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Behavior analysis of fragmental rocks during tunnel excavation using a large-scale 2-D loading apparatus

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Abstract. In Korea, most people live in metropolitan areas. Social infrastructure is concentrated in a small area based on the demands of many people. The development of underground space in urban areas using deep tunnels for roads, railways, subways, communication facilities, and waterway facilities is expanding. This underground space is composed of weathered rock ground with geological joints, and many tunnels have been excavated in such ground. The effect of discontinuity on the behavior of the tunnel must be considered during the design and construction stages. Therefore, in this study, a ground model with three dip angles was created using concrete blocks to analyze the relaxation behavior of the surrounding ground when excavating a tunnel in a rock mass with joints. In addition, a trapdoor tester capable of creating linear and nonlinear settlement was manufactured, and the stress distribution and settlement occurrence tendency of the tunnel top and surrounding ground were analyzed when different settlement shapes occurred. The experimental results showed that the behavior of the top of the trapdoor and the surrounding ground varied depending on the displacement shape of the trapdoor and the inclination of the joint surface of the rock. The results of this experiment suggest a displacement shape that is advantageous to the arching effect depending on the inclination of the joint surface of the upper ground during tunnel excavation. In addition, the loosened ground zone of the upper ground can be identified by considering the friction angle of the rock and the dip angle during excavation.

Keywords: fragmental rocks; joint angle; load transfer; non-linear deformation; trapdoor; tunnel excavation

1. Introduction

In major urban areas, there is active transportation infrastructure development, and the development of underground spaces in these areas using deep tunnels for roads, railways, subways, communication facilities, and waterway facilities is expanding various urban infrastructures and efficiently utilizing land (Han *et al.* 2021). In Korea, most people live in metropolitan areas such as Seoul and Gyeonggi-do; therefore, social infrastructure is concentrated in such areas owing to the demands of large populations. In the past 10 years, the number and length of tunnels in metropolitan areas have increased significantly because of construction projects such as the expansion of existing subway lines, underground roads, and deep high-speed subway tunnels (Fig. 1). Therefore, many construction projects are being undertaken close to or between underground structures, and securing the stability of existing structures or the surrounding ground during excavation is a significant concern (Kim *et al.* 2021, Bae *et al.* 2017, Choi *et al.* 2016, Park *et al.* 2014, Zhou *et al.* 2023). Therefore, when building structures nearby, design and construction methods must be applied to consider the surrounding ground characteristics in detail, and a sufficient review must be conducted in advance to ensure that ground loosening due to excavation occurs in a favorable direction according to the site conditions (Gokhan *et al.* 2023, Geye Li *et al.* 2024)

Generally, the arching effect that occurs within the ground during tunnel excavation reduces the soil pressure on the structure. Currently, it is used as a design concept for various ground structures. Terzaghi defined the arching of soil as a phenomenon in which the applied load is transferred from the soil yield zone to the surrounding area. To more accurately use the arching phenomenon of soil that occurs within the ground for structural design, a quantitative evaluation of the behavior of the upper ground is necessary (Hanan *et al.* 2023). Research on ground arching has mainly been applied to tunnel excavation, and intensive research on the relaxation zone during tunnel excavation has been conducted (Terzaghi 1943, Balla 1963, Atkinson and Potts 1977, Zheng *et al.* 2024, Kim *et al.* 2017, Shahin *et al.* 2004, Li *et al.* 2024). Terzaghi (1954) conducted a trapdoor test to observe the arching process of soil by opening a trapdoor installed at the bottom of the soil to investigate the arching phenomenon. Through this experiment, he proved that ground can occur owing to locally uniform ground deformation. In the past, when analyzing the behavior of the surrounding ground during

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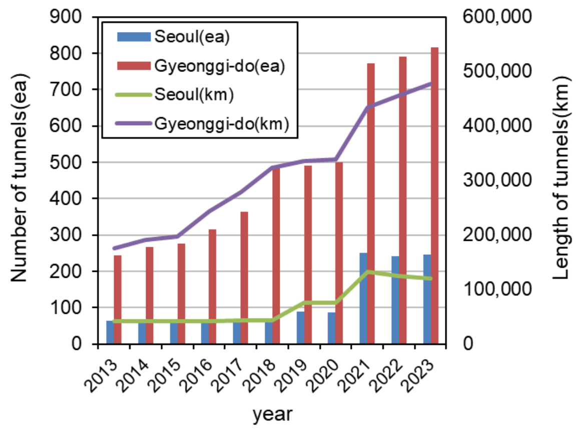


Fig. 1 Increasing trend in the number of tunnels in the metropolitan area of South Korea (MOLIT, 2024)

tunnel excavation, most cases were used measured load values. This occurred because it was challenging to measure the underground displacement of the surrounding ground during model experiments, and the device used for measuring the displacement could affect ground behavior. However, recent research has shown that photo-analysis techniques can be used in addition to measuring the stress of the surrounding ground. With the development of advanced photo-analysis techniques, it has become possible to analyze the behavior of the surrounding ground and the relaxation area by confirming the particle behavior of the surrounding ground during tunnel excavation using continuous photos (Shahin *et al.* 2008, Lee *et al.* 2014, Lee *et al.* 2010, Shin *et al.* 2016).

Many studies arching (Murayama 1968, Adachi 2001, Hong *et al.* 2014, Iglesia *et al.* 2011, Sadrekarimi *et al.* 2010, Thongprapha, et all. 2015, Han *et al.* 2014) related to trapdoor experiments have analyzed the behavior of the surrounding ground by creating a ground model with sand and varying the particle size. Soil ground or intact rock without joints or discontinuities can be considered a continuum. However, in the case of rock containing discontinuities, the behavior of the rock mass can significantly affect the overall behavior of the tunnel and surrounding ground (Yoo 1999). Most studies on the behavior characteristics of the surrounding ground during tunnel excavation in such rock ground models were conducted using numerical analysis (Cundall 1987, Goodman 1968, Desai *et al.* 1984, Hwang *et al.* 2024), and several limitations were identified. Typically, forced displacement is applied to ground model nodes to implement trapdoor displacement. However, this simplifies the displacement generation mechanism, which can occur in a complex manner in the actual ground and may exhibit different behaviors from the model experiment.

