:2 respectively. The rods were 100 mm long, with a density ($\gamma$) of 2.15 gf/cm$^3$, and an internal friction angle ($\phi$) of 30$^\circ$, and cohesion (c) of 0 gf/cm$^2$.

In this model, the roof of the large rectangular shield tunnel is represented by a series of rectangular

Figure 2
MULTI-TRAP DOOR EQUIPMENT




horizontal rigid panels, as can be seen in Figure 2. The trap door apparatus was 1200 mm in width, 300 mm in depth and consisted of 24 panels, each of which was 50 mm in width. Each micro-shield has been represented by one trap-door. Each trap-door is represented by three panels, of width ($B_{ms}$) 150 mm. At the bottom of each panel, a load cell was installed. Every time the load on the panel was changed, it was recorded directly to a computer. Each trap-door was connected to a jack, making downward and upward movement possible. The vertical movement was measured using dial gauges, and this information was automatically recorded to the computer using a data logger. Subsidence was measured using displacement transducers. A laser displacement transducer recorded subsidence, and a roller type displacement transducer recorded horizontal movement of the laser displacement transducer. The data on both displacement transducers was recorded using the same data logger.

### 3.4. Test Procedure

In these tests, the measurements of both, the change in earth pressure. and the change in surface profile are representative of the excavation process for a large rectangular tunnel. Parameters measured were the earth pressures on the multi-trap door and on the fixed panels, length of downward movement, and the subsidence of the surface. The earth pressures were measured in intervals of 0.05 mm and were recorded automatically for each panel.

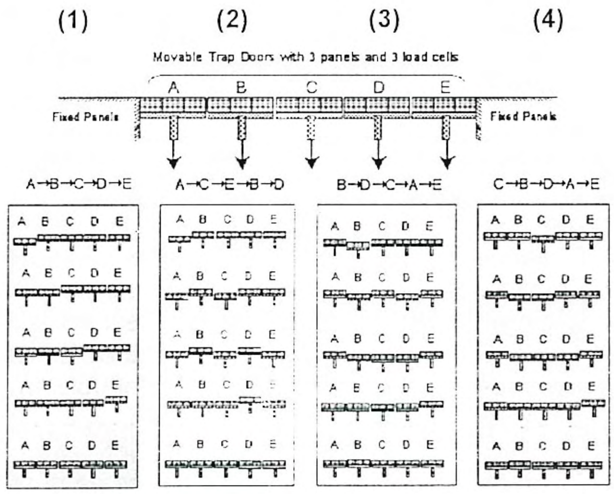
The tests were carried out using the following method:

(1) the space between panels is adjusted to 0.3 mm, and the panels are levelled with a plane tool;
(2) the load cells are calibrated, one load cell for each panel, and three panels for each trap door;
(3) the aluminium rods are piled up horizontally so they are covering all panels, with the axis of the rods parallel to the panels (the rods are compacted, the surface levelled, and the earth pressures checked. This is repeated every 100 mm layers until the desired overburden depth is achieved);
(4) the displacement transducer system is set up in the proper position;
(5) the trap door is moved down manually with the jack, and its movement and earth pressures are measured at intervals of 0.05 mm. The downward movement is stopped after moving through the distance, Δh;
(6) the subsidence of the surface is checked using the displacement transducer;
(7) steps (5) to (7) are repeated for the other trap-doors in the specified sequence;

### 3.5. Model Experiment

Four sequences were used in this study, as shown in Figure 3. The multi-trap doors were moved down a distance Δh, so that the required tail clearance was reached.

Figure 3
SEQUENCES OF MOVEMENT OF TRAP-DOORS




### Test Results

The results will describe the aims and the limitations of the presents series of tests. As an example, the sequence ABCDE, with a downward movement of □h /$B_{ms}$ = 1.3% for a single trap-door (Δh = 2 mm) and the depth (H) of 250 mm, is presented below.

