

Loosening Pressure in Unsaturated Ground: Shear Bands and Soil Arching

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ABSTRACT

The influence of groundwater levels on shallow tunnel excavation mechanisms was explored by analyzing loosening pressure, shear band development, and surface settlement observed in trapdoor tests conducted in saturated and unsaturated ground. Shear bands that initiate at the trapdoor's edge extend upward in shallow overburden height and take on an arch shape in deeper overburden height, with the transitional overburden height approximately twice the trapdoor width. In this transitional overburden height, shear bands extend upward in saturated ground and form an arch-like shape in unsaturated ground, highlighting the influence of groundwater levels on shear band formation in conjunction with overburden height. Additionally, variations in shear band development influences surface settlement, with arch-shaped shear zones associated with relatively minor surface settlement. The loosening pressure, the ultimate pressure on the trapdoor, exhibited significant discrepancies attributed to groundwater level. The loosening pressure increases significantly with overburden height in saturated conditions. Conversely, in unsaturated conditions, it remains nearly constant when the groundwater level is located at the trapdoor, converging to comparatively lower values. Furthermore, the authors' proposed limit equilibrium analysis accurately assesses loosening pressure irrespective of groundwater level, with a lateral pressure coefficient between 1.0 and 1.4 deemed reasonable.

KEYWORDS

Shallow tunnel; unsaturated ground; arching effect; shear bands; surface settlement; loosening pressure.

INTRODUCTION

The loosening pressure on the crown of a tunnel after tunnel excavation is less than the overburden pressure. This phenomenon of reducing the loosening pressure indicates that the potential cost saving in construction could be achieved if the loosening pressure could be precisely evaluated. To investigate the phenomenon, Terzaghi developed the trapdoor test in 1936 (Terzaghi, 1936). It was revealed that the reduction of loosening pressure resulted from the soil arching effect. Subsequently, Terzaghi proposed a simple formula based on the limit equilibrium theory to evaluate the loosening pressure acting on a trapdoor (Terzaghi, 1943). Subsequent investigations into the trapdoor problem in fully dried soils have extensively examined aspects such as loosening pressure, failure surfaces, surface settlement, and lateral earth pressure coefficients. Numerous 2D plane strain trapdoor experiments have been performed to assess the relationship between total vertical pressure and trapdoor displacement, along with the distribution of vertical pressure on the trapdoor and shear bands under various trapdoor widths and overburden heights (e.g., Ladanyi and Hoyaux, 1969; Evans, 1984; Kikumoto, 2004). Adachi et al. (2003) conducted 3D trapdoor tests to examine the mechanical behavior of the surrounding ground during tunnel excavation, confirming that ground loosening leads to an increase in earth pressure on the lowered trapdoor. Furthermore, numerical simulations have shown that a higher overburden ratio reduces normalized loosening pressure (e.g., Koutsabeloulis and Griffiths, 1989; Liang and Xu, 2019). Tanaka and Sakai (1993) observed that the scale effect, involving the relationship between normalized loosening earth pressure and trapdoor width, was not observed in active mode during trapdoor tests and elasto-plastic finite element analysis, likely because progressive failure is less pronounced.

For the evolution of soil arching, both conventional gravity and centrifuge trapdoor tests indicated that soil arch exhibits a curved shape at the maximum arching state, transitions to a triangular shape during the intermediate state, and finally transforms into a rectangular shape at the ultimate state (e.g., Vardoulakis et al., 1981; Evans, 1984; Dewoolkar et al., 2007; Iglesia et al., 2014). Evans (1984) proposed a plasticity theory to evaluate vertical pressure within triangular shear bands by assuming that the dilation angle approaches the friction angle, consistent with the associated flow rule. Iglesia et al. (2014) developed theoretical models to predict the minimum vertical pressure for curved shear bands at maximum arch state and vertical pressure for triangular shear bands during the intermediate state. Both studies concluded that Terzaghi's theory is suitable for assessing loosening pressure at the ultimate state (Evans, 1984; Iglesia et al., 2014). Vardoulakis et al. (1981) conducted 1g small-scale trapdoor tests and developed a modified silo theory to predict vertical pressure on the trapdoor for both active and passive modes. This approach utilized the computed stress ratio (the ratio of vertical to horizontal

normal stresses) derived from a physically meaningful model of the shear band boundary. Building on Terzaghi's theory (Terzaghi, 1943), Kikumoto et al. (2003) proposed a simplified method for evaluating loosening pressure in the 3D trapdoor problem, assuming vertical shear bands. These theories highlight the importance of the lateral earth pressure coefficient, K , in assessing loosening pressure. For 2D trapdoor problems, K -values are expected to vary depending on the soil properties. Terzaghi (1943) empirically recommended $K = 1.0$ for loosening pressure evaluation, while Evans (1984) suggested $K = 1.2$ for maximum arching at transitional state and $K = 0.8$ for the ultimate state, equivalent to the loosening pressure investigated in this study. Chevalier et al. (2012) found that K -values range from 1.1 to 1.3 for sands and up to 1.4 for gravels in their 2D DEM simulations, depending on particle size distribution and overburden height. Meanwhile, da Silva Burke and Elshafie (2021) developed a limit equilibrium framework considering principal stress rotation to calculate K -values in active arching scenarios. For 3D trapdoor problems, a higher K -value, typically around $K = 2.0$, is recommended (e.g., Adachi et al., 2003; Kikumoto et al., 2003). Zhang et al. (2023) proposed an analytical model to evaluate the ground reaction curve (the relationship between the load on the trapdoor and the resulting displacement), although it involves many complex parameters, making it challenging to apply.

Additionally, research has delved into surface settlement and failure mechanisms. Nakai et al. (1997) conducted both 2D and 3D model tests under 1g in Toyoura sand and Kaolin clay ground, respectively. It was revealed that the maximum surface settlement in the 3D test in the sand was slightly smaller than that of the 2D test. In contrast, the 3D test in clay was larger than that of the 2D test. Shear band formation was affected by various factors such as overburden ratio, stress level, soil particle size, and dilatancy behavior (e.g., Stone and Wood, 1992; Dewoolkar et al., 2007; Costa et al., 2009). Murakami et al. (1997) explored shear band formation with a small increment of trapdoor displacement ($\Delta\delta = 0.2$ mm) through DEM simulation considering the rolling friction, in which shear bands were visualized as the pattern of dislocation lines. It was revealed that the shear bands were gradually formed with trapdoor displacement, and particle rotation was concentrated in the zone of shear bands. Dewoolkar et al. (2007) reported that straight shear bands at the trapdoor edge were observed in 1g model tests, while curved shear bands emerged in 75g centrifuge tests, evidencing the influence of stress level on shear band formation. Costa et al. (2009) explored the failure mechanism of a deep trapdoor problem through trapdoor tests under 1g and 45g. Experiment results showed that multiple failure surfaces were developed in shallow conditions ($H/B \leq 2.0$), and a single internal failure surface gradually became inclined to the vertical in deep conditions ($H/B > 2.0$). Liang et al. (2020) explored the relationship between the failure mechanism and

loosening pressure through the trapdoor test under 1g condition, highlighting vertical slip surfaces corresponding to residual loosening pressure and triangular slip surfaces observed at minimum loosening pressure.

In practice, the ground often exists in a partially saturated state. However, there is limited research on trapdoor tests under unsaturated conditions. Jacobsz (2016) conducted trapdoor tests under 50g, investigating cavity mechanisms in loose and dense sand under dry and moist conditions, respectively. He indicated that a small amount of matric suction in moist dense Cullinan sand was sufficient to vertically propagate the influence zone, without measuring suction and considering the variation of suction on the propagation of the cavity. Song et al. (2018) carried out trapdoor tests on unsaturated sand ground to explore loosening pressure acting on a trapdoor and sand displacement at various groundwater levels. However, the ground was somewhat disturbed due to the apparatus design flaws, and information regarding the distribution of earth pressure, failure mechanisms, and surface settlement was lacking. Fang et al. (2020) proposed a simple theory for evaluating loosening pressure in unsaturated ground (unsaturated trapdoor theory), which was validated by Terzaghi's theory (1943) as the ground was assumed to be fully dried or fully saturated. The trapdoor problem in the unsaturated ground is illustrated in Fig. 1; based on the limit equilibrium theory, soil water characteristic curve (van Genuchten, 1980), Bishop effective stress (Bishop, 1959), and Mohr-Coulomb failure criteria, the governing differential equation can be written as

$$\frac{d\sigma_z(z)}{dz} = \frac{\rho_s + eS_r(z)\rho_w}{1 + e}g - \frac{2}{B}K[\sigma_z(z) - u_a + S_r(z)\rho_w g(H - H_w - z)]\tan\phi \quad (1)$$

where σ_z is the loosening pressure at the depth of z ; g is the gravitational acceleration; B is the trapdoor width; H is the overburden height; H_w is the groundwater level, defined as the distance from the trapdoor to the groundwater table; the coefficient K is the ratio of effective horizontal stress to effective vertical stress for the infinitesimal soil element above the trapdoor (as depicted in Fig. 1); u_a is pore air pressure, which is assumed to be zero; ρ_s is solid density; ρ_w is the density of water; e is the void ratio, ϕ is the internal friction angle; $S_r(z)$ is the degree of saturation at the depth of z . Then, the loosening pressure, $\sigma_z(z)$, was derived by solving differential equation (1) under the boundary condition that $\sigma_z(0) = 0$ kPa. Then, a simple, explicit numerical scheme with incremental depth Δz was applied to evaluate the loosening pressure as follows.

$$\sigma_z(z + \Delta z) - \sigma_z(z) = \frac{d\sigma_z}{dz} \Delta z \quad (2)$$

However, the experimental results are needed to assess the performance of the proposed limit equilibrium theory (Fang et al., 2020), particularly given the partially saturated nature of the ground. Therefore, conducting trapdoor tests in unsaturated ground would be valuable for further validation.

In this study, trapdoor tests were conducted on partially saturated ground to assess the effect of groundwater level on loosening pressures impacting tunnels. The movement of the surrounding ground, shear bands, and surface settlements were analyzed to determine the effects of varying groundwater levels, trapdoor widths, and overburden ratios on shear band formation and the arching effect. The configuration of shear bands was specifically discussed to verify the hypothesis of vertically oriented shear bands proposed in the theory by Fang et al. (2020). Additionally, suction profiles derived from the experiments were evaluated to validate the linear suction profile, another hypothesis of the same theory. Furthermore, the experimentally measured loosening pressures were compared with those predicted by the previously established limit equilibrium theory (Fang et al., 2020) to confirm its accuracy and reliability.

OUTLINE OF THE TRAPDOOR TEST

Apparatus

The trapdoor apparatus, depicted in Fig. 2, has been enhanced in this study to accommodate unsaturated ground with varying groundwater levels. This apparatus was modified based on the trapdoor for dry sand designed by Kuwano and Ebizuka (2010). The sealing mechanisms were added at several points to create a more waterproof apparatus. Modification enabled experiments to be conducted at any desired groundwater level. The dimensions of the soil chamber are 80.5 cm x 30.5 cm x 60.0 cm. The bottom of the soil chamber consists of five independent moveable aluminum boxes (a, b, c, d, e) and two fixed bottom plates. A sponge belt is positioned between the aluminum boxes, the front and rear walls, and between the fixing plate and the walls to prevent the sand from falling into the lower area. Two water supply tanks are situated on both sides of the chamber, and the perforated acrylic plate containing a metal netting strainer acts as a partition between the soil chamber and the water tanks. Water flows into or out of the soil chamber through the two perforated acrylic plates, sponge belts, and the gaps between aluminum boxes.

Given the five aluminum boxes at the bottom of the soil chamber, any aluminum box can serve as trapdoors. The width of the trapdoor is adjustable by selecting different combinations of these boxes. For example, for a trapdoor width of 10 cm, aluminum box 'c' is used, while for a width of 20 cm, boxes 'b' and 'c' are combined. The trapdoor is operated by a control jack, and its movement is measured with a contact displacement meter. The remaining aluminum boxes (a, b, d, e for trapdoor width 10 cm, and a, d, e for trapdoor width 20 cm) are fixed by the upper clamps, and those fixed aluminum boxes and the two fixed plates serve as stationary supports (Mahdi et al., 2017).

The distribution of earth pressure acting on the trapdoor and surrounding ground is measured during the trapdoor lowering process. The setup of the load cells (capacity of 86 kPa, resolution of 0.03 kPa) used for this measurement is shown in Figure 2(c). Considering that the trapdoor test is conducted in both saturated and unsaturated ground, waterproofing measures for the aluminum boxes are crucial to protect the enclosed load cells. The detailed configuration of a single aluminum box is presented in Fig. 3. Each aluminum box is equipped with five independent load cells, covered with a membrane and a fixed lid. These load cells are connected to a data logger (Tokyo Measuring Instruments Lab., TDS-302) and a computer, which continuously collects the pressure acting on the aluminum boxes. The coefficients of the load cells were determined using water pressures before each experiment. To minimize the thermal effects on the measurements, the experiment was conducted under a constant room temperature of 20 °C.

Suction profile, surface settlement, and ground deformation were investigated in this study. Suction and water pressure at any given depth can be measured using suction sensors (KYOWA, Model: PGM-02KG; capacity: 20 kPa, resolution: 0.013 kPa). The suction sensor was developed by attaching a ceramic connector to a water pressure gauge, as shown in Fig. 2(d). Both the interior of the ceramic connector (surrounding the pressure sensor) and the ceramic material itself were saturated with water prior to the experiment. The ceramic material has an air entry value higher than the suction levels anticipated in the model experiments. Therefore, this device enables the measurement of both suction in the unsaturated layer and water pressure in the saturated layer. Prior to use, the ceramic connector was saturated under a negative air pressure of -98 kPa for 24 hours. Surface settlement was mapped using a ground surface profiling system, which includes laser displacement scanners X and Z (e.g., Adachi et al., 2003; Kikumoto, 2004), as depicted in Fig. 2(a). The profiling system was mounted on a pair of independent beams above the soil chamber to prevent any vibrations caused by the movement of laser displacement scanner Z from affecting the load cells. Shear bands were analyzed using the Particle Image Velocimetry (PIV) technique, with a high-resolution camera positioned in front of the apparatus to collect images.

The generation of unsaturated ground

The process of generating unsaturated ground is illustrated in Fig. 4. To reduce friction between the inner wall of the soil chamber and the surrounding ground, the inner wall was coated with Teflon lubricant (e.g., Hossain et al., 2013). The effectiveness of Teflon lubricant in reducing friction between the side wall and sand has been previously reported (e.g., Zheng et al., 2021; Tatsuoka and Haibara, 1985). After allowing approximately 15 minutes for the Teflon to dry, water was alternately introduced into and drained from the soil chamber through the two valves. Load cell readings were recorded as the water table height was adjusted to 0 cm, 10 cm, 20 cm, 30

cm, and 40 cm, with a total of 10 data points collected for each load cell. These readings were then used to determine the coefficients of the load cells based on static pressures.

Following this, the experimental procedure to generate unsaturated ground began. The saturated ground was prepared using the water pluviation method, and the water was drained to the specified groundwater level. Initially, water was introduced into the soil chamber via two valves until the water level reached 15 cm above the chamber's base, as shown in Fig. 4(a). The valves were then closed, and a suction sensor was positioned at the bottom near the left edge to reduce its impact on earth pressure measurements. The suction sensors in the saturated zone measured pore water pressure, and the primary purpose of installing a sensor at the base of the apparatus was to verify that the hydrostatic pressure at this height aligns with the theoretical hydrostatic pressure determined by the groundwater level set during the experiment. The sand layers were deposited using the water pluviation method. The sand was passed through a sieve just below the water surface to ensure uniform ground condition. Since the ground was generated with multiple layers, an individual layer height, H_1 , was determined based on the desired overburden height, H . When the desired overburden height was 20 cm or greater, the height of each layer was set to 10 cm; otherwise, it was set to half of the desired overburden height. After completing each layer, a suction sensor was buried in the ground, and additional water was introduced into the chamber through the valves to raise the water table to (H_1+15) cm. This maintained a consistent 15 cm distance between the water table and the ground surface. It ensured that the sand was always deposited from the same height, resulting in uniform dry density throughout the ground. Once the desired overburden height, H , was reached, the saturated ground was created with the water table at a height of $(H+15)$ cm, and a minimum of three suction sensors were positioned in the ground, as shown in Fig. 4(c). To create unsaturated conditions, the water table was then lowered from the fully saturated state, allowing water to drain gradually through the valves until the desired groundwater level, H_w , was reached, as depicted in Fig. 4(d).

Photographing and surface settlement measurement

The trapdoor test was performed by gradually lowering the trapdoor using the control jack. The displacement of the trapdoor was monitored using a contact displacement meter with a range of 10.0 mm and a resolution of 0.01 mm. Initially, the laser displacement scanner Z was moved from right to left to profile the ground surface (e.g., Adachi et al., 2003; Kikumoto, 2004). A photograph was taken from the front of the soil chamber by the fixed high-resolution digital camera. Then, the trapdoor was incrementally lowered by 1.0 mm intervals until reaching the maximum displacement of 5.0 mm, with the laser displacement scanner Z scanning the ground surface at 1.0 mm intervals. Simultaneously, a photograph was retaken using the fixed camera.