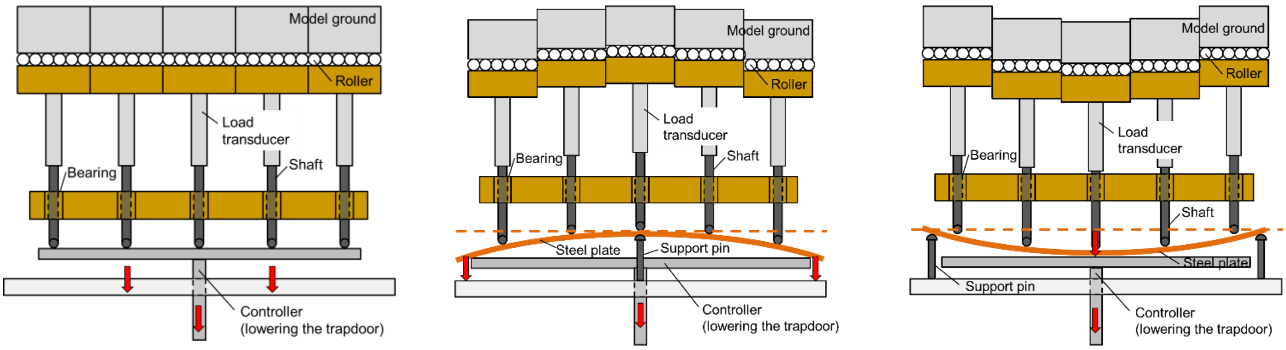
In addition, for various reasons, such as the surrounding ground conditions, tunnel cross-section size, and excavation method, the tunnel upper ground may experience nonlinear settlement during actual tunnel excavation (Hanan *et al.* 2024, Shen *et al.* 2006). A linear settlement shape may occur if the upper ground is homogeneous, and the overall settlement occurs at the tunnel crown. However, nonuniform ground deformation may occur depending on the ground characteristics or tunnel excavation order. For example, a convex-shaped displacement is created if collapse occurs at the shoulder or if the side-drift method is applied to excavate from the tunnel shoulder. In addition, if the top-drift method is applied to excavate the tunnel crown first or if poor ground is located at the top of the tunnel, the ground settlement is concentrated at the tunnel crown, which results in a concave-shaped displacement. Thus, the displacement shape of the crown during the tunnel excavation may be linear or nonlinear, and the upper ground of the tunnel may behave differently under each condition. Therefore, in this study, to analyze the relaxation behavior of the surrounding ground during tunnel excavation in a rock mass, including joints, a ground model with three different joint angles was created using concrete blocks. In addition, a trapdoor tester that can implement linear and nonlinear settlements was manufactured. The stress distribution and settlement occurrence trends of the tunnel top and surrounding ground were analyzed for different settlement shapes, and the relaxation region range was identified.

2. Model test

2.1 Trapdoor

A trapdoor that can implement three types of displacement shapes (uniform, convex, and concave) was manufactured (Fig. 2). To implement convex and concave displacement shapes (Figs. 2(b) and 2(c)), the trapdoor was manufactured in five pieces, each of which could move independently. Even the displacement shape (Fig. 2(a)), which is the same as that of the existing trapdoor, is divided into five pieces such that the load on the upper part of the trapdoor can be measured as a detailed load distribution. Because each piece moved only up and down, each piece was connected to a shaft and passed through a guide plate with a bearing installed to prevent lateral displacement. Therefore, the shaft that penetrates the guide plate is in contact with the upper part of the controller. When the controller moves downward, the shaft also moves; that is, the trapdoor moves as one piece. In addition, a flexible thin steel plate and a pin that supports the steel plate without being affected by the movement of the controller are used to implement a curved displacement. The steel plate is located on top of the controller, and the shaft is in contact with the steel plate so that the trapdoor displacement can be implemented in the same shape as that of the steel plate.

When the controller moves downward during the trapdoor experiment, the weight of the concrete block on top of the trapdoor acts as an external force and presses the steel plate. The part where the support pin is installed is not in contact with the top of the controller but is supported by the support pin so that only the part that touches the controller is deformed to implement a curved displacement. Therefore, a support pin can be installed at the center or at the left and right ends depending on the displacement shape (convex and concave curves) that you want to implement.



(a) Uniform deformation shape (b) Convex deformation shape (c) Concave deformation shape

Fig. 2 Trapdoor capable of implementing linear and nonlinear deformation shapes

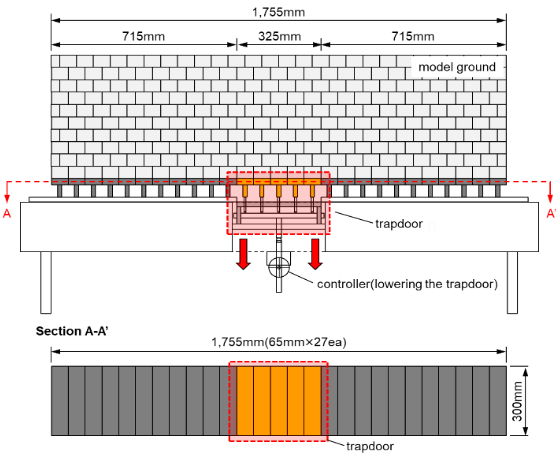


Fig. 3 Model test box

Table 1 Test variables

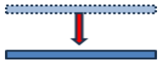
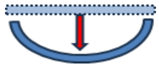
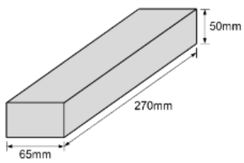
Deformation Shapes	Dip Angle	Case Name
Uniform deformation 	0°	U-A00
	30°	U-A30
	60°	U-A60
Convex deformation 	0°	V-A00
	30°	V-A30
	60°	V-A60
Concave deformation 	0°	C-A00
	30°	C-A30
	60°	C-A60