***The effect lowering multi-trap door has on the surface subsidence.*** Figure 4 shows the subsidence of the surface along the multi-trap-door at each stage of downward displacement for a single trap-door. In this sequence, when a trap-door was moved down, the weight supported by nearby trap-doors was changed. This zone of influence has a width that is approximately two times the width of a trap-door, and therefore, has an effect on the next two closest trap-doors to the right. After all trap-doors are lowered, a wide area of subsidence is created. The maximum subsidence value obtained was almost 2.0 mm.

***The effect lowering multi-trap door has on the distribution of earth pressure.*** Figure 5 shows the distribution of the change in earth pressures ($\Delta\sigma_v$), where the initial earth pressure, $\gamma H$. Here $\Delta\sigma_v = \sigma_{v,i} - \sigma_{v,0}$, where $\sigma_{v,i}$ is the earth pressure on a trap-door at the $i^{th}$ stage, when that was moved down and $\sigma_{v,0}$ is the earth pressure on the trap-door at the initial stage. The earth pressure acting on the lowered trap-door decreases while the earth pressure on the other adjacent trap-doors increases. The distance of influence distance has a range of approximately twice the width of one trap-door, which measured from the lowered trap-door.

***The effect lowering has on the distribution of earth pressure in earth pressure increment.*** The curves in Figure 6 show the increment of earth pressures ($\sigma_{v,i} - \sigma_{v,i-1}$) acting on the multi-trap door at every stage of movement of the trap-door just before the succeeding trap-door is lowered. This is shown by fixing the centre of the width of every trap-door at point 0 (0,0) when that trap-door is lowered. The other trap-doors are there by adjusted in relation to this centred trap-door. Except for the curve of trap-door A, the increment of earth pressures on the right and left sides are different. The increment of earth pressure on the right side is less than the increment of earth pressure on the left side, and the zones of influence are almost the same on both side. For trap-door A, the relationship is symmetric. This reason for this tendency is that the amount of the increment on the left side (the disturbed ground mass) is bigger than the increment on the right side (the undisturbed ground mass). These results indicate that the stress history plays on important role in stress redistribution in the excavation process.

Figure 7 shows the result of normalised earth pressure on each trap-door, where the earth pressures on the multi-trap door, $\sigma_v$, are continuously recorded. The values of the normalised earth pressure ($\sigma_v/\gamma H$) in ordinate axis are obtained by averaging the normalised earth pressure of three load cells on one trap-door. The value of 1 (one) represents the initial state of the earth pressure.

The influence of lowering a trap-door on the other trap-doors is a function of the distance between them. This phenomenon can be seen in Figures 5 and 6, that the

Figure 4
SUBSIDENCE OF SURFACE
ABCDE-Case, h = 250 mm, Δh = 2.0 mm

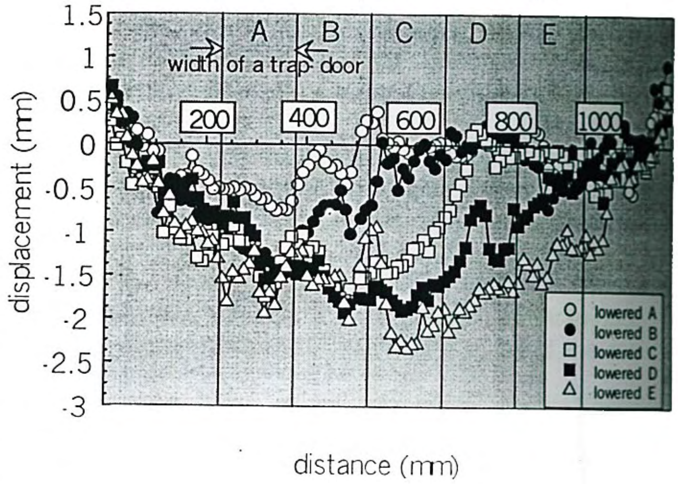



Figure 5
CHANGE IN EARTH PRESSURE FROM INITIAL VALUE ABCDE-Case, h = 250 mm, Δh = 2.0 mm