Soil properties and parameters determination

In this experiment, the saturated and unsaturated ground were modeled using Toyoura sand. The specific gravity of Toyoura sand is 2.66 g/cm^3 , and the maximum and minimum densities are 1.65 and 1.33 g/cm^3 , respectively (Wu et al., 2013). The dry density of Toyoura sand was measured directly. After a trapdoor test was completed, the wet sand was dried in a drying furnace and weighed to get the mass M_s ; then, the dry density was identified using the formula $\rho_d = M_s / (A \cdot H)$, where A is the bottom area of the soil chamber. In this study, the dry density was found to be 1.57 g/cm^3 , corresponding to a relative density of 79.5% . Additionally, the saturated and submerged densities of the sand were 1.98 g/cm^3 and 0.98 g/cm^3 , respectively.

The suction profile is measured using the suction sensors. Then, the degree of saturation is determined using the soil water characteristic curve (SWCC). In the limit equilibrium theory (Fang et al., 2020), the van Genuchten equation (1980) is used to evaluate the degree of saturation, expressed as

$$S_r = (S_{max} - S_{min})\{1 + (\alpha s)^n\}^{-m} + S_{min} \quad (3)$$

where $\langle \rangle$ denotes Macaulay brackets; S_{max} and S_{min} are the maximum and minimum degrees of saturation, respectively, and α , m , and n are material parameters. S_{min} , α , m , and n are unknown parameters.

The relationship between the degree of saturation and suction for Toyoura sand has been experimentally determined by Unno et al. (2008). Then, the parameters of S_{min} , α , m , and n were determined through the best fitting of the experimental result, as shown in Fig. 5. The corresponding parameters are listed in Table 1. Additionally, the critical state friction angle ϕ for fully saturated sand was determined to be 33.7° based on direct shear tests.

Test patterns

The overburden ratio was set to values no larger than 2 for the trapdoor problem under shallow conditions (e.g., McNulty, 1965; Evans, 1984; Koutsabeloulis and Griffiths, 1989). Therefore, for the trapdoor test conducted under saturated and unsaturated conditions, the overburden ratio was set to 0.5, 1.0, 1.5, and 2.0. In addition, two different widths of the trapdoor, 10 cm, and 20 cm, were employed. For each overburden ratio and the trapdoor width, various trapdoor tests under the different groundwater level were also carried out to explore the impact of groundwater levels on loosening pressure, shear bands, and surface settlement. The specific test patterns are summarized in Fig. 18.

Profiles of suction and saturation degree

In order to investigate the suction profile of unsaturated ground, at least three suction sensors were positioned vertically at intervals of H_1 to measure the pore water pressure at different depths of the ground, as shown in Fig. 4(d). The distribution of the pore water pressure and the suction profile for different trapdoor widths ($B = 10$ cm, 20 cm) and groundwater levels ($H_w = 0.0H, 0.5H$) are illustrated in Figs. 6 and 7. The profiles of pore water pressure under different groundwater levels were found to be linear and in agreement with theoretical predictions ($u_w = \rho_w g (z + H_w - H)$). Pore air pressure was assumed to be zero, as its effect was considered negligible (e.g., Pufahl et al., 1983; Vahedifard et al., 2016; Sahoo et al., 2018). According to the definition of suction ($s = < u_a - u_w >$), the profiles of suction in the unsaturated zone were linear, as shown in Figs. 6(b) and 7(b). This observation corroborated the assumption of the linear suction profile in the previously proposed limit equilibrium theory (Fang et al., 2020). Additionally, the degree of saturation S_r is determined based on the van Genuchten equation of Toyoura sand, and the profiles of the degree of saturation are shown in Fig. 6(c) and 7(c).

RESULTS AND DISCUSSION

Shear band formation

Shear band formation was visualized through deviatoric strain based on the Particle Image velocimetry (PIV) technique in this study (Shahin et al., 2006; Shahin et al., 2011). The displacement of the ground mesh resulting from trapdoor movement was analyzed using photos taken at the front of the soil chamber using the commercial PIV software Flownizer (DITECT). Then, the strain tensor $\boldsymbol{\varepsilon}$ ($\boldsymbol{\varepsilon} = \mathbf{B}_m : \mathbf{u}$) was calculated based on the displacement $\mathbf{u}$ and the strain-displacement tensor $\mathbf{B}_m$. The deviatoric strain was calculated through the components of the strain tensor, which can be written as follows.

$$\varepsilon_d = \frac{2}{3} \sqrt{\varepsilon_x^2 + \varepsilon_y^2 + 3 \left(\frac{\gamma_{xy}}{2} \right)^2 - \varepsilon_x \varepsilon_y} \quad (4)$$

where ε_d is the deviatoric strain; ε_x is strain in horizontal direction; ε_y is strain in the vertical direction; $\gamma_{xy} (= 2\varepsilon_{xy})$ is the engineering shear strain.

The evolution of shear bands with trapdoor displacement is illustrated in Fig. 8. Herein, the trapdoor width is 10 cm, the overburden height is $2.0B$, and the groundwater level varies at $0.0H$, $0.5H$, and $1.0H$. Figure 8 demonstrates that the shear bands for all cases are developed at the edge of the trapdoor in the early stage of trapdoor displacement ($\delta = 1.0$ mm). A curved inner shear band appears along the edge of the trapdoor, especially when the groundwater level is $0.0H$. These relatively vague shear bands become more apparent as the normalized trapdoor displacement increases. When the trapdoor displacement increases to 2.0 mm ($0.02B$), the shear bands

vertically in the saturated ground ($H_w = 1.0H$) extend to the ground surface. In contrast, under unsaturated conditions ($H_w = 0.0H, 0.5H$), the outer shear bands develop vertically near the trapdoor, subsequently extending obliquely toward the trapdoor center near the ground surface. The inclination of the inner shear band is influenced by factors such as overburden height and trapdoor scale. The measured inclination angles are 11.6° for $H_w = 0.5$ and 20.8° for $H_w = 0.0H$, as shown in Fig. 8. These values deviate from predictions based on existing theories, such as the friction angle ($\phi = 33.7^\circ$) (e.g., Iglesia et al., 2014), the angle of dilation (e.g., Dewoolkar et al., 2007), or $45^\circ - \phi/2$ (e.g., da Silva Burke and Elshafie, 2021b). This discrepancy highlights the limitations of these theories in capturing the effects of overburden height and trapdoor scale, which are significant in the context of this study.

Regardless of the shear band configuration, load transfer occurs due to the upward shear stress along the shear bands acting on the soil above the trapdoor. At the same time, the inner shear band further forms an arch-like shape. When the inner arch-like shape of the shear band develops, the load is transferred due to the reoriented major principal stress (e.g., Chevalier et al., 2012; da Silva Burke and Elshafie, 2021b; George and Dasaka, 2023). This stress reorientation stabilizes the ground above it during trapdoor descent, indicating the formation of a soil arch above the trapdoor. The shape of the shear bands remains unchanged until the trapdoor displacement reaches 5.0 mm ($0.05B$), indicating that the shear bands correspond the ultimate state. While the shear bands become thicker with increasing trapdoor displacement, this thickening is attributed to the larger deviatoric strain caused by the increased trapdoor displacement.

To clearly illustrate the shear bands at the ultimate state, shear bands corresponding to the trapdoor displacement of 5.0 mm are presented for different trapdoor widths, overburden heights, and groundwater levels, as depicted in Figs. 9 and 10. In these cases, the trapdoor widths are 10 cm and 20 cm, with corresponding overburden heights of $0.5B$, $1.0B$, $1.5B$, and $2.0B$, while the groundwater level varies at $0.0H$, $0.5H$, and $1.0H$. Figs. 9 and 10 display certain anomalies, such as the line appearing near the surface in Fig. 10 (b). This anomaly arises because, as the trapdoor descends, parts of the calculation grid near the ground surface lose sand particles, causing displacement identification errors at the top nodes of the mesh. These anomalies are localized and do not affect the overall conclusions of the study. Additionally, the shear bands for $B = 20$ cm, $H = 1.0B$, $H_w = 0.0H$, $0.5H$, and $1.0H$ are not included in Fig. 10 as the image analysis was skipped for some cases due to the low resolution of the images.

When the overburden height doesn't exceed $1.0B$, as shown in Fig. 9(a) and Fig. 10(a), the shear bands extend slightly inclined towards the ground surface under various trapdoor widths and groundwater levels, revealing similar failure planes under both saturated and unsaturated conditions. These results suggest that the

soil arch at the maximum arching stage cannot be sustained with increasing trapdoor displacement because the limited overburden height for a fully developed arch is 1.5-2.0 times the trapdoor width (e.g., Terzaghi, 1943; Iglesia et al., 2014). Additionally, in this shallow ground ($H = 1.0B$), load transfer occurs due to the upward shear stress along the shear bands acting on the soil above the trapdoor. Additionally, when the overburden height is $1.5B$, the shear bands become more inclined at lower groundwater levels, as shown in Fig. 9(b). This observation suggests that the groundwater level plays a significant role in the formation of shear bands.

In the case of an overburden height of $2.0B$ with a trapdoor width of 20 cm, the effect of groundwater level on shear bands is more distinct, as illustrated in Fig. 10(b). Under saturated conditions ($H_w = 1.0H$), shear bands develop vertically at the trapdoor edges and gradually incline towards the trapdoor due to dilation, as the confining pressure decreases further in the ground above the trapdoor. In unsaturated conditions ($H_w = 0.0H, 0.5H$), multiple shear bands form. An inner arch-like shear band forms across the trapdoor, suggesting the formation of a soil arch above it. The outer shear bands propagate from the trapdoor edges, extending slightly inclined toward the surface. At $H_w = 0.5H$, these outer shear bands reach closer to the surface, while they stop short of the ground surface when $H_w = 0.0H$. A notable fault is observed near the ground surface when $H_w = 0.0H$, indicating the development of a new soil arch above it. These observations imply that the groundwater level has a clear influence on the shear band formation.

Consequently, Figs. 8, 9, and 10 reveal that shear bands initially develop at the trapdoor edge. In the case of the shallow overburden height ($H = 1.0B$), these shear bands extend to the ground surface without forming an arch-like shape, leading to relatively higher loosening pressure and increased surface settlement. In contrast, in the case of deeper overburden height ($H = 1.5B, 2.0B$), the shear bands exhibit greater inclination with a lower groundwater level. Moreover, an inner arch-like shear band appears as the overburden height is $2.0B$, indicating the formation of a soil arch above the trapdoor, which results in lower loosening pressure and reduced surface settlement. These findings suggest that the transitional overburden height is approximately $2.0B$, while also highlighting the combined influence of groundwater levels and overburden height on shear band formation. Additionally, the outer shear bands are unable to propagate to the ground surface when the unsaturated zone is more pronounced, potentially leading to the formation of faults due to significant suction. This fault indicates that a stable soil arch is formed above it, resulting in a remarkable reduction in surface settlement. These findings indicate that the assumption of the vertical sliding surfaces for simplicity in the limit equilibrium theory (Fang et al., 2020) is reasonable because the outer shear bands display only a slight inclination.

Surface settlement

The stability at the shallow tunnel face is an important index to assess tunnel collapse (e.g., Soranzo et al., 2015), and the surface settlement should be strictly restrained. Therefore, the surface settlement normalized by the applied trapdoor displacement in both saturated and unsaturated ground is explored in this section. At a trapdoor displacement of $0.02B$, the normalized surface settlement profiles under different overburden heights and groundwater levels are shown in Fig. 11.

When the overburden height is no larger than 20 cm, the impact of groundwater level on the normalized surface settlement profiles cannot be observed regardless of trapdoor width, as illustrated in Fig. 11(a), (b), (c). However, with a trapdoor width of 20 cm and an overburden height of $2.0B$, the normalized surface settlement profiles shift upward as the groundwater level lowers, as seen in Fig. 11(d). Additionally, Fig. 11 demonstrates that the normalized surface settlement profiles rise with a higher normalized overburden height, irrespective of trapdoor width, suggesting that the normalized overburden height significantly affects surface settlement. To further investigate these findings, the normalized maximum surface settlement is defined to investigate the effects of trapdoor width and groundwater level on surface settlement, as shown in Fig. 12.

Figure 12 shows that the normalized maximum surface settlement approached a value of 1.0 when the normalized overburden height is no larger than $1.0B$, regardless of trapdoor width and groundwater level. This occurs because the funnel-type shear bands are observed in this shallow overburden height ($H \leq 1.0B$), as evidenced by Figs. 9(a) and 10(a), thus the soil mass above the trapdoor collapses and descends with the trapdoor. In contrast, the normalized maximum surface settlement becomes smaller with a higher overburden height ($H > 1.0B$), irrespective of groundwater levels, due to the inclined shear bands. Additionally, an inner arch-like shape shear band forms, particularly when the overburden height is $2.0B$, as depicted in Fig. 9(b) and 10(b), leading to further reduction of surface settlement. Notably, the groundwater level has a substantial impact only when the trapdoor width is 20 cm and the overburden height is $2.0B$. This mechanism can be explained by the SWCC of the ground material, as shown in Fig. 7. When the thickness of the unsaturated layer is less than 20 cm (corresponding to a suction of 2 kPa at the ground surface), there is minimal change in the degree of saturation across the unsaturated layer. However, as the unsaturated layer thickness increases to 40 cm (corresponding to a suction of 4 kPa at the ground surface), a significant variation in the degree of saturation occurs, which significantly affects the shear band formation, as depicted in Fig. 10(b). A soil arch forms above the fault as the groundwater level is $0.0H$, resulting in a considerably smaller maximum surface settlement. In a word, these findings suggest that surface settlement is influenced by both overburden height and groundwater level.

These results indicate that the scaling effects of the SWCC should be considered in laboratory experiments for unsaturated ground. For instance, when performing model tests on a ground structure intended for construction on sandy soil, it is necessary to scale down the SWCC to create a distinct unsaturated zone within the model ground. One approach to achieve this is employing coarser particles than the actual soil, thereby accentuating the variations in the SWCC.

Impact of groundwater level on total pressure distribution

The distribution of total pressure under groundwater levels of $0.0H$, $0.5H$, and $1.0H$, for the overburden height of $2.0B$ and the trapdoor width of 10 cm is presented in Fig. 13. The initial pressure, σ_{z0} , under different groundwater levels is also provided in Fig. 13. The total pressure is normalized by initial pressure to mitigate its influence on the distribution of total pressure. In all cases, despite the groundwater level, as the trapdoor is lowered, the soil zone can be divided into two zones based on the changing property of the total pressure: the active zone and the stationary zone. The figure shows that the total pressure acting on the trapdoor is reduced compared to its initial value and gradually diminishes from the center of the trapdoor towards its end. This region has been designated as the "active zone" in this study. In contrast, in the stationary zone (i.e., the soil zone above the stationary support), the total pressure at the end of the trapdoor is larger than the initial pressure. It gradually decreases to initial pressure when moving away from the trapdoor. This clearly shows the transfer of earth pressure from the active zone to the stationary zone due to the soil arching effect. For different groundwater levels, the figure indicates that the total pressure acting on the active zone becomes smaller for lower groundwater levels. Moreover, for the saturated case ($H_w = 1.0H$), the total pressure shows almost the same value when the trapdoor displacement is 0.2 and 2.0 mm, whereas there is a significant difference for unsaturated ground ($H_w = 0.0H, 0.5H$).

Figs. 14 and 15 illustrate the variation in the normalized total and effective pressures acting on the trapdoor as the normalized trapdoor displacement increases under different trapdoor widths, overburden heights, and groundwater levels. Trapdoor widths are 10 cm and 20 cm, while the normalized overburden heights are $0.5B$, $1.0B$, $1.5B$, and $2.0B$. The total and effective pressures exerted on the trapdoor are normalized by the initial total pressure ($\rho_{sat}gH$) and effective pressure ($\rho_{sub}gH$) of saturated soil at the same overburden height. Similarly, the trapdoor displacement is normalized with respect to the trapdoor width. The normalization of pressures facilitates direct comparisons of pressure variations across cases with different groundwater levels and provides an intuitive understanding of changes relative to initial pressures in saturated conditions. To ensure clarity, the initial pressures used for normalization are annotated in the figures. For saturated soil, the initial normalized total and effective pressures in saturated soil are approximately 1.0, reflecting minor fluctuations in experimental results. In contrast,

the normalized initial effective pressure in unsaturated soil is higher due to the contribution of suction, which increases the effective pressure.

The figures show a significant and rapid reduction in the normalized total and effective pressures as the trapdoor is lowered during the initial stage of the experiment. The normalized trapdoor displacement corresponding to the initial stage is $0.005B$, irrespective of trapdoor width, overburden height, and groundwater level. As the normalized trapdoor displacement increases to $0.01B$, the normalized total and effective pressures decrease slowly to a minimum, indicating a full soil arch or maximum soil arch develops above the trapdoor. With further increases in the normalized trapdoor displacement, the normalized total and effective pressures slightly increase as the normalized overburden height is $0.5B$ ($B = 20$ cm) and $1.0B$ ($B = 10$ cm), as shown in Fig. 14(a) and 15(a). This increase occurs because the soil arch cannot be sustained at this shallow overburden height (e.g., Terzaghi, 1943; Iglesia et al., 2014); the failure zone expands, and the angle of shear bands to the vertical decreases, resulting in increased soil mass supported by the trapdoor. When the trapdoor width is 20 cm and the overburden height is $1.0B$, the normalized total and effective pressures nearly remain consistent, suggesting that the ground reaction curve might be influenced by trapdoor width, as presented in Fig. 15(b). Conversely, as the normalized overburden height is $1.5B$ and $2.0B$, the normalized total and effective pressures remain constant, as depicted in Figs. 14(b), 14(c), and 15(c). This finding indicates that the soil arch stabilizes at the maximum soil arch stage and transitions to the ultimate state, likely due to the low stress level associated with the 1g small-scale test. Therefore, in this study, the total and effective pressures at the displacement of $0.02B$ are defined as the total and effective loosening pressures, respectively.