Table 2 Characteristics of the concrete block

 50mm 270mm 65mm	Width (mm)	Height (mm)	Length (mm)
	65	50	270
	Unit weight (kN/m^3)	Modulus of elasticity (MPa)	Wall friction (°)
	20.4	15,000	37

In addition, when the trapdoor is lowered, the ground on top of the trapdoor undergoes shearing behavior owing to the arching phenomenon, and the concrete block used as the ground model may experience friction with the upper part of the trapdoor. To offset the effect of this friction and restrain the vertical displacement, a roller (aluminum steel pipe) was installed on the trapdoor to set the boundary conditions, and concrete blocks were stacked on top to create the ground model.

2.2 Model test box

The experiment was performed in a model test box (Fig. 3) manufactured with dimensions of 1750 (width) × 300 mm (length). A load transducer was attached to the bottom of the model test box to measure the load change at the top of the trapdoor and surrounding ground. The bottom of the model test machine was divided into sections to refine the load distribution of the surrounding ground, and the central part that could move up and down was divided into five pieces; 11 pieces were manufactured on the left and right sides, for a total of 27 pieces.

2.3 Test conditions

In this study, model experiments were performed for three deformation shapes and three dip angles, and it was expected that different results would occur in the trapdoor experiment, depending on the deformation shape and joint angle of the trapdoor. The three deformation shapes are the uniform deformation shape, as in the existing trapdoor experiment, and the nonlinear deformation shapes (convex and concave deformation shapes). A ground model was built with concrete blocks to analyze the stress relaxation behavior of the surrounding ground during tunnel excavation in a rock mass. The joint angles in the model were 0°, 30°, and 60°. Vertical joints may occur between blocks, in addition to joint angles, when the ground model is composed of concrete blocks. The ground model was built by intersecting vertical joints to minimize this influence. The friction angle of the concrete blocks was estimated to be approximately 37°, and the ground model was constructed with smaller (30°) and larger (60°) joint angles. Table 1 lists the test variables and case names in the experiment. The specifications of the concrete blocks used in the experiments are listed in Table 2.

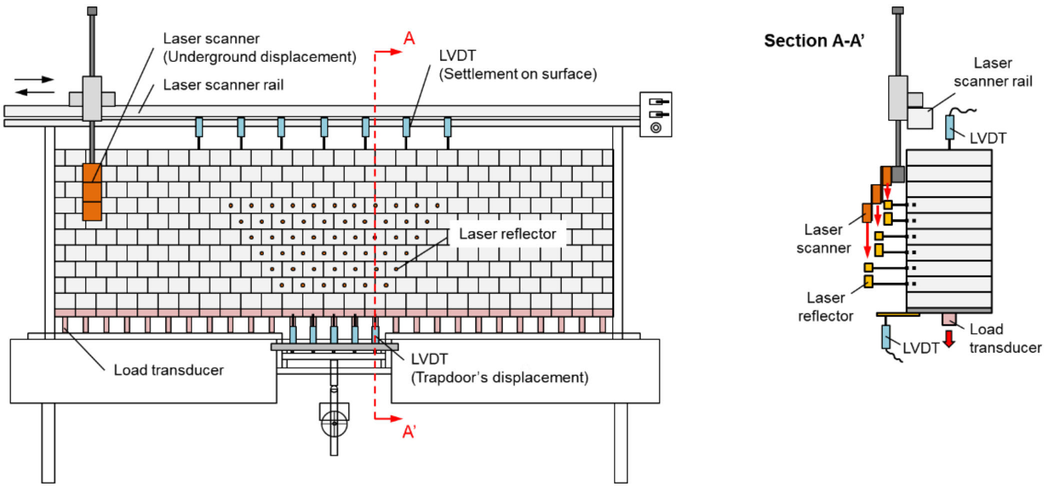


Fig. 4 Measuring system

Table 3 Characteristics of the measuring equipment

Type	Load Transducer	LVDT	Laser	Data Logger
Capacity	1 kN	25~50 mm	105 mm	30 Channels
Sensitivity	0.5 N	0.01 mm	0.01 mm	-
Manufacturer	Bongshin (Korea)	Tokyo Sokki (Japan)	Leuze (Germany)	Tokyo Sokki (Japan)
Quantity	27 EA	12 EA	3 EA	1 EA

The trapdoor width was 325 mm, which is approximately 1/30 of the actual diameter of a 10 m tunnel. The joint spacing in the model test was 50 mm, whereas the actual joint spacing was approximately 1.5 m; therefore, the joint spacing in the ground model was considered wide (International Society for Rock Mechanics [ISRM], 1981).

2.4 Measuring system

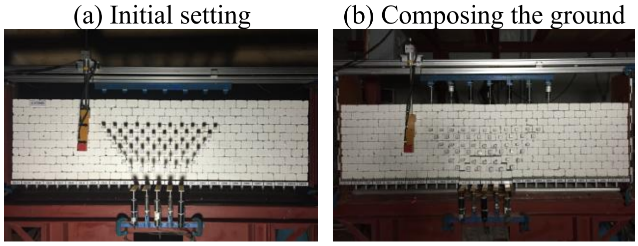
In this experiment, 27 load transducers were used to measure load changes in the surrounding ground when the trapdoor was lowered. They were installed on each of the 27 pieces at the bottom of the model test box. Five load transducers were used for the trapdoor, which could move up and down, and 11 were used for the left and right sides of the trapdoor. In addition, a linear variable differential transformer (LVDT) was used to measure the ground settlement and displacement of the trapdoor.