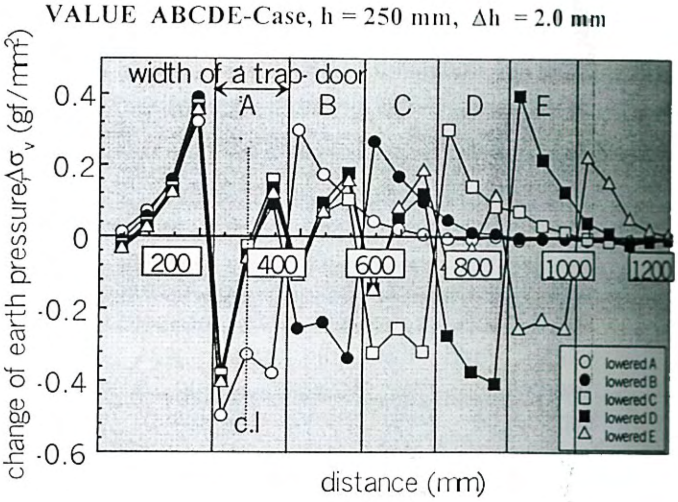
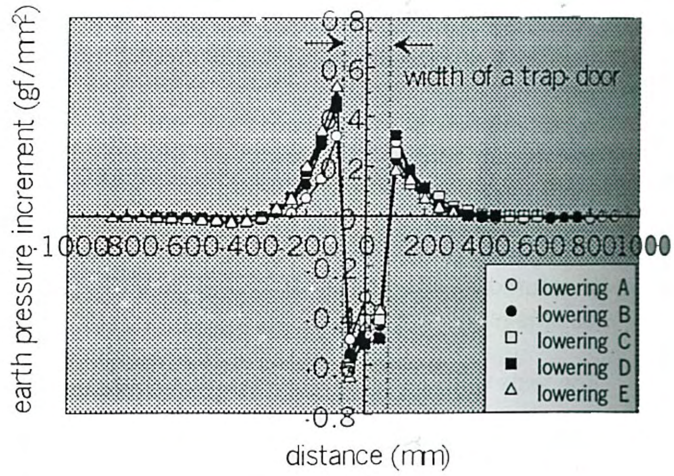



Figure 6
EARTH PRESSURE INCREMENT CURVES ADJUSTED TO THE CENTRE OF EACH OF EACH TRAP-DOOR ABCDE-case, h = 250 mm, Δh = 2.0 mm



lowering of one trap-door will influence the earth pressure on the preceding and succeeding lowered trap-doors with different magnitudes. The magnitude of each change in normalised earth pressures on each trap-door because of the lowering of the $n^{th}$ neighbouring trap-door can be seen in Table 1. The symbol $\Delta\alpha(n)$ represents the change in normalised earth pressures transferred from $n^{th}$ neighbour trap-door of a referred trap-door before the referred trap-door is moved. The symbol of $\Delta\beta(n)$ is used in case of the referr d trap-door has been moved. For example in a case of trap-door E from the lowering sequence of ABCDE, trap-door E receives the change in normalised earth pressure amounts to $\Delta\alpha$ **(4)** as a result of the lowering of trap-door A, $\Delta\alpha$ **(3)** because of the lowering of trap-door B, $\Delta\alpha$ **(2)** from the lowering of trap-door C and $\Delta\alpha$ **(1)** from the lowering of trap-door D. These conditions happened in condition which, trap-door E has not been moved yet. The amounts of $\Delta\beta$ **(4,3,2, and 1)** give a condition in which, the referred trap-door has been moved. The explanation of this matter can be seen also in Figure 8.

When considering the total width of the tunnel span of the five trap-doors ($B = B_{mt} * 5 = 750$ mm), it was found that, for H/B=0.33, where the value of H is 250 mm, the earth pressure on a trap-door due to the movement of the third and fourth trap-door do not change, while for H/B=0.67 (H=500 mm), the earth pressure on a trap door is not influenced by movement of the fourth trap-door. For H/B=1 (H=750 mm), however, the earth pressure on a trap-door is influenced by the movement of the fourth trap-door.