Additionally, the normalized total and effective pressures at a specific normalized trapdoor displacement vary with different groundwater levels. The normalized total pressure significantly decreases with a lower groundwater level, since the upward shear stress along shear bands becomes larger due to the larger suction. The normalized effective pressure in the saturated ground ($H_w = 1.0H$) is lower than that in the unsaturated ground ($H_w = 0.0H$) in most cases, except when the trapdoor width is 20 cm and the corresponding overburden height is $2.0B$, as shown in Figs. 14, 15(a), and Fig. 15(b). When the trapdoor width is 20 cm and the overburden height is $2.0B$, the normalized effective pressure becomes consistent with a lower groundwater level, because the unsaturated zone is more pronounced, as depicted in Fig. 15(c). These results highlight that the groundwater level influences the normalized total pressure and effective pressures, and the unsaturated state of the ground should be considered in the trapdoor test.

To further investigate the effect of the groundwater level on total and effective loosening pressures, the relationship between the experimental total and effective loosening pressures and the groundwater level is summarized, and the limit equilibrium theory (Fang et al., 2020) is also employed to investigate it. Regarding the application of the limit equilibrium theory (Fang et al., 2020), the determination of dry density, internal friction angle, and parameters of the SWCC was previously discussed above. Another crucial parameter in the limit equilibrium theory was the lateral earth pressure coefficient K . The K -value is expected to vary depending on soil properties and overburden height. Terzaghi (1943) empirically proposed $K = 1.0$ for loosening pressure evaluation, and Kikumoto (2004) confirmed its validity through experiments. Evans (1984) suggested $K = 0.8$ for predicting ultimate pressures on trapdoors, while Chevalier et al. (2012) found K -value ranging from 1.1 to 1.4 through 2D DEM simulations, depending on particle size distribution and overburden height. Despite discrepancies, these studies generally indicate that K -values at the limit equilibrium state exceed the at-rest earth pressure coefficient, K_0 , as vertical stress reductions above the trapdoor surpass horizontal stress reductions. Meanwhile, da Silva Burke and Elshafie (2021b) incorporated principal stress rotation and continuous arcs of principal stresses in their limit equilibrium theory to evaluate K .

Figure 16 compares experimental effective loosening pressures with theoretical values from the proposed limit equilibrium theory (Fang et al., 2020) for varying K -values in saturated soil. Despite some scatter, the experimental results support K -values between 1.0 and 1.4. The K -value, $K = 1.2$, was subsequently used for unsaturated soil analyses. Fang et al.'s (2020) theory, which extends Terzaghi's (1943) framework, assumes consistent parameters applicability for both saturated and unsaturated soils.

Fig. 17 illustrates the impact of groundwater level on the total and effective loosening pressures observed from the experiment and predicted by the limit equilibrium theory (Fang et al., 2020). The testing conditions for Fig. 17 are a trapdoor width of 10 cm and 20 cm, an overburden height of $2.0B$, and varying groundwater levels of $0.0H$, $0.5H$, and $1.0H$. Firstly, as shown in the figure, the theoretical initial total and effective pressures and loosening pressures are represented by solid lines, while the experimental results are depicted by open symbols. During the early stages of the research, multiple tests were conducted for each testing condition to verify repeatability. As shown in Figure 17, the results are consistently reproducible across most conditions. However, for the condition with $B = 20$ cm, $H = 2.0B$, and $H_w = 1.0H$, which was conducted during the latter stages of the study, only one test was performed. This decision was made based on the demonstrated consistency of results under similar experimental setups. The initial total and effective pressures and the loosening pressures observed experimentally align well with the predictions made by the limit equilibrium theory (Fang et al., 2020).

Additionally, it is observed that despite significant differences in groundwater level, the corresponding initial total pressure remains almost constant, indicating that the reduction in water mass resulting from variations in the thickness is negligible. This phenomenon was also demonstrated by measuring the drained water mass when lowering the groundwater level. However, a higher groundwater level leads to greater total loosening pressure becomes higher. This result can be attributed to the lower confining pressure and shear strength due to lower suction, which led to lower upward friction during failure. The corresponding effective loosening pressure exhibits only a slight decrease, however, the reduction of the effective loosening pressure compared to the initial effective pressure is relatively small, highlighting the influence of groundwater level on effective loosening pressure.

Prediction of loosening pressure for various overburden heights and groundwater depths

This section compares the experimental and theoretical loosening pressure under different trapdoor widths, overburden heights, and groundwater levels. A series of trapdoor tests were performed in both saturated and unsaturated ground, as detailed in Fig. 18, and the total and effective loosening pressures for the trapdoor width of 10 cm and 20 cm are shown in Fig. 19 and 20, respectively. These figures summarize loosening pressures across all experimental cases with different overburden heights and groundwater levels.

Since the overburden depths vary among cases, a common normalization value cannot be applied. Therefore, the actual total and effective loosening pressures are presented. To facilitate comparison, dashed lines are included in the figures to illustrate the relationship between overburden height and initial pressures under saturated conditions. Multiple experiments were conducted under identical conditions, and all observed data are plotted as open symbols in Figs. 19 and 20. The figures demonstrate good repeatability in the observed total and effective loosening pressures for each condition.

Additionally, the theoretical loosening pressures evaluated by the limit equilibrium theory are plotted as solid lines in Figs. 19 and 20, corresponding to various groundwater levels and overburden heights. For reference, the initial total pressure (total overburden pressure), $\rho_{\text{sat}}gH$, and initial effective pressure (effective overburden pressure), $\rho_{\text{sub}}gH$, for saturated soils are shown by the dashed lines.

In Figs. 19(a) and 20(a), the dashed lines illustrate the magnitude of the total loosening pressure relative to the total overburden pressure in saturated soils. In unsaturated soils, the wet density is lower than that of saturated soils, resulting in a slightly reduced total overburden pressure under unsaturated conditions.

In Fig. 19(b), the dashed line represents the initial effective pressure (effective overburden pressure) for saturated soils. Comparing the dashed line with the effective loosening pressure reveals that, in saturated soils, the effective loosening pressure is lower than the effective overburden pressure. However, in unsaturated soils,

the effective loosening pressure exceeds the effective overburden pressure for saturated soils, particularly when the groundwater table is deeper. This phenomenon is due to the suction effect, which increases the effective confining pressure, as defined by Bishop's effective stress. The higher effective loosening pressure in unsaturated soils enhances the shear resistance along the sliding surface, thereby resulting in relatively lower total loosening pressure. In Fig. 19(b), the dashed line represents the initial effective pressure (effective overburden pressure) for saturated soils.

The figures indicate that, despite the trapdoor width and the overburden height, the total loosening pressure decreases with lower groundwater level, while the corresponding effective loosening pressure increases. This outcome can be attributed to the elevated suction resulting from the unsaturated condition. Therefore, the upward friction acting on the ground above the trapdoor is increasing due to the higher effective pressure, leading to a lower total loosening pressure in the unsaturated ground. Additionally, the effective loosening pressure gradually increases and then remains constant with increasing the normalized overburden height. The constant effective loosening pressure implies that a stable soil arch is formed above the trapdoor.

Since the total loosening pressure, which determines the magnitude of stress applied to tunnel support, is of significant concern to engineers, the normalized total loosening pressures under different groundwater levels and trapdoor widths were analyzed to investigate scaling effects in unsaturated ground, as shown in Fig. 21. The total loosening pressure was normalized by the initial total pressure ($\rho_{sat}gH$, where ρ_{sat} is the saturated density) under saturated condition, with the overburden height H fixed at $2.0B$.

For saturated ground ($H_w = 1.0H$), the normalized total loosening pressures are identical for different trapdoor widths, indicating no scale effect (e.g., Evans, 1984; Fang et al., 2020). For unsaturated soils ($H_w = 0.0H, 0.5H$), the normalized total loosening pressures remain nearly constant for trapdoor width between 10 cm and 20 cm, indicating no apparent scaling effect within this apparatus scale range. However, simulations for unsaturated soils with $H_w = 0.0H$ reveal that normalized total loosening pressures increase as the trapdoor widths increase from 20 cm to 100 cm, confirming the presence of a scaling effect.

Consequently, the experimental total and effective loosening pressure are closely captured by the limit equilibrium theory for both trapdoor widths of 10 cm and 20 cm. This finding indicates that the limit equilibrium theory can nicely evaluate loosening pressure on a tunnel in the unsaturated ground. Furthermore, the scaling effect in unsaturated ground is identified through the limit equilibrium theory. This scaling effect in unsaturated soils is attributed to differences in the vertical profiles of the degree of saturation within the unsaturated zone, which are governed by the soil water characteristic curve. These findings emphasize the importance of considering

both groundwater conditions and apparatus scale when evaluating loosening pressures, as they directly influence the stress distribution and tunnel support requirements in engineering applications.

CONCLUSIONS

The influence of groundwater levels on shallow tunnel excavation mechanisms was discussed through trapdoor tests conducted in both saturated and unsaturated ground. The loosening pressure, the ultimate asymptotic pressure on the trapdoor, was compared with the values predicted by the previously proposed limit equilibrium theory (Fang et al., 2020).

The study verified the presence of two vertical shear bands, as hypothesized by Fang et al. (2020), under unsaturated conditions. The shear bands were observed originating from both edges of the trapdoor and extending upward to the ground surface in all test patterns. The configuration of groundwater level and overburden height significantly influenced the formation of shear bands. Specifically, shear bands developed and extended to the ground surface in a shallow overburden height of $1.0B$ regardless of groundwater level without forming an arch-like shape. Conversely, in the transitional overburden height of approximately $2.0B$, shear bands developed upward in the saturated ground and exhibited an arch-like shape in the unsaturated ground. Within this transitional overburden height, the arch-like shaped shear bands became more significant with lower groundwater levels, highlighting the influence of groundwater level on shear band formation in conjunction with overburden height.

Surface settlements were primarily influenced by overburden height; the surface settlement became smaller with deeper overburden height ($H > 1.0B$), irrespective of trapdoor width. This trend indicates that a more inclined shear band, especially the arch-like shape shear band, exhibits a more substantial effect at higher overburden height. Additionally, in the unsaturated ground, surface settlement exhibits clear differences even with identical overburden height, particularly relative to the trapdoor width. Specifically, the impact of groundwater level became significant only when the trapdoor width was 20 cm, and the overburden height reached 40 cm. These findings highlight the existence of a scale effect on the SWCC, which significantly influences surface settlement. Consequently, when conducting model experiments in unsaturated ground, it is crucial to consider the similarity of the SWCC.

The variation of the normalized total and effective pressures exerted on the trapdoor with the normalized trapdoor displacement showed similar trends in both saturated and unsaturated soils when the overburden height is larger than $1.0B$. The normalized total and effective pressures decreased rapidly to a minimum value and then stabilized as the trapdoor displacement exceeded $0.02B$. This stabilized value of total pressure is referred to as the

loosening pressure. Notably, the groundwater level influenced these pressures; as the groundwater level became higher, the loosening pressure became larger. This pattern suggests that reduced suction associated with higher groundwater levels leads to decreased confining pressure and shear strength, increasing the risk of tunnel collapse, particularly after significant rainfall or agricultural irrigation.

The applicability of the previously limit equilibrium theory by authors (Fang et al., 2020) was investigated by comparing the observed loosening pressure with the predicted results. The outer shear bands observed in all test cases developed to the ground surface, supporting the validity of the assumption made in the limit equilibrium theory regarding the vertical sliding surfaces from the edges of the trapdoor. Furthermore, referring to previous studies (e.g., Terzaghi, 1943; Evans, 1984; Chevalier et al., 2012) and an investigation of the sensitivity of the K value, K was recommended between 1.0 and 1.4 in this study. Consequently, it can be confirmed that the previously proposed limit equilibrium theory (Fang et al., 2020) can properly predict the loosening pressure after tunnel excavation in both saturated and unsaturated ground, reinforcing the assumption mentioned above's plausibility.

In conclusion, our study demonstrates the formation of shear bands, ground surface settlement, vertical pressure distributions on the trapdoor, and the effects of overburden depth and groundwater levels on both total and effective loosening pressures. These findings provide critical insights into the behavior of unsaturated soils during tunneling. Furthermore, the experimental results validated the theoretical framework for loosening pressure, which accounts for unsaturated soil properties. Parametric studies confirmed the framework's ability to predict loosening pressures under various overburden heights and groundwater conditions with accuracy. Nonetheless, we acknowledge the inherent limitations of small-scale 1g tests in replicating the stress conditions of real tunnels, which may affect shear band formation, as discussed by other researchers (Dewoolkar et al., 2007; da Silva Burke and Elshafie, 2021a). However, the primary objective of this study was to validate the theoretical solution derived from limit equilibrium theory using 1g experimental results, with the intent to extrapolate real-scale behavior through validated mathematical models. Additionally, the experimental findings will serve as a basis for future studies, including numerical simulations such as finite element analyses of unsaturated soils.

DATA AVAILABILITY STATEMENT

All data generated or used during the study are available from the corresponding author upon reasonable request.

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552 NOTATION

553 *The following symbols are used in this paper:*

554	A	bottom area of soil chamber
555	B	trapdoor width
556	$\mathbf{B}_m$	strain-displacement tensor
557	e	void ratio
558	g	gravitational acceleration
559	H	overburden height
560	H_1	overburden height of a single layer
561	H_w	groundwater level
562	K	lateral earth pressure coefficient
563	M_s	total mass of wet sand after drying
564	S_{max}, S_{min}	maximum and minimum degrees of saturation
565	S_r	degree of saturation
566	s_{max}	maximum surface settlement
567	s	suction
568	$\mathbf{u}$	displacement vector
569	u_a, u_w	pore air and pore water pressure
570	z	vertical coordinate
571	α, m, n	material parameters for van Genuchten's soil water characteristic curve
572	γ_{xy}	engineering shear strain ($= 2\varepsilon_{xy}$)
573	δ	displacement of trapdoor
574	$\boldsymbol{\varepsilon}$	strain tensor

575	ε_d	deviatoric strain
576	$\varepsilon_x, \varepsilon_y$	strain in horizontal and vertical direction
577	ρ_d, ρ_{sat}	dry and saturated density
578	ρ_s	solid density
579	ρ_w	density of water
580	σ_{z0}, σ_z	initial total vertical pressure and loosening pressure (after tunnel excavation)
581	ϕ	internal friction angle

582 REFERENCES

- 583 Adachi, T., Kimura, M. and Kishida, K. (2003), Experimental study on the distribution of earth pressure and
584 surface settlement through three-dimension trapdoor tests, *Tunneling and Underground Space*
585 *Technology*, 18, 171–183.
- 586 Bishop, A. W. (1959), The principle of effective stress, *Teknisk Ukeblad*, 39, 859–863.
- 587 Britton, E. J. and Naughton, P. J. (2011), The arching phenomena observed in experimental trap door model tests,
588 *Geo-Frontiers 2011: Advances in Geotechnical Engineering*. GSP211: 788-797.
- 589 Chevalier, B., Combe, G. and Villard, P. (2012), Experimental and discrete element modeling studies of the
590 trapdoor problem: influence of the macro-mechanical frictional parameters, *Acta Geotech.*, 7, 15–39.
- 591 Costa, Y. D., Zornberg, J. G., Bueno B. S. and Costal C. L. (2009), Failure mechanisms in sand over a deep active
592 trapdoor, *J. Geotech. Geoenviron. Eng.*, 135(11), 1741–1753.
- 593 Dewoolkar, M. M., Santichaianant, K., and Ko, H. Y. (2007), Centrifuge modeling of granular soil response over
594 active circular trapdoors, *Soils Found.*, 47 (5): 931-945.
- 595 da Silva Burke, T. S. and Elshafie, M. Z. E. B. (2021a), Arching in granular soils: experimental observations of
596 deformation mechanisms, *Geotechnique* 71, NO. 10, 866-878.
- 597 da Silva Burke, T. S. and Elshafie, M. Z. E. B. (2021b), Arching in granular soils: Limit state equilibrium,
598 *Geotechnique* 71, NO. 8, 700-713.
- 599 Evans, C.H. (1984), *An examination of arching in granular soils*, Master Thesis, Massachusetts Institute of
600 Technology, USA.
- 601 Fang, X., Kikumoto, M. and Cui, Y. (2020), A theory of loosening earth pressure above a shallow tunnel in
602 unsaturated ground, *Int. J. Numer. Anal. Meth. Geomech.*, 44: 1495-1508.

George, T. I. and Dasaka, S. M. (2023), Mechanics of arch action in soil arching, *Acta Geotechnica*, 18: 1991-2009.

Hossain, M. M., Minkwitz, R. and Sue, H. J. (2013), Minimization of surface friction effect on scratch-induced deformation in polymers, *Polym. Eng. Sci.*, 53: 1405-1413.

Iglesia, G. R., Einstein, H. H. and Whitman, R. V. (2014), Investigation of Soil arching with centrifuge tests, *J. Geotech. Geoenviron. Eng.*, 140 (2): 04013005.

Jacobsz, S.W. (2016), Trapdoor experiments studying cavity propagation. *Proc. of the first Southern African Geotechnical Conference*. Pretoria, South Africa, 159-164.

Kikumoto, M. (2004), *Study on earth pressure mechanics around a tunnel*, Ph.D. thesis, Kyoto university (In Japanese).