In addition, a laser was used to measure the underground displacement. A reflector was installed in front of the concrete block such that the laser could detect the displacement, and a rail was installed on top of the model test box for precise measurement. The laser was moved left and right each time the trapdoor was lowered to measure the ground displacement. The measured data were stored using the TDS-303 Data Logger (Tokyo Ssoki Kenkyujo Co., Ltd.).

2.5 Laboratory test procedure

The test procedure (Fig. 5) included ground preparation installation, trapdoor lowering, and measurements. Concrete blocks were used in the same positions to ensure homogeneous composition of the ground model. In addition, because the lowering speed of the trapdoor can affect the behavior of the surrounding ground, it was lowered at a constant speed of 0.2 mm/min to ensure control.

(a) Initial setting (b) Composing the ground



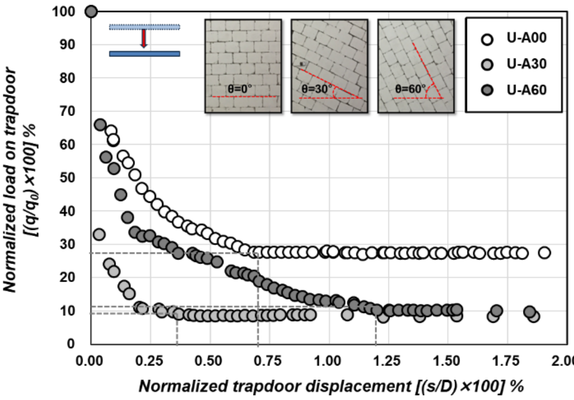
(c) Measuring system setting (d) lowering the trapdoor

Fig. 5 Test procedure

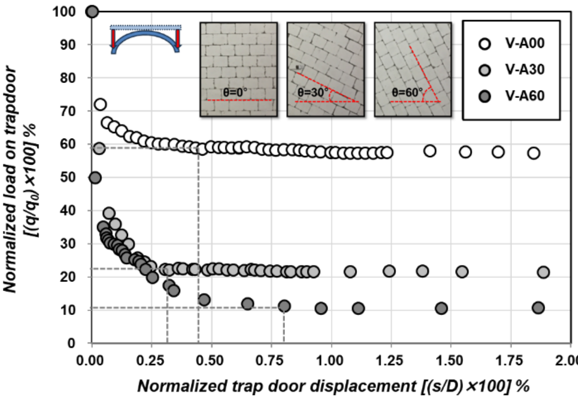
3. Results and analysis

3.1 Vertical load on the trapdoor

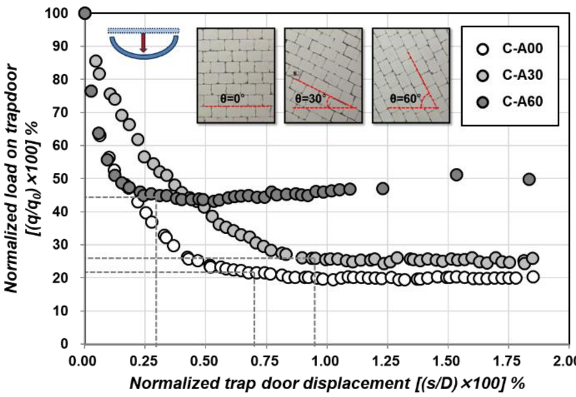
The vertical load (q) acting on the upper part of the trapdoor was measured when the door was lowered.



(a) Uniform deformation shape



(b) Convex deformation shape



(c) Concave deformation shape

Fig. 6 q-s curve

According to the trapdoor displacement ($\boldsymbol{s}$), the vertical load was expressed in a graph and normalized for comparison in each experimental case. Fig. 6 shows the load applied to the upper part of the trapdoor when it was lowered. The vertical axis represents the load ratio ($\boldsymbol{q}/\boldsymbol{q_0}$ × 100%) normalized to the initial vertical load ($\boldsymbol{q_0}$) before the trapdoor was lowered, and the horizontal axis represents the trapdoor displacement ($\boldsymbol{s}/\boldsymbol{D}$ × 100%) normalized to the trapdoor width ($\boldsymbol{D}$). Under all experimental conditions, the initial load decreased significantly to a minimum value as the trapdoor was lowered and then converged or the load increased again. The ground above the trapdoor was maximally relaxed when the load applied to the upper part of the trapdoor was at its minimum (critical point).

In addition, the displacement of the trapdoor and magnitude of the load applied to the upper part of the trapdoor, which was confirmed to be the critical point, were measured differently depending on the deformation shape of the trapdoor and the dip angle of the ground model. When the deformation shape of the trapdoor was uniform, a minor load was applied to the top of the trapdoor at a joint angle of 30°. When the deformation shape was convex, a minor load was applied to the trapdoor at a joint angle of 60°. For a concave deformation shape, the smallest load was applied to the top of the trapdoor when the joint angle was 0°.