Without considering the lowering sequences of the multi-trap door, the graph between the normalised earth pressures on the multi-trap door, on which the normalised earth pressure indicates the maximum value within the five trap-doors, after all the trap-door are lowered completely (the y-axis) and the amount of movement (the x-axis) are shown in Figure 9. For a movement of 0.5 mm, the normalised earth pressure reaches the magnitude of less than 1.0 (one) for an overburden height of 750 mm, while it is greater than 1.0 (one) for a 250 mm of overburden height. The curves show a similarity for various of overburden height. From these curves it can also be seen that movements greater 1.5 mm ($\Delta h/B_{mt}$□1.0%) produce a little change in earth pressure suggesting that the ground has achieved a steady loosening condition, i.e. the condition is like a Terzgahi's loosening earth pressure state.

From various of lowering case, in generally, the loads ($P_v$) acting vertically on multi-trap door vary between 20%γH and 140%γH per unit of area of the horizontal sections.

Figure 7

**NORMALISED EARTH PRESSURE**

**ABCDE-case, H = 250 mm, Δh = 2.0 mm**

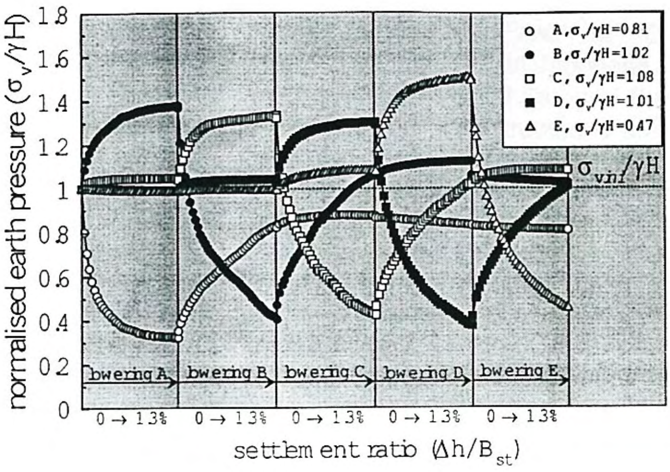



Figure 8

**ANNOTATION OF CHANGE IN NORMALISED EARTH PRESSURE**

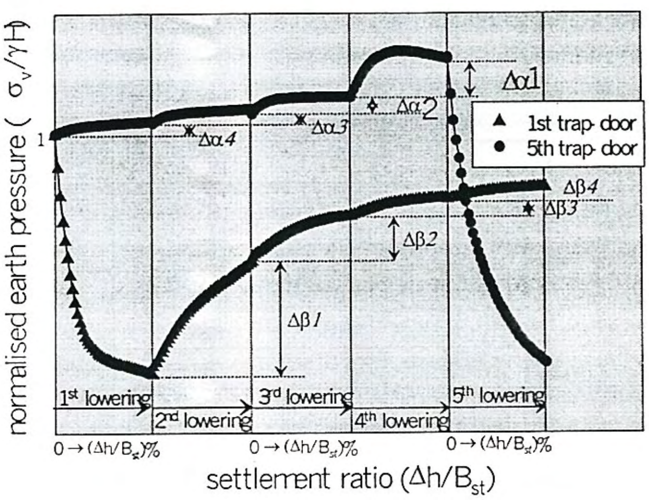



Figure 9

**NORMALISED EARTH PRESSURE FOR DIFFERENT VALUE OF MAXIMUM MOVEMENT**

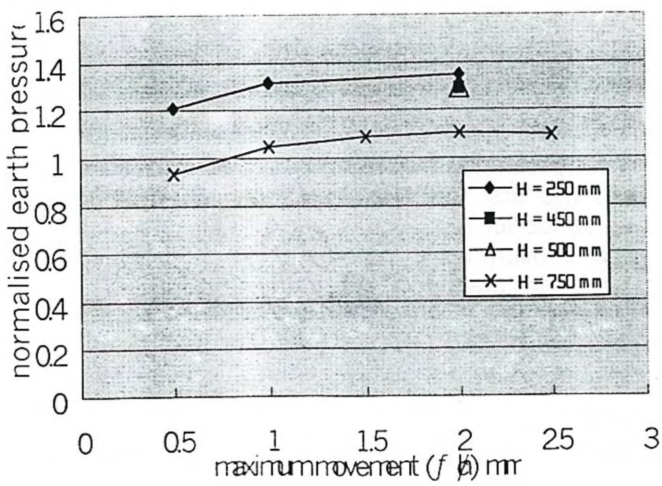


Figure 10

STRESS HISTORY ON TRAP-DOOR EXPERIENCING MAXIMUM EARTH PRESSURE

for Δh=2.5 mm and H=750 mm

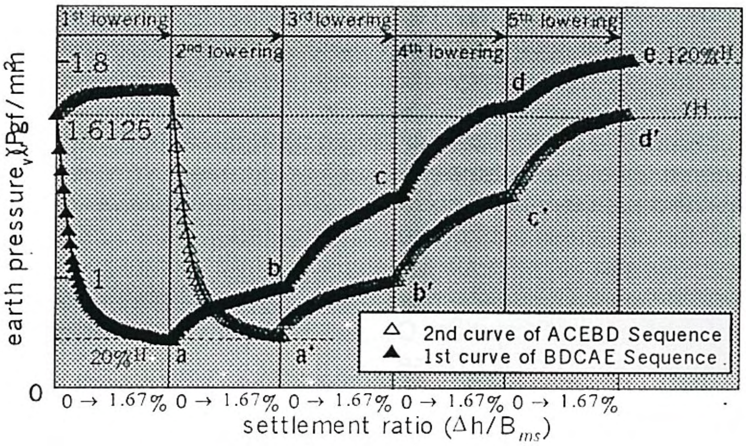



Table 1

THE MAGNITUDE OF THE CHANGE OF NORMALISED EARTH PRESSURE