Kikumoto, M., Kimura, M., Kishida, K. and Adachi, T. (2003), Three dimensional trapdoor experiments and its numerical analyses on the mechanical behavior during tunnel excavation, *J. JSCE*, 750/III-65, 145–158 (in Japanese).

Koutsabeloulis, N. C. and Griffiths, D. V. (1989), Numerical modeling of the trap door problem, *Géotechnique*, 39(1), 77–89.

Kuwano, R. and Ebizuka, H. (2010), Trapdoor tests for the evaluation of earth pressure acting on a buried structure in an embankment, *Proc. 9th Int. sym. on New Technologies for Urban Safety of Mega Cities in Asia*, USMCA, Kobe.

Ladanyi, B. and Hoyaux, B. (1969), A study of the trapdoor problem in a granular mass, *Can. Geotech. J.*, 6 (1): 1-14.

Liang, L. J. and Xu, C. J. (2019), Numerical and theoretical research on stress distribution in the loosening zone of the trapdoor problem, *Int. J. Numer. Anal. Meth. Geomech.*, 43 (7): 1426-1447.

Liang, L. J., Xu, C. J., Chen, Q. Z. and Chen, Q. S. (2020), Experimental and theoretical investigation on evolution of soil-arching effect in 2D trapdoor problem, *Int. J. Geomech.*, 20 (6): 06020007.

McNulty, J. W. (1965), *An experiment study of arching in sand*, Technical Report No. I-674, US. Waterways Experiment Station, Vicksburg.

Murakami, A., Sakaguchi, H. and Hasegawa, T. (1997), Dislocation, vortex and couple stress in the formation of shear bands under trapdoor problems, *Soils Found.*, 37 (1): 123-135.

631 Mahdi, A., Han, J., Jawad, S. and Abdulrasool, G. (2017), Investigation of stability of soil arching under surface
632 loading using trapdoor model tests, *Proc. 19th Int. Conf. on Soil Mechanics and Geotechnical*
633 *Engineering, Seoul*: 889-892.

634 Nakai, T., Xu, L. M. and Yamazaki, H. (1997), 3D and 2D model tests and numerical analyses of settlements and
635 earth pressures due to tunnel excavation, *Soils Found.*, 37 (3): 31-42.

636 Pufahl, D., Fredlund, D. G. and Rahardjo, H. (1983), Lateral earth pressures in expansive clay soil, *Can. Geotech.*
637 *J.*, 20, 228–241.

638 Sahoo, J. P. and Ganesh, R. (2018), Active earth pressure on retaining walls with unsaturated soil backfill, *Proc.*
639 *Ground Improvement and Earth Structures*, 1–19.

640 Song, J. H., Chen, K. F., Li, P., Zhang, Y. H. and Sun, C. M. (2018), Soil arching in unsaturated Soil with different
641 water table, *Granular Matter*, 20 (4): 1-11.

642 Soranzo, E., Tamagnini, R. and Wu, W. (2015), Face stability of shallow tunnels in partially saturated Soil:
643 centrifuge testing and numerical analysis, *Geotechnique* 65, NO. 6, 454–467.

644 Stone, K. J. L. and Wood, D. M. (1992), Effects of dilatancy and particle size observed in model test on sand,
645 *Soils Found.*, 32 (4), 43–57.

646 Tanaka, T. and Sakai, T. (1993), Progressive failure and scale effect of trapdoor problems with granular materials,
647 *Soils Found.*, 33 (1): 11-22.

648 Tatsuoka, F. and Haibara, O. (1985), Shear resistance between sand and smooth or lubricated surfaces, *Soils and*
649 *Found.*, 25 (1): 89-98.

650 Terzaghi, K. (1936), Stress distribution in dry and saturated sand above a yielding trapdoor, *Proc. 1st Int. Conf.*
651 *on Soil Mechanics and Foundation Engineering*, Cambridge, Mass., 35–39.

652 Terzaghi, K. (1943), Theoretical soil mechanics, *John Wiley & Sons*, 66–76.

653 Unno, T., Kazama, M., Uzuoka, R. and Sento, N. (2008), Liquefaction of unsaturated sand considering the pore
654 air pressure and volume compressibility of the soil particle skeleton, *Soils Found.*, 48 (1), 87–99.

655 Vahedifard, F., Leshchinsky, D., Mortezaei, K. and Lu, N. (2016), Effective stress-based limit-equilibrium
656 analysis for homogeneous unsaturated slopes, *Int. J. Geomech.*, 16(6), D4016003.

657 van Genuchten, M. Th. (1980), A closed-form equation for predicting the hydraulic conductivity of unsaturated
658 soils, *Soil Sci. Soc. Am. J.*, 44, 892–898.

659 Vardoulakis, I., Graf, B. and Gudehus, G. (1981), Trapdoor problem with dry sand: a statical approach based upon
660 model test kinematics, *Int. J. Numer. Anal. Meth. Geomech.*, 5: 57-78.

661 Wu, Y., Yamamoto, H. and Yao, Y. (2013), Numerical study on bearing behavior of pile considering sand particle
662 crushing, *Geomech. Eng.*, Vol. 5, No. 3: 241-261.
663 Zheng, J., Li, L. and Daviault, M.(2021), Experimental Study on the Effectiveness of Lubricants in Reducing
664 Sidewall Friction, *International Journal of Geomechanics*, Vol. 2, No. 5: 06021010.
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Table 1 Parameters in van Genuchten equation for soil–water characteristic curves of Toyoura sand.

Parameter	Description	Value
S_{max}	Maximum degree of saturation	1.00
S_{min}	Minimum degree of saturation	0.06
α (kPa ⁻¹)	Fitting parameter	0.24
m	Fitting parameter	0.71
n	Fitting parameter	3.54

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670 Fig. 1. Trapdoor problem in unsaturated ground.

671 Fig. 2. Schematic diagram of the apparatus (a) front view; (b) section view of A-A; (c) top view, and (d)

672 suction sensor.

673 Fig. 3. Schematic diagram of the trapdoor (a) overview; (b) section A-A; (c) exploded view.

674 Fig. 4. Process of unsaturated model ground generation: (a) filling with water up to 15 cm above the

675 trapdoor; (b) generating the model ground using the water pluviation method (maintaining a 15

676 cm height difference between the ground surface and water level); (c) completion of the

677 generation of fully saturated ground; (d) lowering the groundwater level to the designated level

678 through drainage.

679 Fig. 5. Soil water characteristic curve of Toyoura sand under drying path.

680 Fig. 6. Vertical distribution of (a) pore water pressure; (b) suction; and (c) degree of saturation in

681 unsaturated ground for the groundwater level of $H_w = 0.5H$ and $H_w = 0.0H$ ($B = 10$ cm, $H =$

682 $2.0B$).

683 Fig. 7. Vertical distribution of (a) pore water pressure; (b) suction; and (c) degree of saturation in

684 unsaturated ground for the groundwater level of $H_w = 0.5H$ and $H_w = 0.0H$ ($B = 20$ cm, $H =$

685 $2.0B$).

686 Fig. 8. Evolution of shear bands with lowering of trapdoor in (a) saturated ground ($H_w = 1.0H$); (b)

687 unsaturated ground ($H_w = 0.5H$); and (c) unsaturated ground ($H_w = 0.0H$) ($B = 10$ cm, $H =$

688 $2.0B$).

689 Fig. 9. Shear bands at the trapdoor displacement of 5.0 mm for (a) $B = 10$ cm, $H = 1.0B$; (b) $B = 10$ cm,

690 $H = 1.5B$; and (c) $B = 10$ cm, $H = 2.0B$ under different groundwater levels ($H_w = 0.0H, 0.5H,$

691 $1.0H$).

692 Fig. 10. Shear bands at the trapdoor displacement of 5.0 mm for (a) $B = 20$ cm, $H = 0.5B$; and (b) $B =$

693 20 cm, $H = 2.0B$ under different groundwater levels ($H_w = 0.0H, 0.5H, 1.0H$).

Fig. 11. Surface settlement profiles at trapdoor displacement $d = 0.02B$ under different trapdoor widths and overburden heights (a) $B = 10$ cm, $H = 1.0B$; (b) $B = 10$ cm, $H = 2.0B$; (c) $B = 20$ cm, $H = 1.0B$; and (d) $B = 20$ cm, $H = 2.0B$.

Fig. 12. Maximum surface settlement at trapdoor displacement $\delta = 0.02B$ versus normalized overburden height for different trapdoor widths (a) $B = 10$ cm; and (b) $B = 20$ cm.

Fig. 13. Distributions of normalized total earth pressure in (a) saturated ground ($H_w = 1.0H$); (b) unsaturated ground ($H_w = 0.5H$); and (c) unsaturated ground ($H_w = 0.0H$) ($B = 10$ cm, $H = 2.0B$).

Fig. 14. Variation in normalized total and effective pressures acting on the trapdoor with normalized trapdoor displacement under different groundwater heights $H_w = 0.0H, 0.5H, 1.0H$: (a) $B = 10$ cm, $H = 1.0B$; (b) $B = 10$ cm, $H = 1.5B$; (c) $B = 10$ cm, $H = 2.0B$.

Fig. 15. Variation in normalized total and effective pressures acting on the trapdoor with normalized trapdoor displacement under different groundwater levels $H_w = 0.0H, 0.5H, 1.0H$: (a) $B = 20$ cm, $H = 0.5B$; (b) $B = 20$ cm, $H = 1.0B$; (c) $B = 20$ cm, $H = 2.0B$.

Fig. 16. (a) Total and (b) effective loosening pressures with normalized overburden height by using different lateral earth pressure coefficient K under saturated conditions ($B = 10$ cm, $H_w = 1.0H$).

Fig. 17. Effect of the groundwater level on total and effective loosening pressures: (a) $B = 10$ cm, $H = 2.0B$; (b) $B = 20$ cm, $H = 2.0B$.

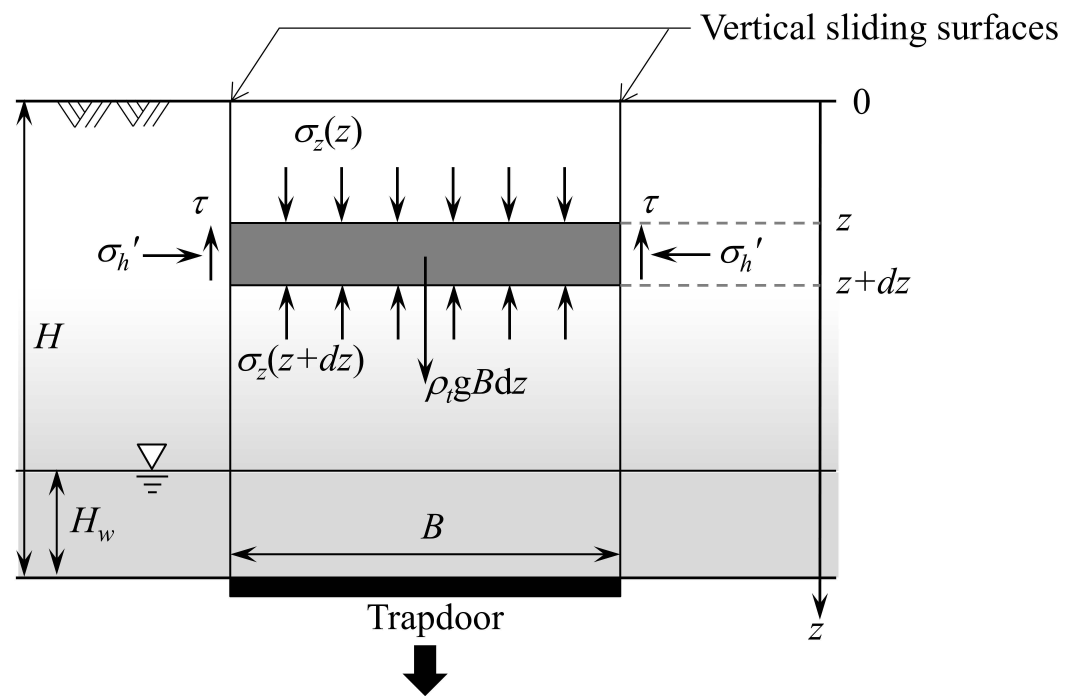
Fig. 18. Test patterns for trapdoor test in saturated and unsaturated ground.

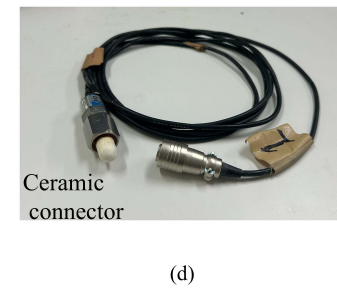
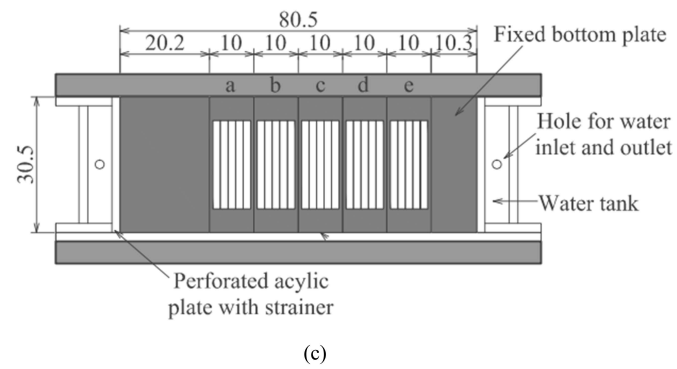
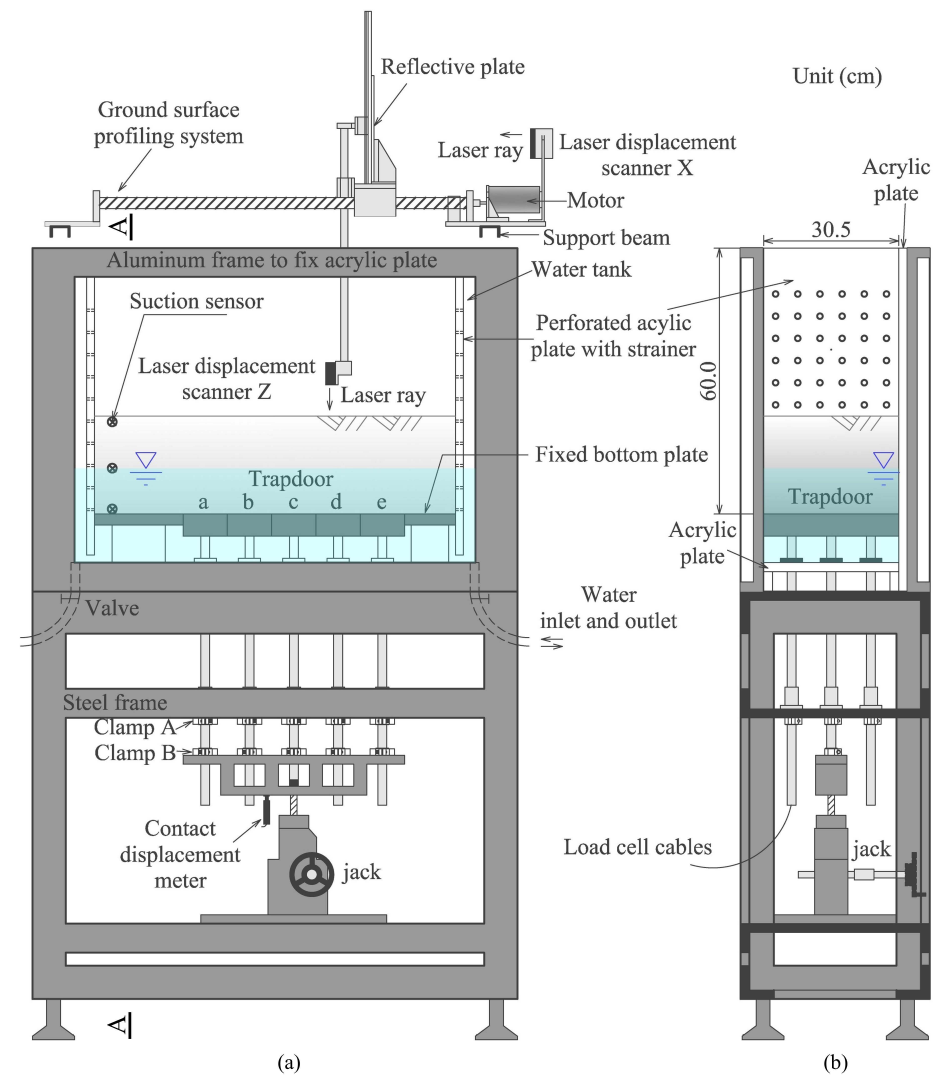
Fig. 19. Experimental and theoretical (a) total loosening pressure; and (b) effective loosening pressure with normalized overburden height under different groundwater levels $H_w = 0.0H, 0.5H$, and $1.0H$ ($B = 10$ cm) (dashed lines represent initial total and effective pressures in saturated ground for reference).