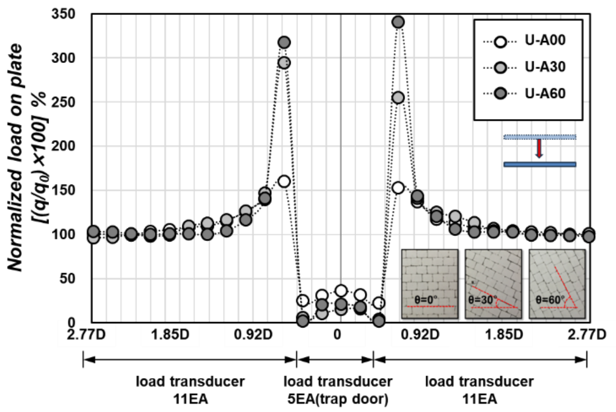
3.2 Load transfer around the trapdoor

The load transfer pattern was confirmed to vary depending on the displacement shape and joint angle. The vertical axis represents the load ratio normalized to the initial vertical load ($\boldsymbol{q}/\boldsymbol{q_0}$×100%). The horizontal axis represents the width of the model box, and the center where the trapdoor is located is indicated. When the trapdoor was lowered, the load was transferred to the surrounding ground; however, it was confirmed that there was no effect beyond a certain range (2.0$\boldsymbol{D}$). In addition, because the total load increase/decrease measured by the load transducer was confirmed to be 0, it was concluded that the model tester size did not affect the performance of the experiment.

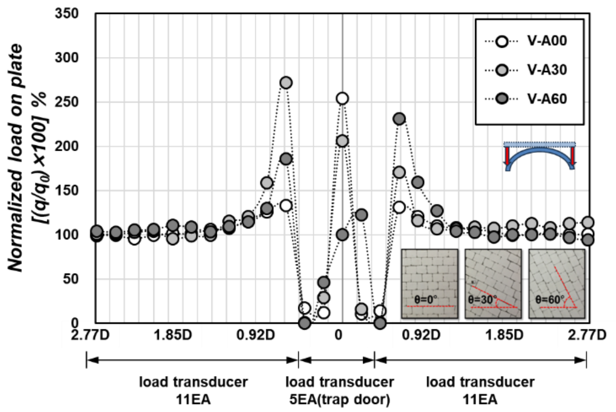
As a result of the load transfer analysis, for a uniform deformation shape, a load transfer similar to that in Terzaghi's trapdoor test occurred (Terzaghi 1943). However, when the trapdoor deformation shape was convex or concave, the load transfer pattern was different (Fig. 7). In the convex deformation shape, the load was transferred widely in the surrounding ground; however, in the concave deformation shape, the load transfer occurred locally.

3.3 Settlement on the ground surface

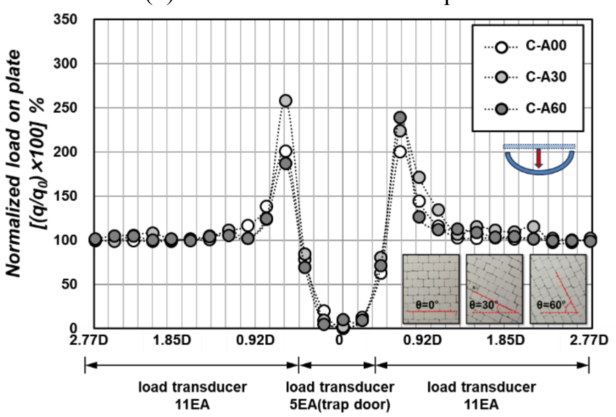
The ground model surface settlement ($\boldsymbol{s_s}$) was normalized to the surface settlement of the trapdoor displacement ($\boldsymbol{s}$) ($\boldsymbol{s_s}/\boldsymbol{s}$ × 100%) and analyzed. The LVDT measured the surface settlement and displacement of the trapdoor. Surface settlement occurred differently depending on the deformation shape of the trapdoor and the dip angle (Fig. 8). For all deformation shapes, the largest settlement occurred at the center of the surface when the joint angle was 0°; however, the maximum surface settlement occurred in different places when the dip angles were 30° and 60°. When the dip angle was 30°, the maximum surface settlement occurred in the direction of the slope (right side). When the dip angle was 60°, the maximum surface settlement occurred in the direction opposite of the slope (left side). These results were attributed to the influence of the joint friction of the concrete block. In other words, when the joint angle was 30°, shear resistance was possible owing to joint friction; however, when the joint angle was 60°, a load exceeding the friction resistance range was applied, and a relaxation area developed in the direction opposite of the slope.