| Case | Δα1 | Δα2 | Δα3 | Δα4 | Δβ1 | Δβ2 | Δβ3 | Δβ4 |
|---|---|---|---|---|---|---|---|---|
| Δh=0.5 mm, H=250 mm | 0.22 | 0.04 | 0 | 0 | 0.33 | 0.05 | 0 | 0 |
| Δh=1.0 mm, H=250 mm | 0.29 | 0.05 | 0 | 0 | 0.44 | 0.07 | 0 | 0 |
| Δh=2.0 mm, H=250 mm | 0.3 | 0 | 0 | 0 | 0.5 | 0.1 | 0 | 0 |
| Δh=2.0 mm, H=450 mm | 0.26 | 0.09 | 0.05 | 0 | 0.43 | 0.15 | 0.08 | 0.02 |
| Δh=2.0 mm, H=500 mm | 0.25 | 0.11 | 0.06 | 0 | 0.41 | 0.17 | 0.08 | 0.03 |
| Δh=0.5 mm, H=750 mm | 0.13 | 0.07 | 0.05 | 0.03 | 0.19 | 0.1 | 0.06 | 0.04 |
| Δh=1.0 mm, H=750 mm | 0.15 | 0.08 | 0.07 | 0.05 | 0.27 | 0.15 | 0.1 | 0.05 |
| Δh=1.5 mm, H=750 mm | 0.15 | 0.1 | 0.09 | 0.05 | 0.31 | 0.19 | 0.12 | 0.07 |
| Δh=2.0 mm, H=750 mm | 0.14 | 0.1 | 0.08 | 0.06 | 0.36 | 0.18 | 0.11 | 0.06 |
| Δh=2.5 mm, H=750 mm | 0.13 | 0.11 | 0.08 | 0.06 | 0.33 | 0.21 | 0.14 | 0.08 |

*all values must be multiplied by γH to get the magnitude of change in earth pressure*

## IV. DISCUSSION

Figure 10 shows a comparison of stress history on the second lowering trap-door, i.e. C, of ACEBD sequence and the first lowering trap-door, i.e. B, of BDCAE sequence for Δh=2.5 mm and H=750 mm. Each curve was chosen as a representative date indicated the maximum magnitude of earth pressure at the final lowering stage from the five trap-doors. The earth pressure on the lowered trap-door decreased from its original value, γH=1.6125 gf/mm$^2$, to a minimum. It was attained about 20%γH, at following the lowering stage, this earth pressure increased . The BDCAE-case resulted the maximum magnitude of earth pressure about 120%γH acting on the trap-door.