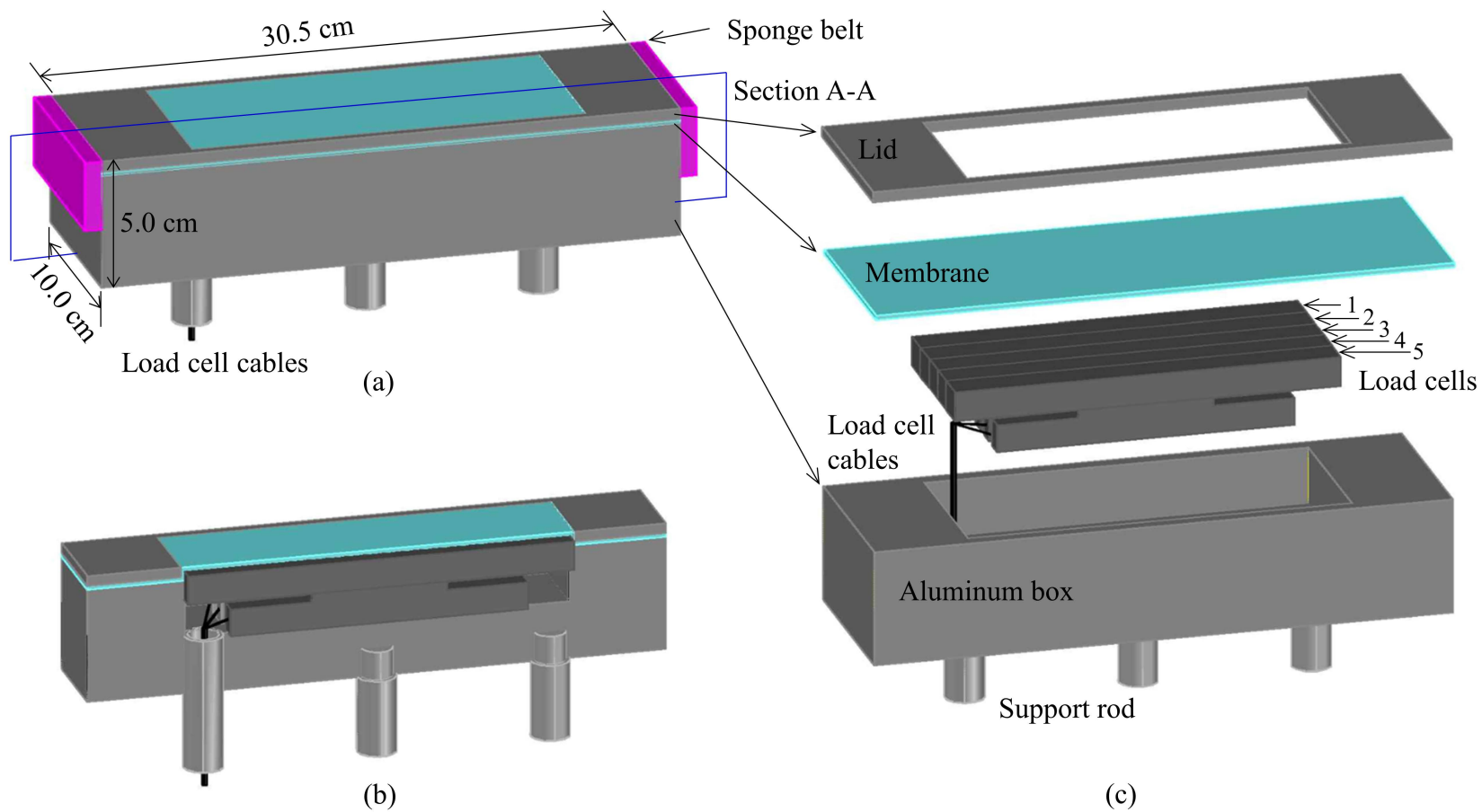
Fig. 20. Experimental and theoretical (a) total loosening pressure; and (b) effective loosening pressure

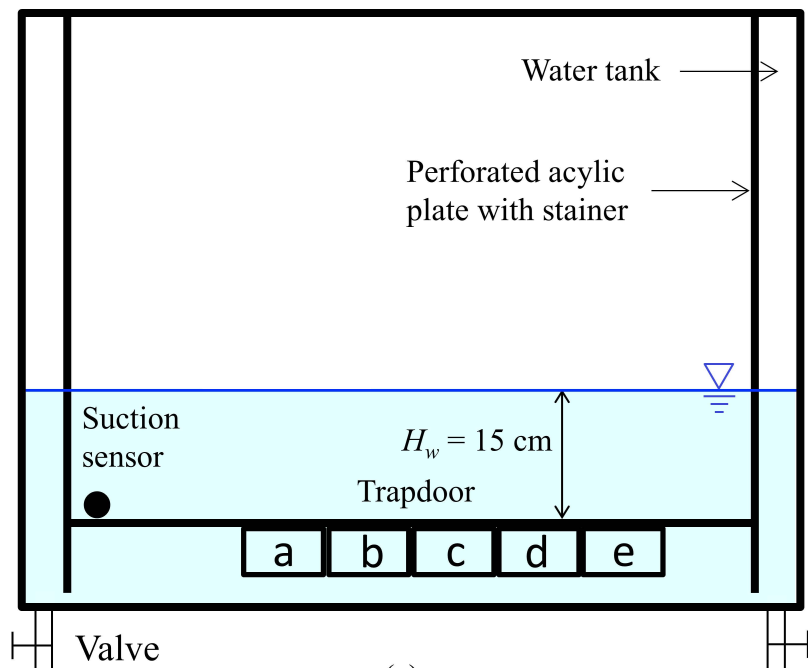
with normalized overburden height under different groundwater levels $H_w = 0.0H$, $0.5H$, and $1.0H$ ($B = 20$ cm) (dashed lines represent initial total and effective pressures in saturated ground for reference).

Fig. 21. Experimental and theoretical normalized total loosening pressures with trapdoor width under different groundwater levels $H_w = 0.0H$, $0.5H$, and $1.0H$ ($H = 2.0B$, ρ_{sat} is saturated density).

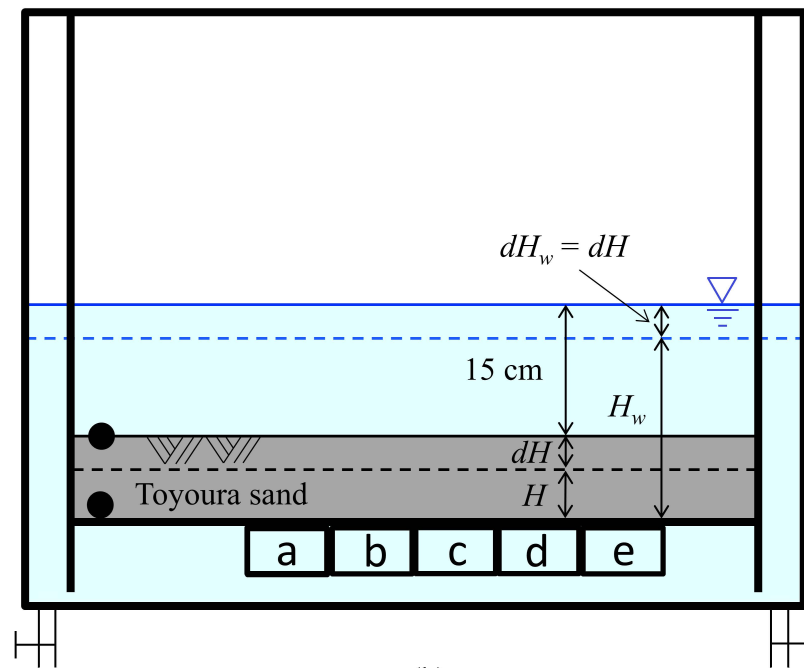




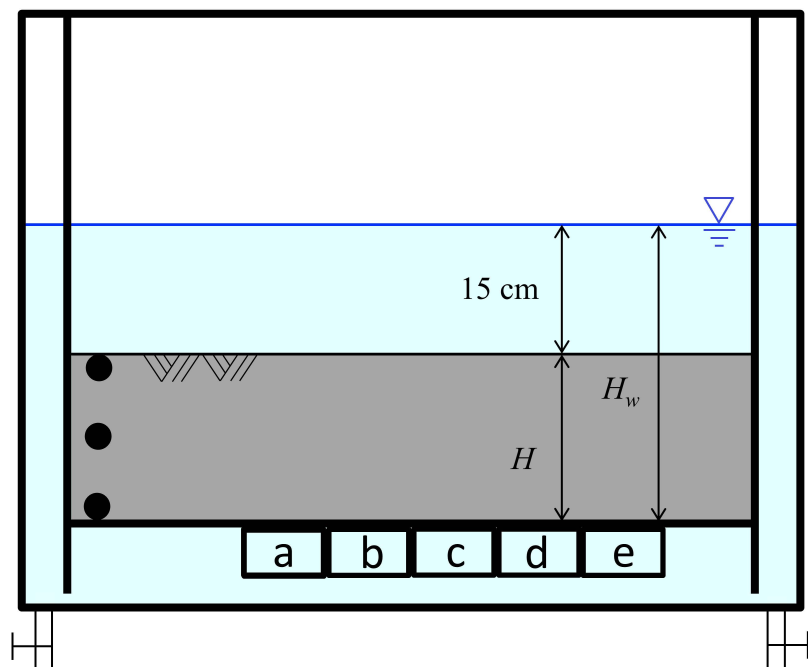




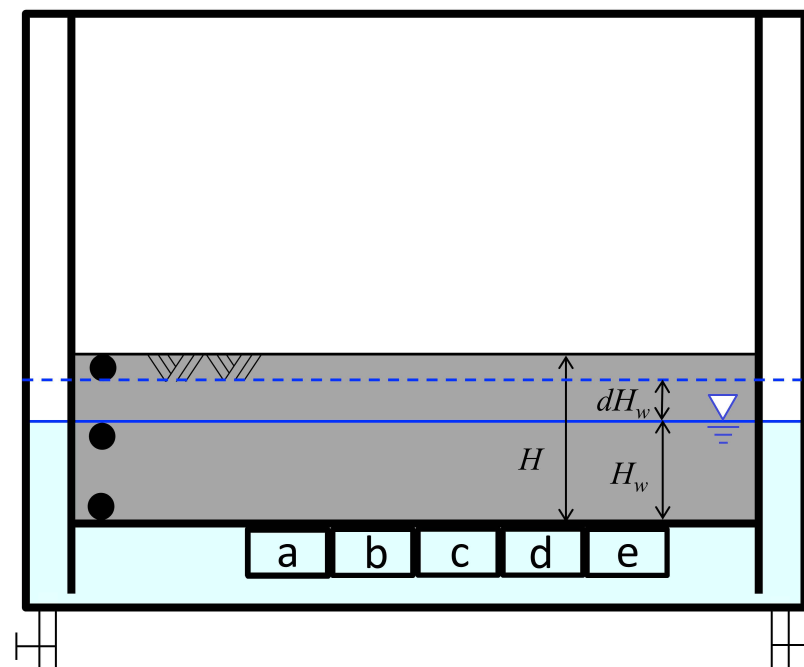
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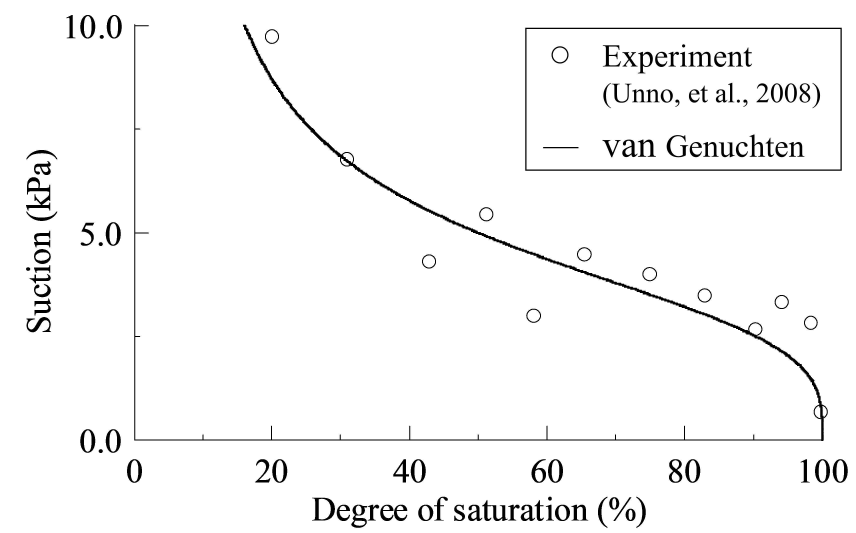
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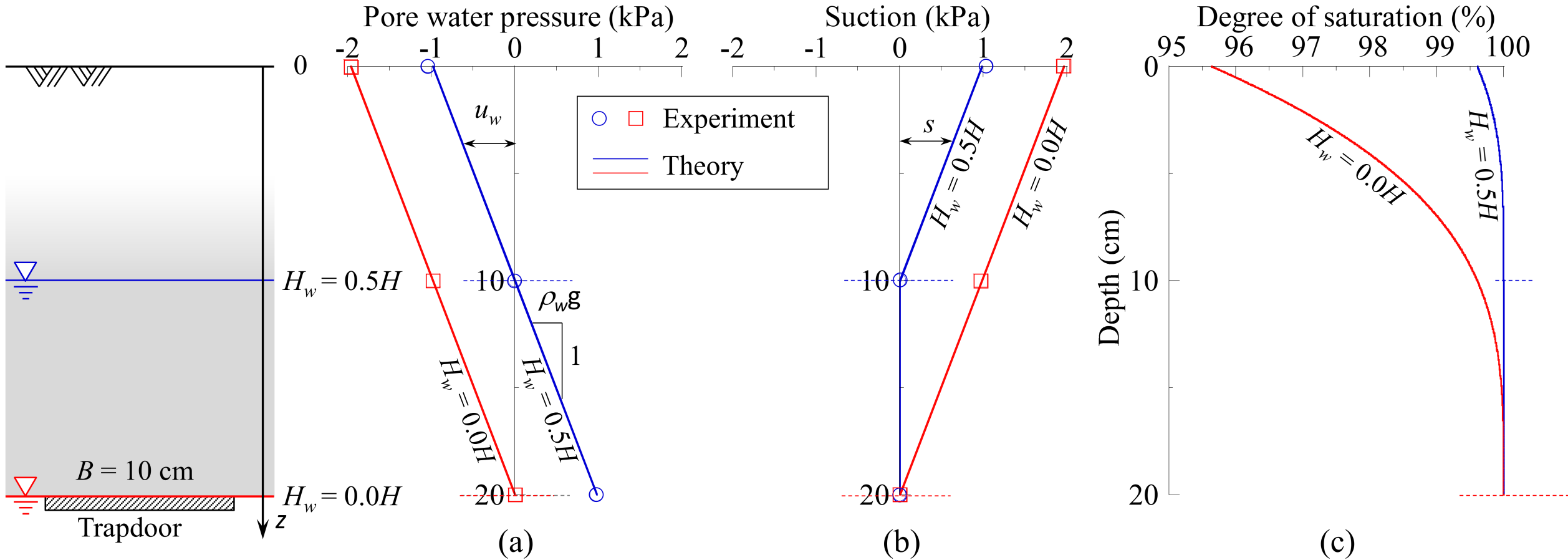