(a) Uniform deformation shape

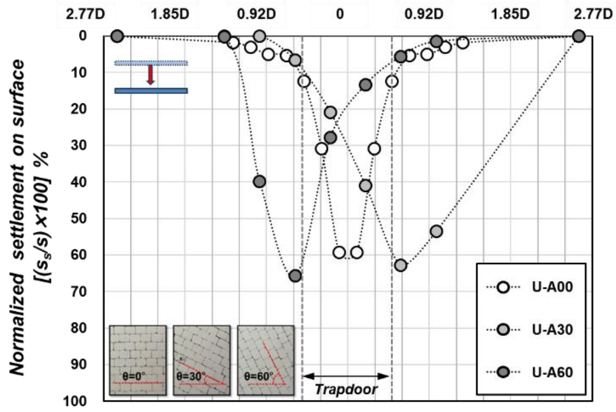


(b) Convex deformation shape

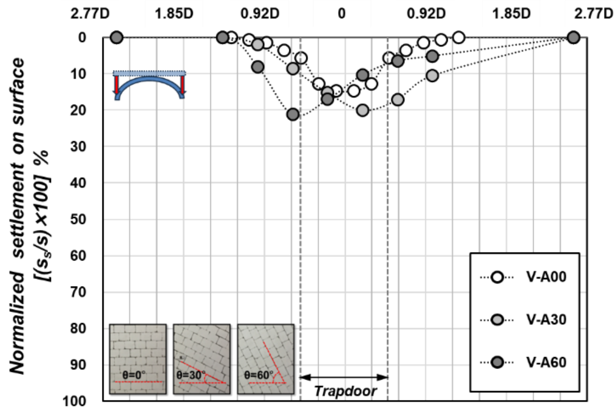


(c) Concave deformation shape

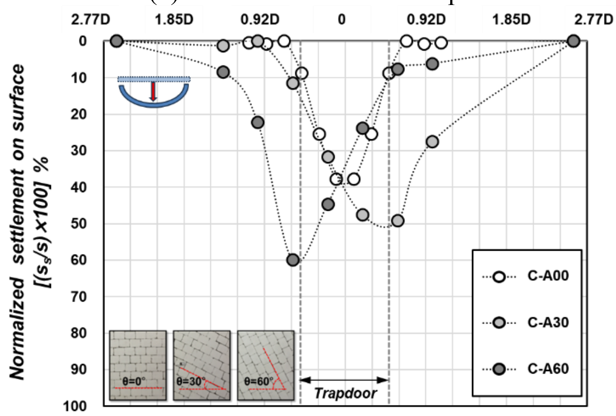
Fig. 7 Load transfer



(a) Uniform deformation shape



(b) Convex deformation shape



(c) Concave deformation shape

Fig. 8 Settlement on the ground surface

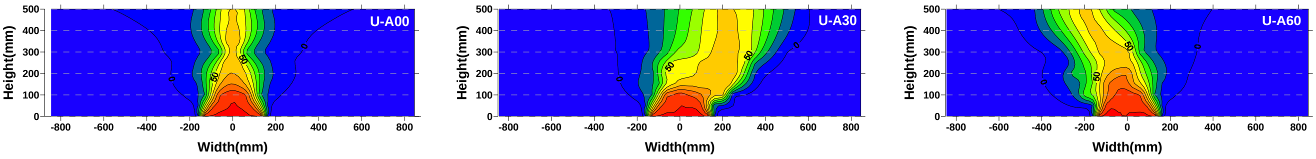
When the deformation shape of the trapdoor was uniform, the surface settlement was up to 60%–70% of the trapdoor displacement, and when the deformation occurred in a concave curve, the settlement was up 40%–60%. However, when the deformation shape of the trapdoor was a convex curve, a small settlement of approximately 15%–20% of the trapdoor displacement was observed.

The area where surface settlement occurred was wide or narrow, depending on the deformation shape of the trapdoor. When the deformation shape of the trapdoor was uniform and concave, it occurred in a narrow area. However, when deformation occurred along the convex curve, settlement occurred over a relatively wide area.

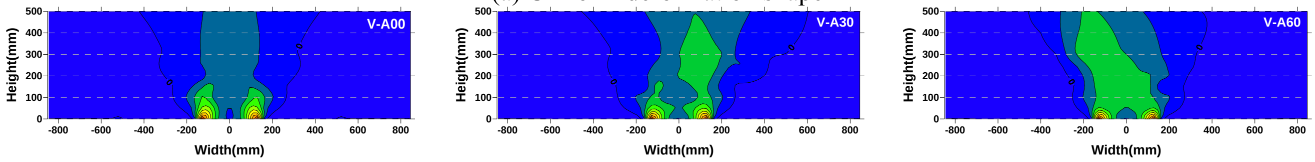
It is advantageous to have less ground displacement when excavating tunnels. However, in situations where major facilities are located in the area adjacent to the tunnel and surface settlement must be induced in a narrow area, a uniform or concave deformation shape may be advantageous.

3.4 Underground displacement

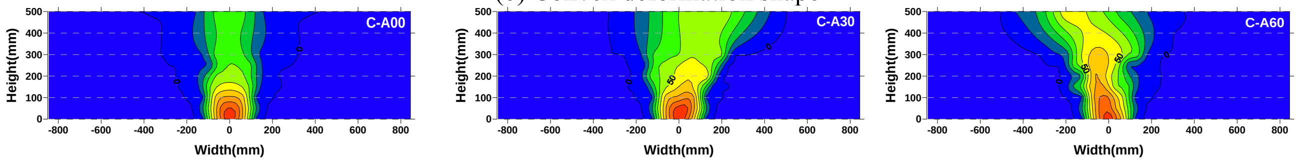
The displacement ($\boldsymbol{d_u}$) of the upper ground with respect to the trapdoor displacement ($\boldsymbol{s}$) was normalized ($\boldsymbol{d_u}/\boldsymbol{s}$ × 100%). The Surfer program was used to evaluate the data with respect to ground displacement tendency (Fig. 9).



(a) Uniform deformation shape



(b) Convex deformation shape



(c) Concave deformation shape

Fig. 9 Underground displacement

It was possible to verify the displacement tendency generated by the trapdoor that was transmitted to the upper surface. Different results were obtained depending on the trapdoor deformation shape and dip angle. When the deformation shape of the trapdoor was a uniform and concave curve, a relatively large ground displacement (50% of the trapdoor displacement) occurred; when it was a convex curve, a small ground displacement (20% of the trapdoor displacement) occurred. In addition, when deformation occurred in the form of a convex curve, displacement occurred over a wide area, whereas deformation along a concave curve occurred within a narrow area.

Based on these results, we conclude that it is safe to induce deformation in a convex curve when excavating a tunnel. However, to control the occurrence of ground displacement in a narrow area owing to structures in adjacent locations, it may be advantageous to induce displacement in the form of a concave curve. However, because relatively large stresses may be concentrated in the tunnel excavation section, sufficient tunnel reinforcement must be secured.

4. Discussion

When excavating a tunnel, the deformation shape of the tunnel top is nonlinear, mainly for various reasons such as the condition of the surrounding ground and the tunnel excavation method. Unlike the existing trapdoor test, this study manufactured a model tester to implement the deformation shape of the trapdoor as convex and concave curves and attempted to confirm the effect. In addition, this study aimed to determine the impact of the dip angle on a rock model using concrete blocks in a trapdoor test.