At the final stage, each step of the curves indicated the same increasing in earth pressure as the order of lowering of each trap-door was same, namely in a case of the same of *n* of β(n). For example ab and a'b', bc and b'c', cd and c'd' were forming the same step shaped respectively because the sequences of movement of the five trap-doors of both cases were perfectly same regarding 2$^{nd}$ trap-door (in the case of Δ) and 1$^{st}$ trap-door (in the case ▲).

Based on the results through out various tests, it suggests the earth pressure acting on each trap-door should be estimated by superimposing each increment of earth pressure in consideration of the sequence of the downward movement of the multi-trap door. We should be noticed also that the final earth pressure on each trap-door may be exceed the overburden pressure according to the sequence of excavation stage.

**Summary**

The study of using multi-trap door equipment can be used broadly in the case of multi-excavation stage of underground openings. We suggest that the results of this research are available for a tunnel that will be constructed using New Austrian Tunnelling Method (NATM) of multi-drift type of excavation and shield method of multi-shield type of excavation. It can be applied also for twin or more tunnels situated very closely.

**References**

- Bulson, P.S. *Buried Structures Static and Dynamic Strength.* Chapman and Hall, London, New York, 1985.
- Edagawa, S. et. all. A Consideration of MMST Method. *Proc. of Annual Meeting of Civil Engineering,* 1997, in Japanese.
- Fukumoto, K., et. all. Estimation of Mechanism for Stress Distribution Reorganised by Yielding Continuous Four Trap Doors. *Proc. of Annual Meeting of Geotechnical Engineering,* 1998, in Japanese.
- Konda, T., et. all. Study on Design of a Pair of Shield Tunnels Situated very closely by Centrifugal Model Test. *Proc. 23rd General Assembly of The International Tunnelling Association*, 1997, pp. 151-156.
- Ladanyi, B., Hoyaux, B. A Study of The Trap-door Problem in a Granular Mass. *Canadian Geotechical Journal*, 1969, 6, 1.
- Murayama, S. Earth Pressure on Vertically Yielding Section in Sand Layer. *Disaster Prev. Research Inst. Annuals*, Kyoto University, 1968, in Japanese.
- Murayama S., Matsuoka, H. Earth Pressure on Tunnels in Sand Ground. *Proc. of Civil Engineering, JSCE*, 1971, Vol. 187, in Japanese.
- Nagatani H, et. all. An Experimental Study of Earth Pressure on Very Closely Constructed Parallel Tunnels. *Report No. 46, Kajima Technology Research Dept.,* 1998, in Japanese
- Ono, K., Yamada, M. Study on the Arch Action above the Tunnel Driven in the Cohesionless Sand. *Proc. Of Civil Engineering, JSCE*, 1983, Vol. 339.
- Sinha, R.S. *Underground Structures Design and Construction.* Elsevier, 1991.
- Szechy, K. *The Art of Tunnelling.* Akademiai Kiado Budapest, 1966.
- Tarumi, H., Yamamoto, Y., et. all. Study on Vertical Earth Pressure Distribution in Sand by Trap Door Test. *Proc. of Annual Meeting of Tunnel Engineering*, Japan, 1992, Vol. 2, in Japanese.
- Terzaghi, K. Stress Distribution in Dry and in Saturated Sand above a Yielding trap-door. *Proc. 1st International Conference Soil Mechanic Foundation Engineering*, Cambridge, Massachusetts, 1936, 1, pp. 307-311.
- Terzaghi, K. *Theoretical Soil Mechanics*, John Wiley and Sons, New York, 1959.

*Penulis :*

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