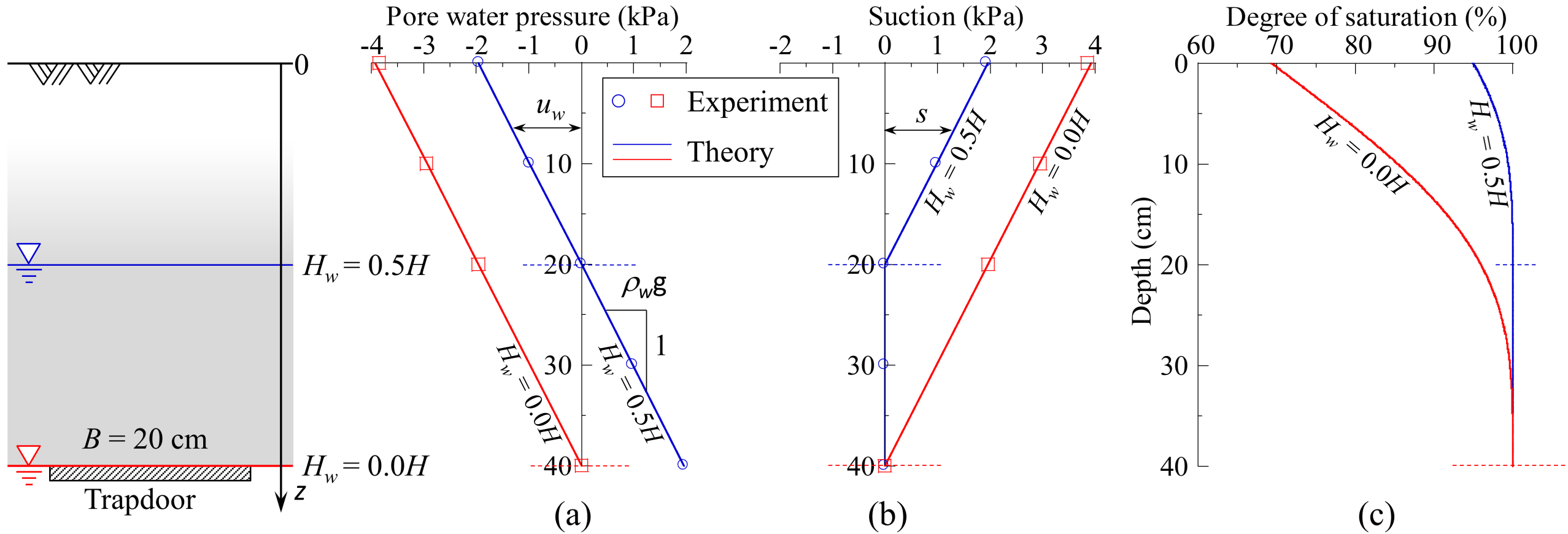
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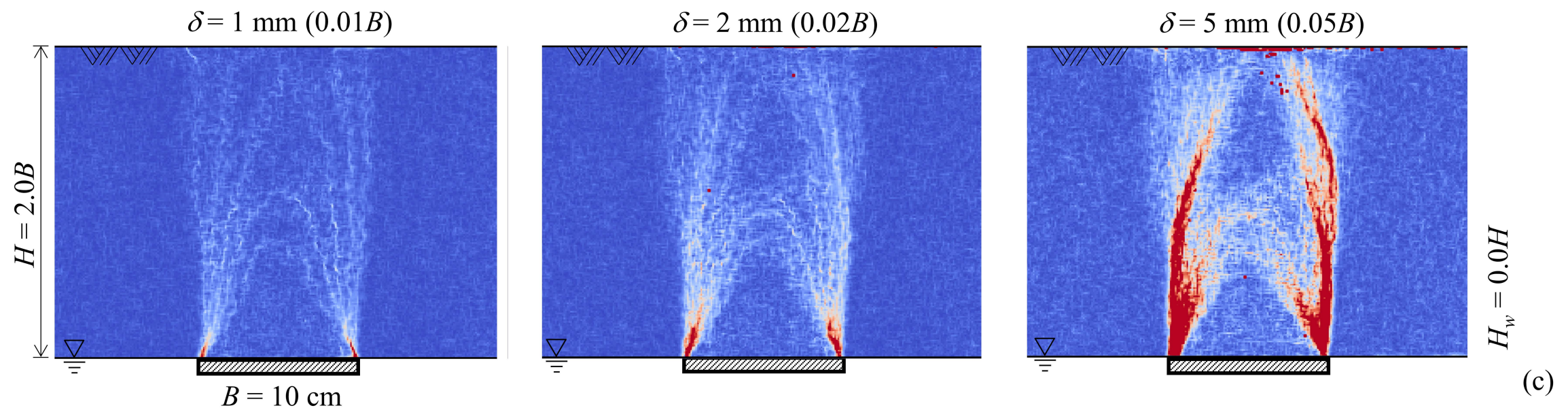
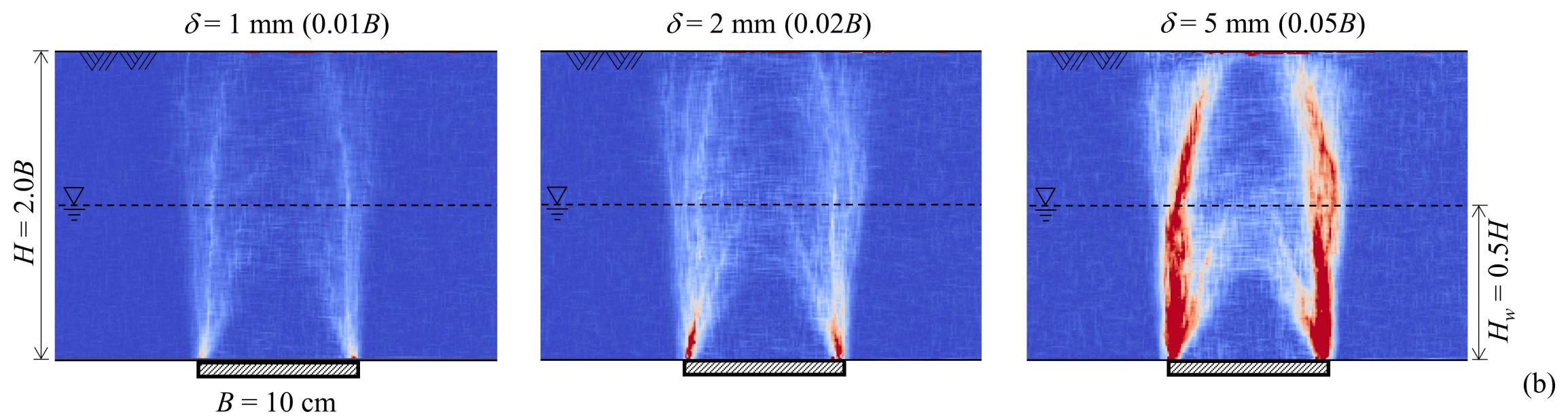
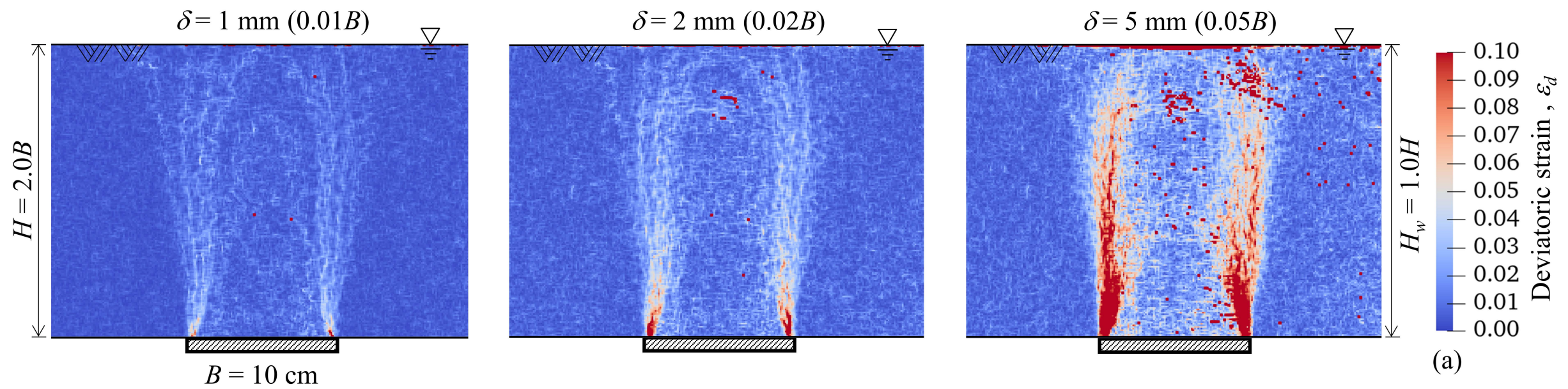


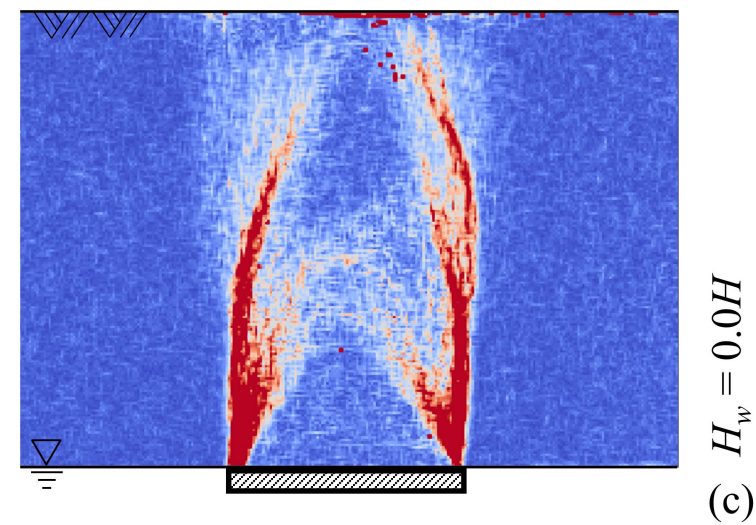
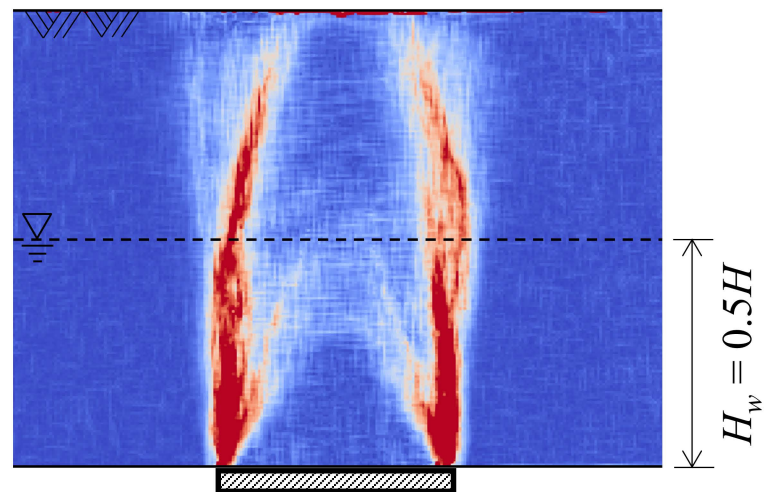
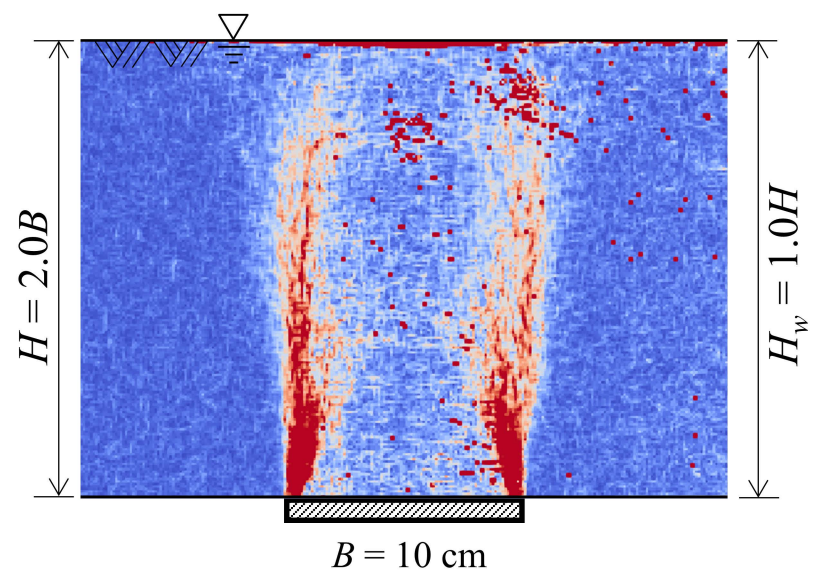
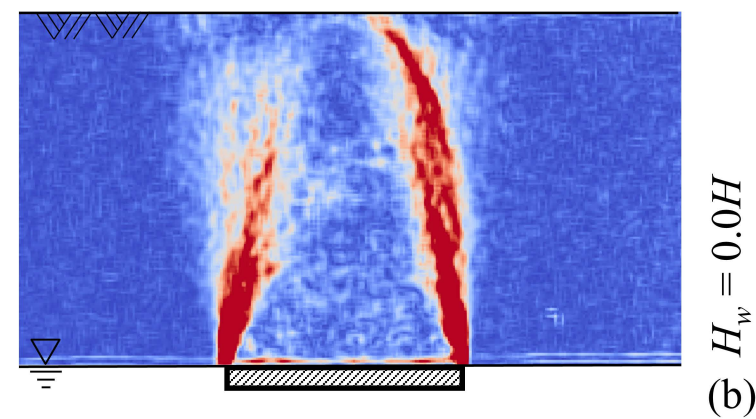
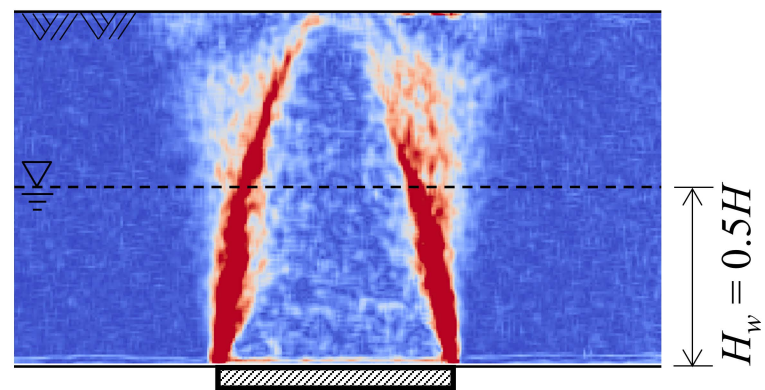
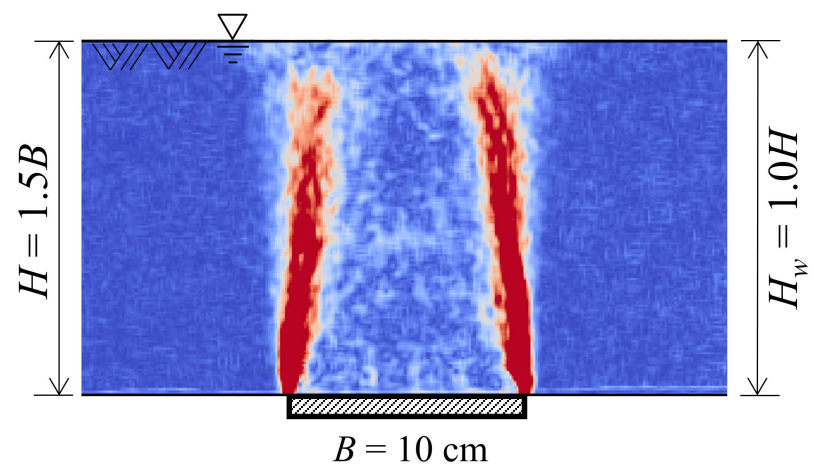
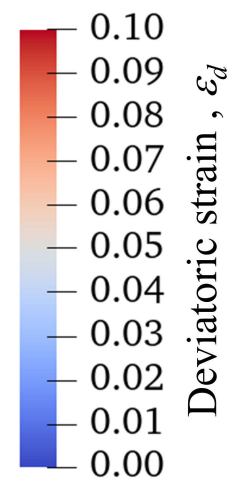
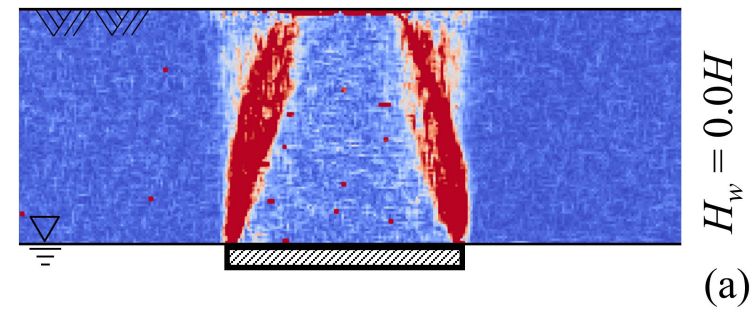
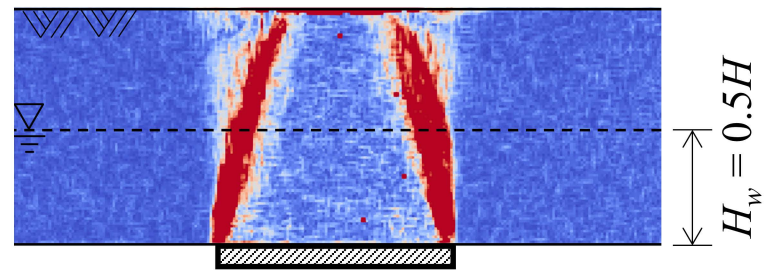
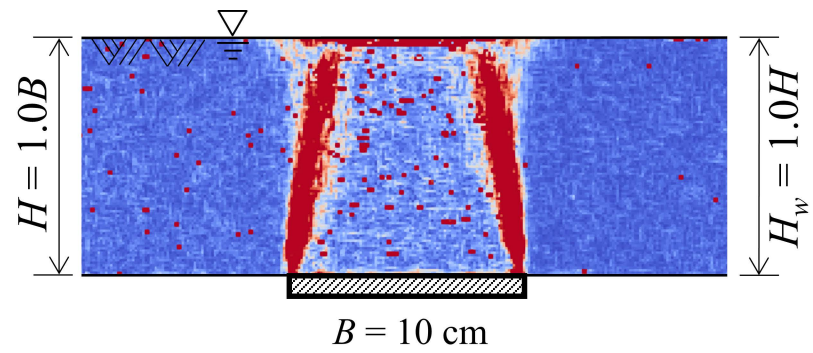
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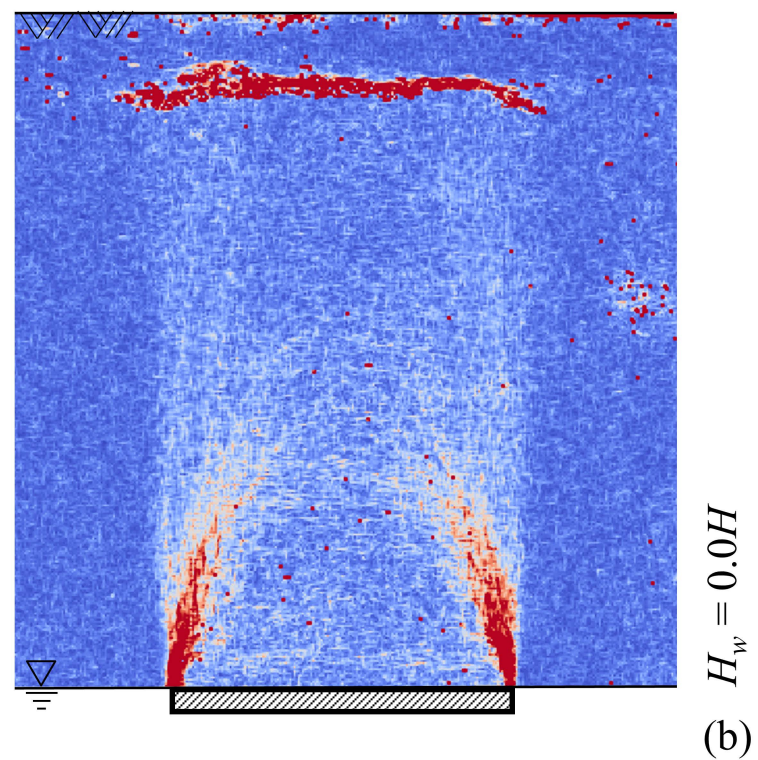
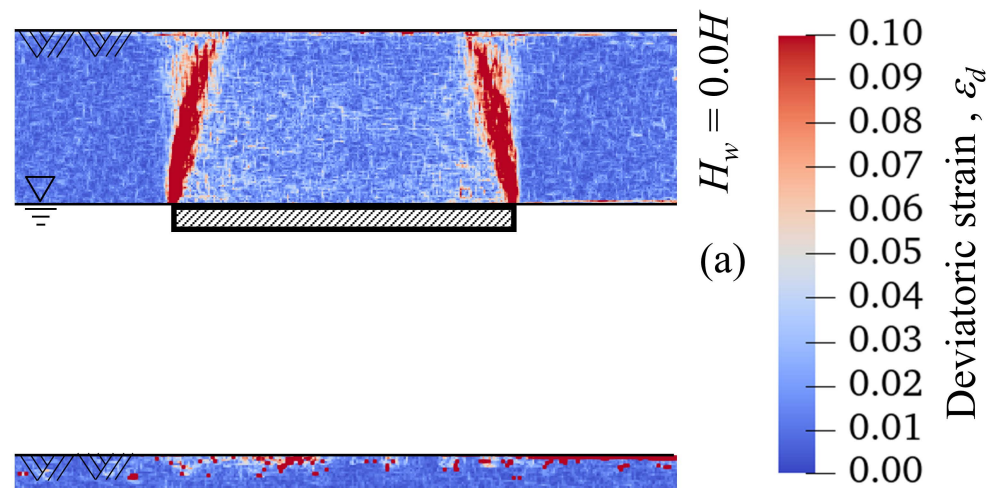
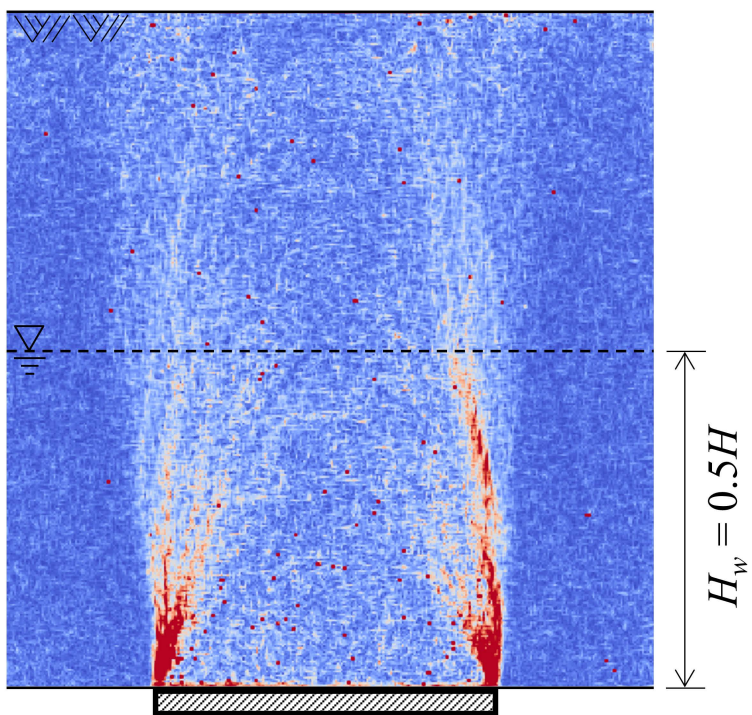
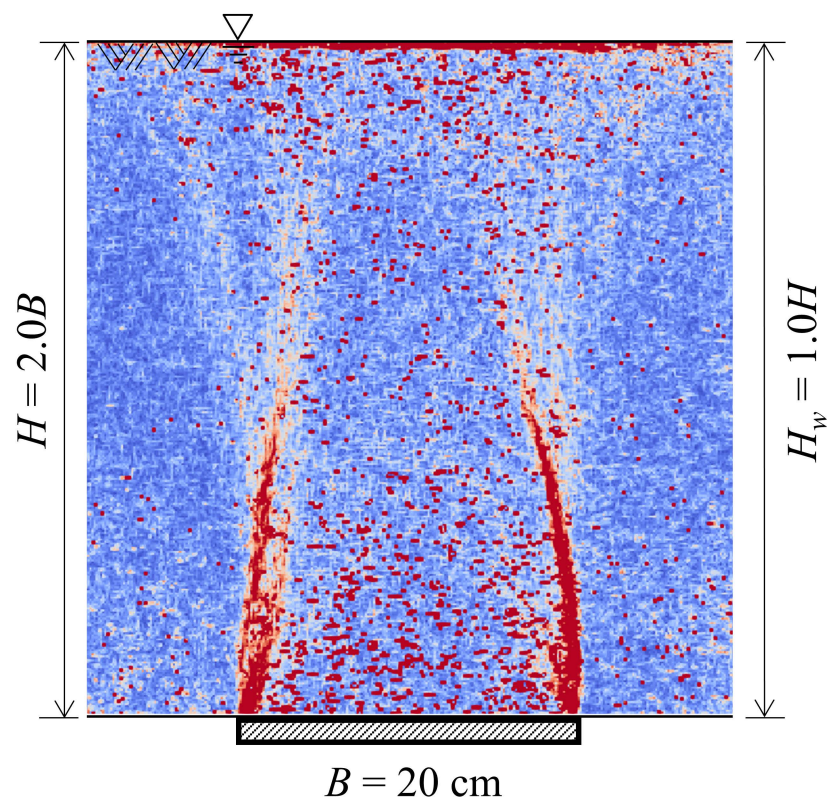
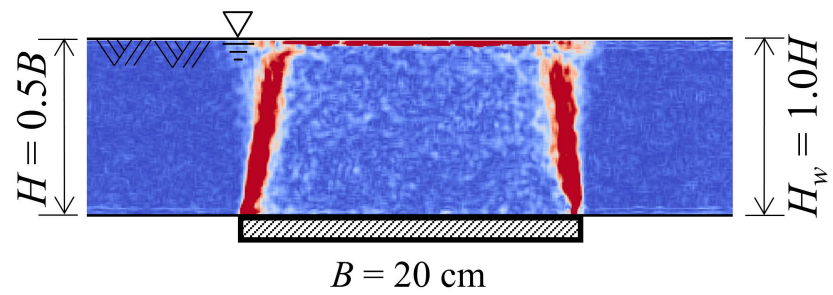