Analysis of the change in the load applied to top of the trapdoor when the trapdoor moved confirmed that the load decreased rapidly and then converged or increased again in all tests. However, different aspects were confirmed

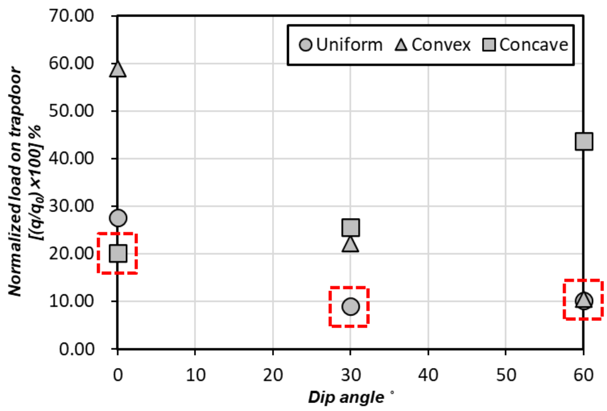
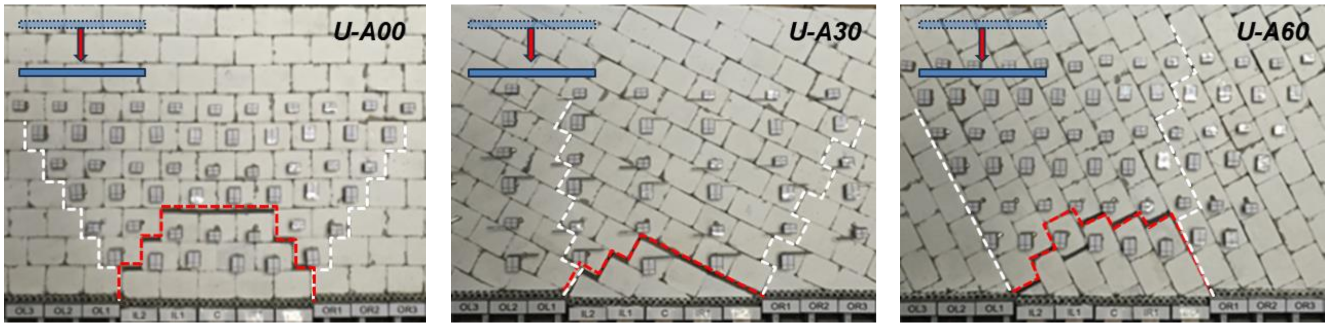


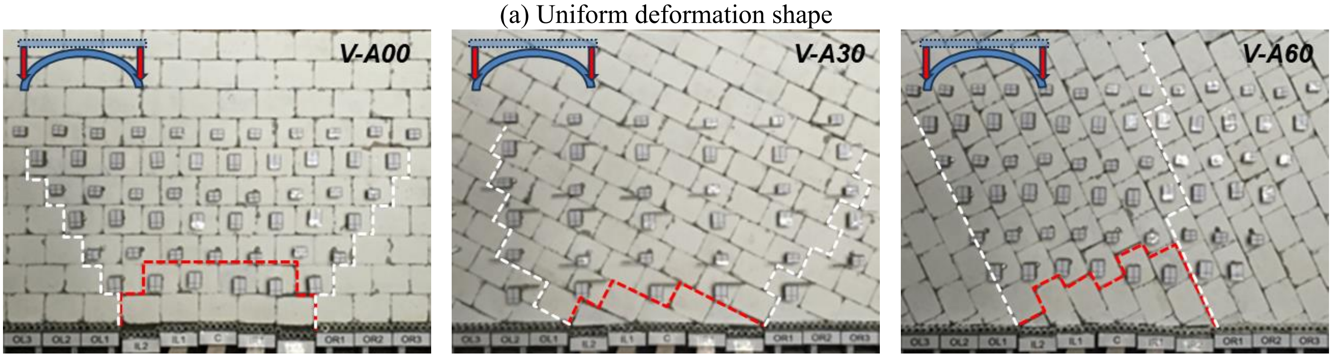
Fig. 10 Relaxation load according to the dip angle

depending on the deformation shape of the trapdoor and the dip angle.

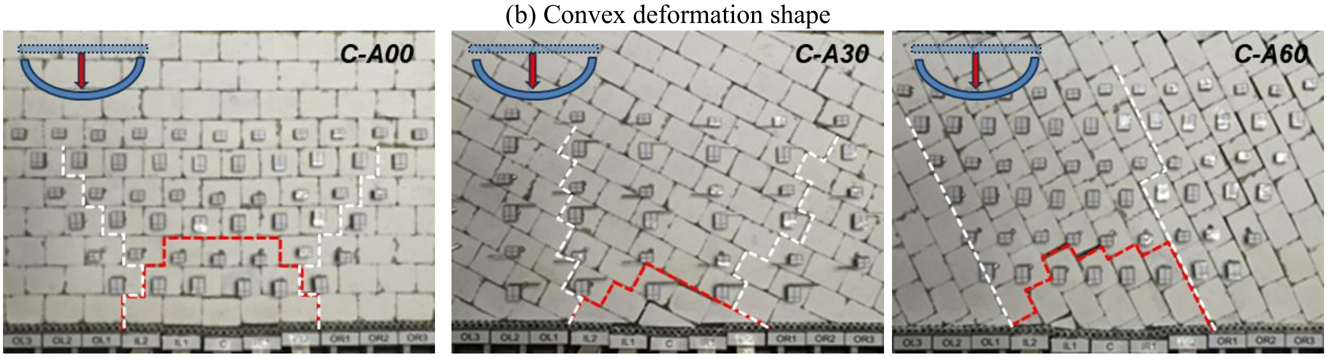
Fig. 10 shows the load value when the load applied to the top of the trapdoor converged in the load-settlement curve. When the joint angle was 0°, the load was significantly reduced when the settlement shape was a concave deformation shape. When the joint angle was 30°, the load was significantly reduced when the deformation shape was uniform. When the joint angle was 60°, the load was significantly reduced when the deformation shape was uniform, and a convex curve and different trends were observed depending on the joint angle. The significant reduction in the load applied to the top of the trapdoor can be considered a practical effect of the arching phenomenon on the surrounding ground, and regarding the results above, the deformation shape advantageous for arching can be identified depending on the joint angle. A convex deformation shape was beneficial for tunnel excavation. However, this experiment confirmed that a convex deformation shape is disadvantageous in ground where a horizontal joint (dip angle = 0°) is developed. When a convex deformation shape occurred, displacement occurred on the left and right sides of the trapdoor, and the load was



(a) Uniform deformation shape



(b) Convex deformation shape



(c) Concave deformation shape

Fig. 11 Loosened ground zone

concentrated at the center of the trapdoor. This effect was significant when the joint slope was 0°.