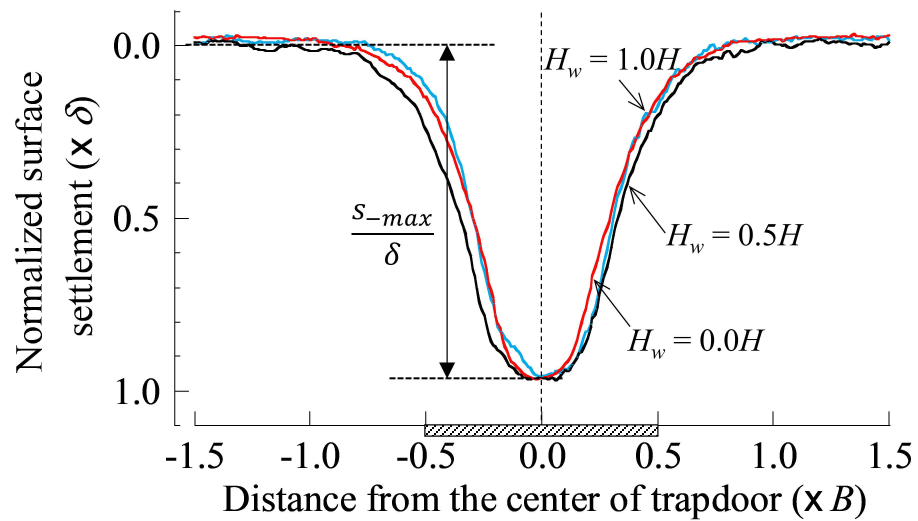




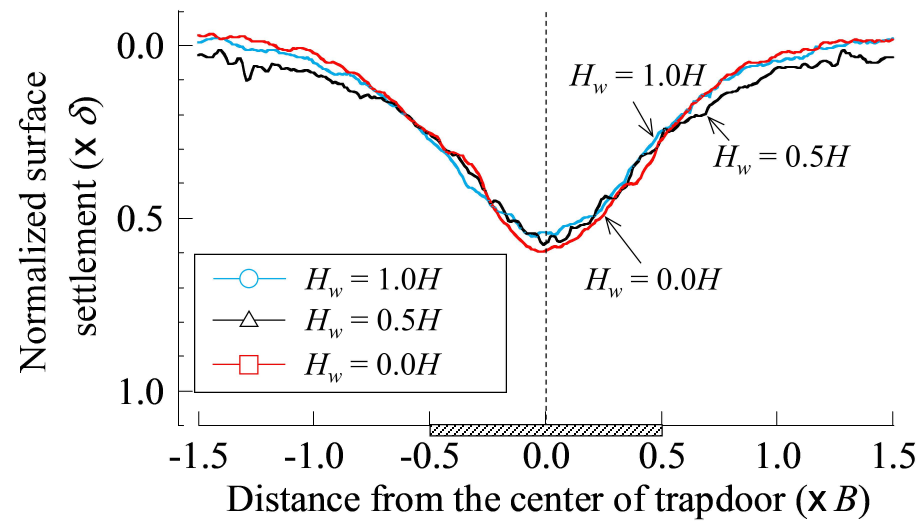




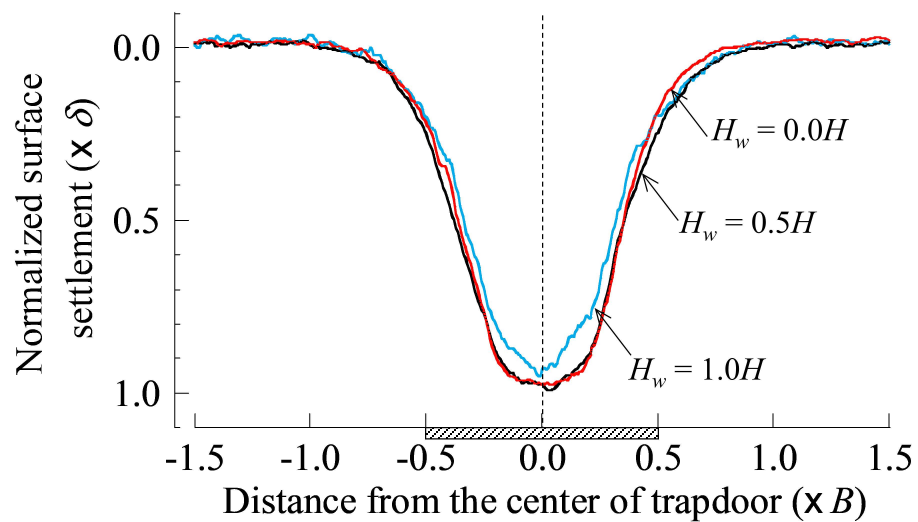




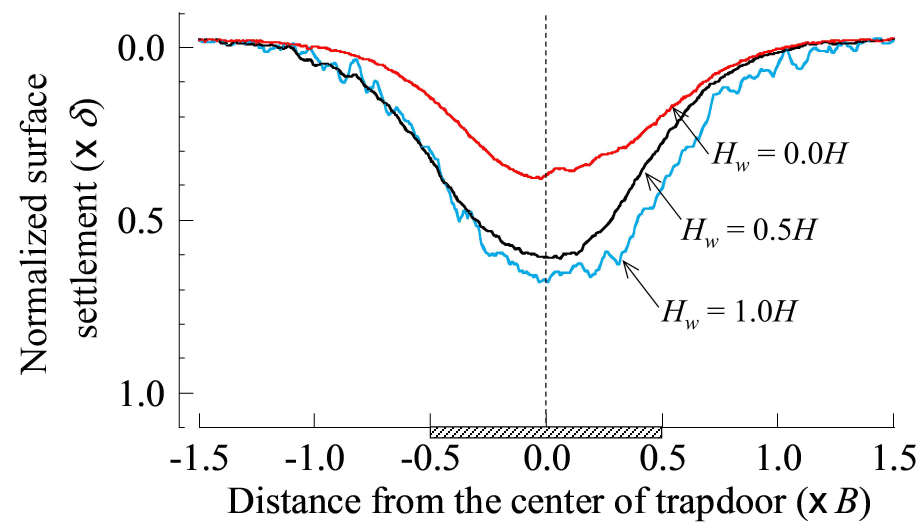
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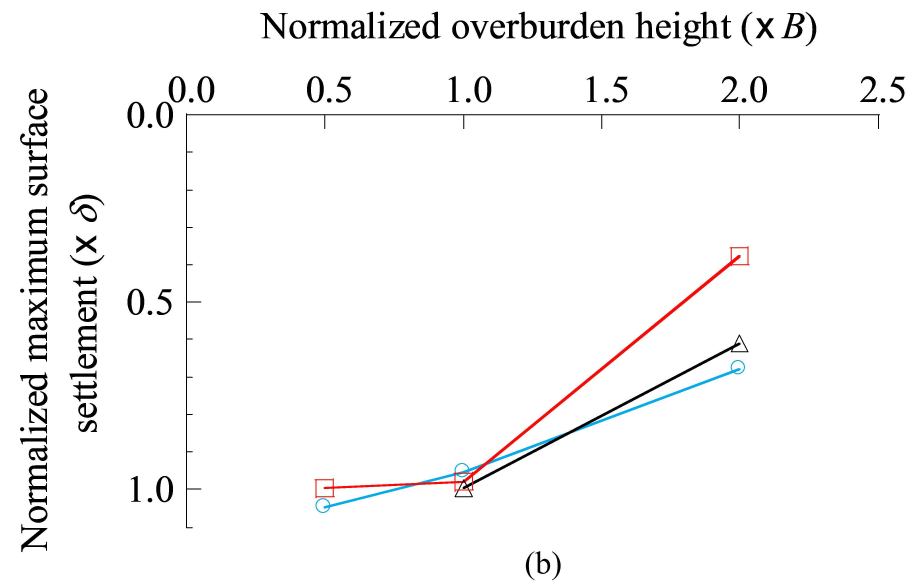
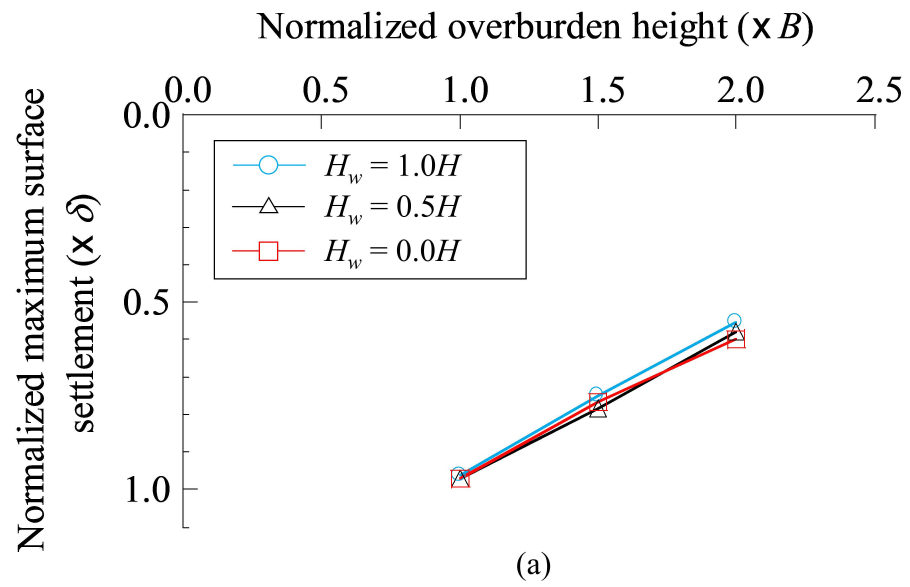
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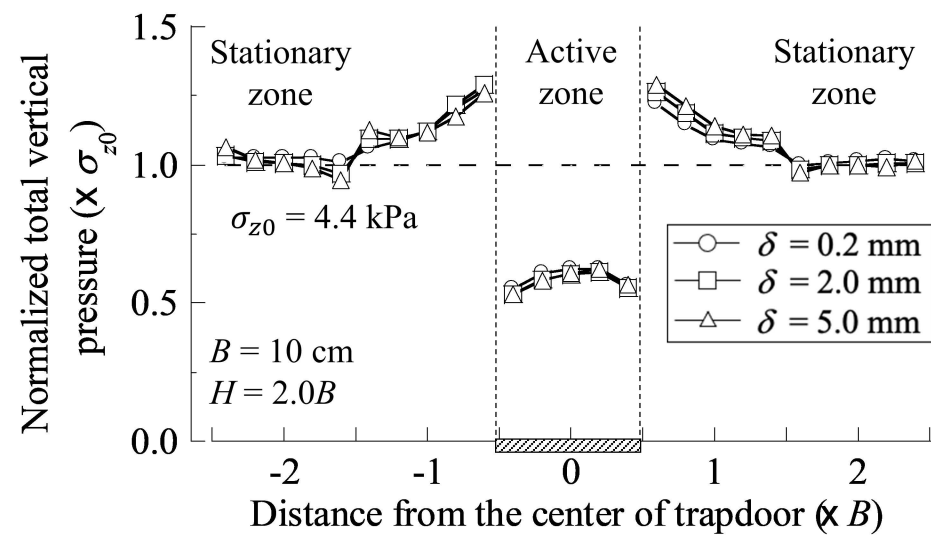