By checking the load transfer pattern of the ground around the trapdoor, the most significant load was found to occur at the boundary of the trapdoor when the settlement shape of the trapdoor was uniform. This is because the area where settlement occurred was the widest among the three cases. In addition, in the case of the convex deformation shape, load transfer occurred widely, whereas in the case of the concave deformation shape, it was confirmed to occur locally.

In addition, although the subsidence patterns differed, a common load transfer occurred depending on the joint slope. When the joint slope was 0°, the load transfer occurred symmetrically on both sides, whereas when the joint slope was 30°, a more significant load was transferred in the direction opposite of the slope (left side), and when the joint slope was 60°, a more substantial load was transferred in the direction of the slope (right side). This was interpreted as a result of whether the ground model could resist subsidence when divided into cases in which the joint slope was larger or smaller than the friction angle (37°) of the concrete block.

Fig. 11 is an enlarged photograph of the ground model around the trapdoor after the experiment. It can be visually confirmed that the model behaved differently depending on the trapdoor deformation shape and dip angle. When the trapdoor was lowered, the gap in the upper ground was confirmed to indicate separation in the upper ground, which formed differently for each condition (deformation shape and dip angle).

The test was conducted using concrete blocks to form the discontinuous ground. Composing a consistent ground model was challenging at the beginning of the experiment. Repeated experiments found the locations where the blocks fit well, and the concrete blocks were placed in those exact locations when creating the ground model. Unlike continuous ground, in discontinuous ground, the experimental values may differ significantly depending on the degree of interlocking; therefore, caution is essential. In addition, when linear and nonlinear displacement shapes occur, the degree of block dislodging may differ and must be considered. Linear displacement occurred in a larger area than nonlinear displacement, even with slight displacement.

Therefore, the smallest displacement was required for the load acting on the upper part of the trapdoor to converge. When the deformation shape was convex or concave, a more significant displacement was required for convergence compared with the uniform deformation shape. Because the area affected when displacement occurs may differ, this will need to be supplemented later. In addition, the experiment conducted in this study ignored the longitudinal behavior during tunnel excavation and performed a two-dimensional (2D) model experiment to analyze the transverse behavior. However, the arching effect occurs three-dimensionally on the ground, and the results differ from those analyzed in two dimensions (Chen *et al.* 2022). Therefore, if numerical analysis is used to confirm the three-dimensional behavior or a study is conducted on the tunnel excavation direction, it is expected that three-dimensional analysis will be possible by confirming the behavior of the surrounding ground in the longitudinal direction of the tunnel. Furthermore, valuable insights are expected to be obtained by analyzing the behavior of the surrounding ground during tunnel excavation under various slope-angle combinations.

5. Conclusions

In this study, a model experiment was conducted to verify the load change in the surrounding ground and the deformation behavior when nonlinear deformation occurred in a rock ground model with joints. The ground model was constructed using concrete blocks with dip angles of 0°, 30°, and 60°, and the blocks were crossed to cancel the effects of the vertical joints. In addition, a trapdoor was directly manufactured such that nonlinear trapdoor deformation could occur, and uniform, convex, and concave deformation shapes were implemented. Load transducers, LVDTs, and laser sensing were used to verify the load change and displacement occurrence behavior of the surrounding ground. When trapdoor displacement occurred, the load on the upper part of the trapdoor initially decreased significantly. Subsequently, the minimum load value was measured and converged or increased again. The load applied to the top of the trapdoor was measured differently based on the displacement shape and joint angle, and the amount of settlement at which the critical point occurred was measured differently.

The load transfer pattern was confirmed to vary depending on the displacement shape and joint angle. When the displacement shape of the trapdoor was uniform, a load transfer similar to that in Terzaghi's trapdoor test occurred. However, the load transfer pattern differed when the trapdoor deformation shape was convex or concave. In the convex deformation shape, the load transfer occurred widely in the surrounding ground; however, in the concave deformation shape, the load transfer occurred locally.

In all displacement shapes, when the joint angle was 0°, the largest settlement amount was at the center of the ground; however, when the joint angles were 30° and 60°, the maximum ground settlement occurred in different places. When the joint angle was 30°, the maximum ground subsidence occurred in the direction of the slope (right); when the joint angle was 60°, the maximum ground subsidence occurred in the direction opposite of the slope (left). These results were due to the influence of joint friction.

When the deformation shape was uniform and concave, surface settlement occurred at 40%–60% of the trapdoor displacement. However, a relatively minimal ground subsidence of about 15%–20% occurred when the shape was a convex curve.

The underground displacement was measured by laser scanning when the trapdoor was lowered. The zone of loosened ground was widest for the convex deformation shape, and the ground displacement was small. In the case of the concave deformation shape, the loosened ground zone occurred locally, and the ground displacement was significant. From the results of this experiment, it is possible to present a deformation shape that is advantageous to the arching effect according to the dip angle conditions of the joint surface of the upper ground during tunnel excavation, and to calculate the displacement required for the load to converge. In addition, it is possible to identify the zone of loosened ground in the upper ground by considering the friction angle of the rock and the dip angle of the surface during excavation.

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