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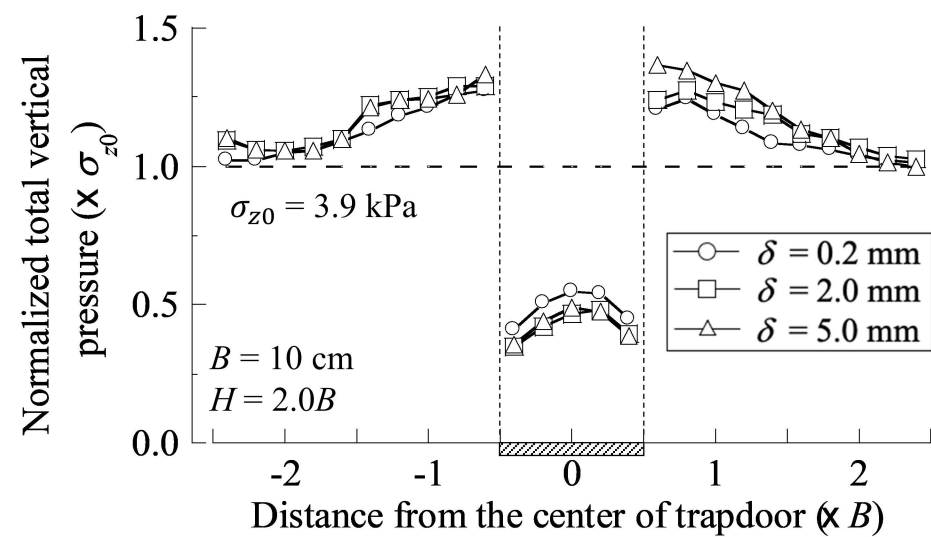


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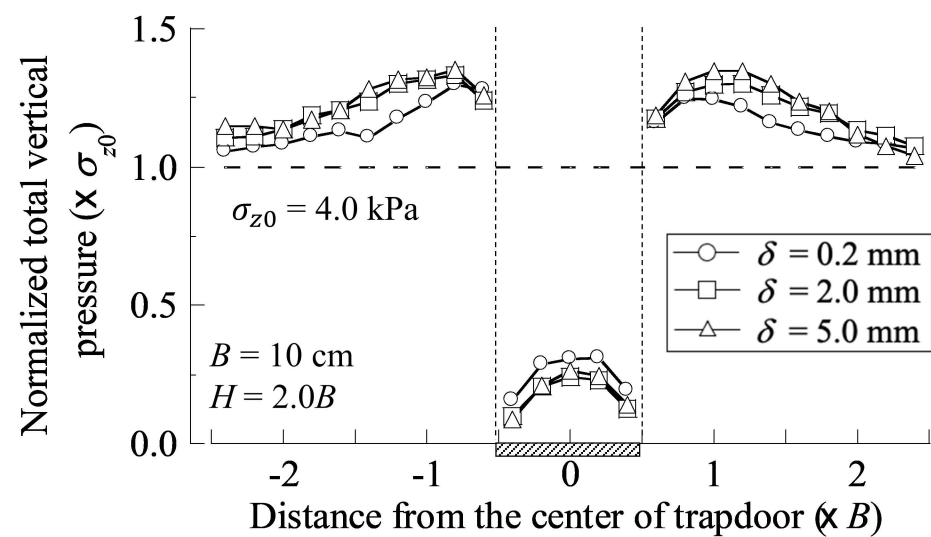




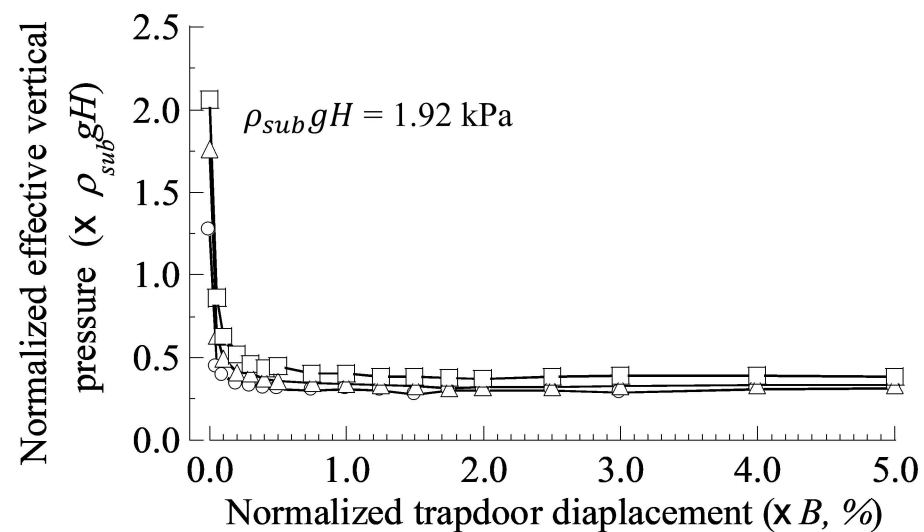
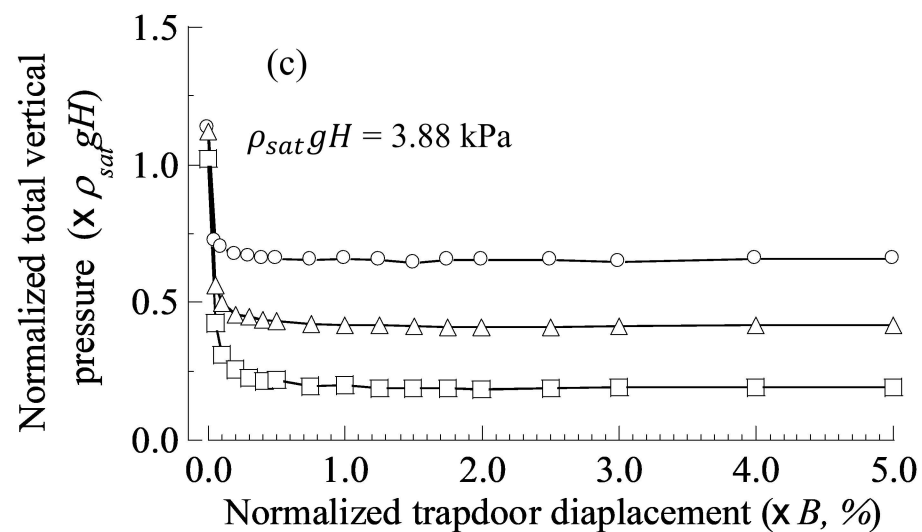
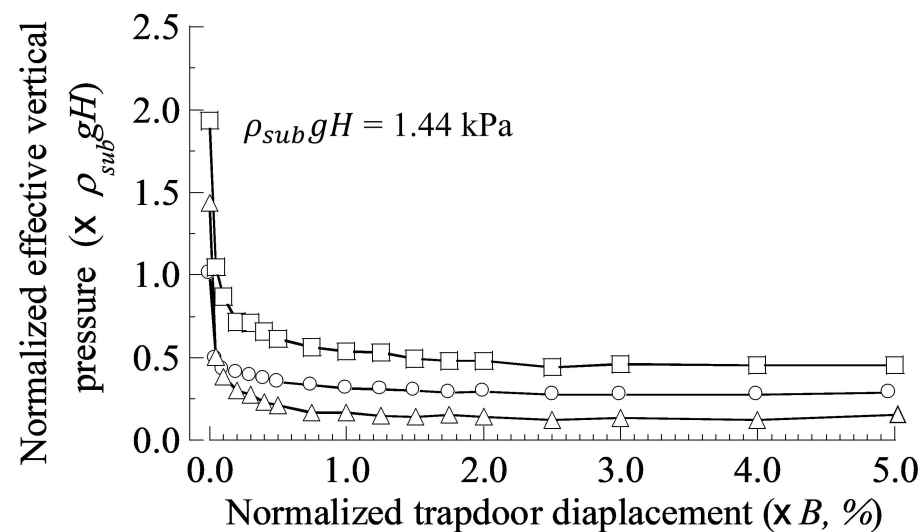
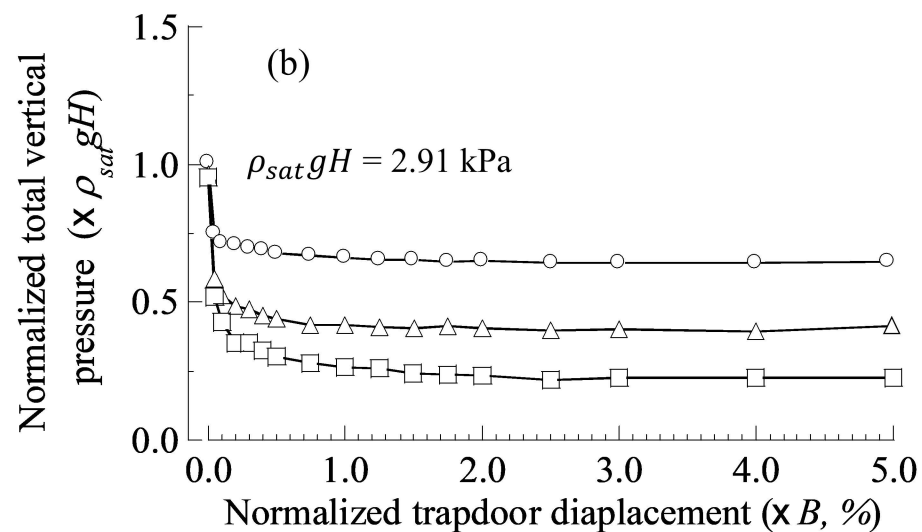
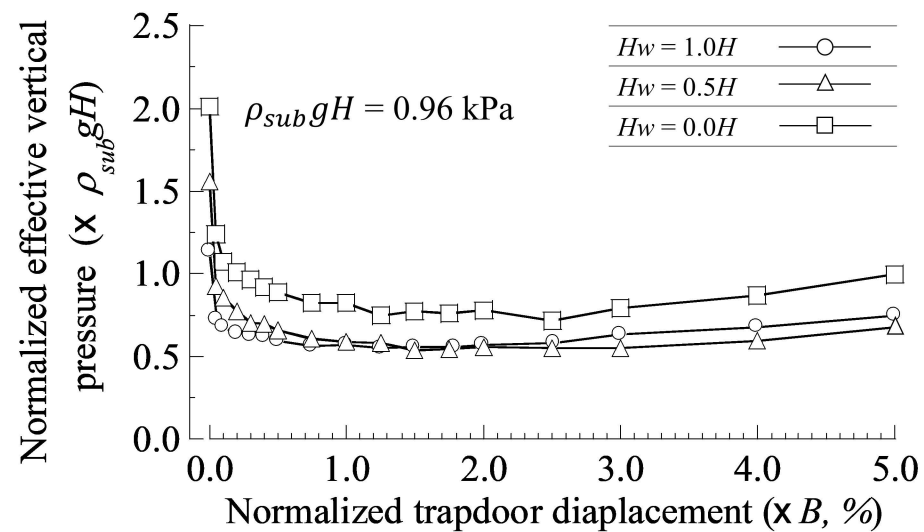
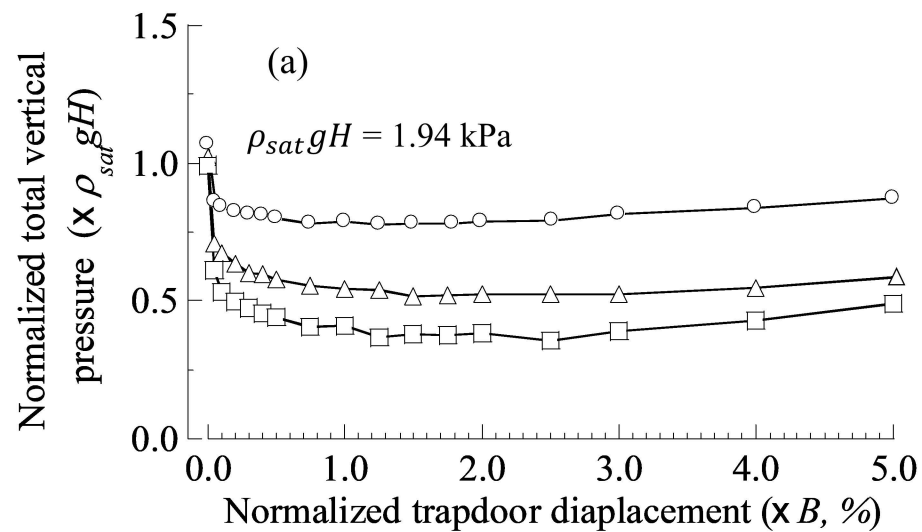
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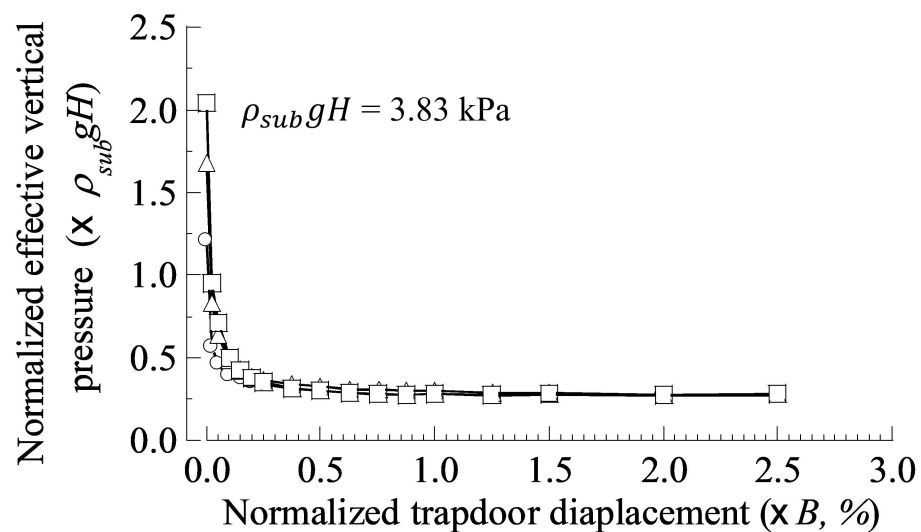
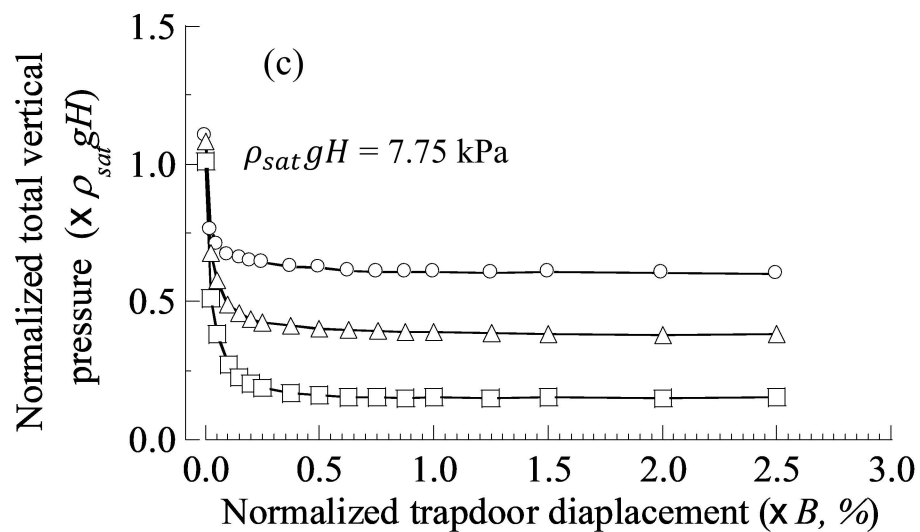
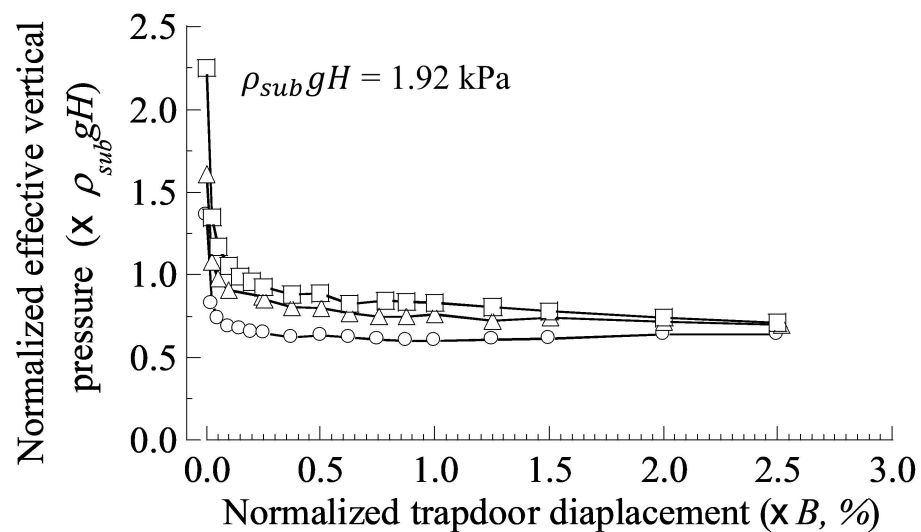
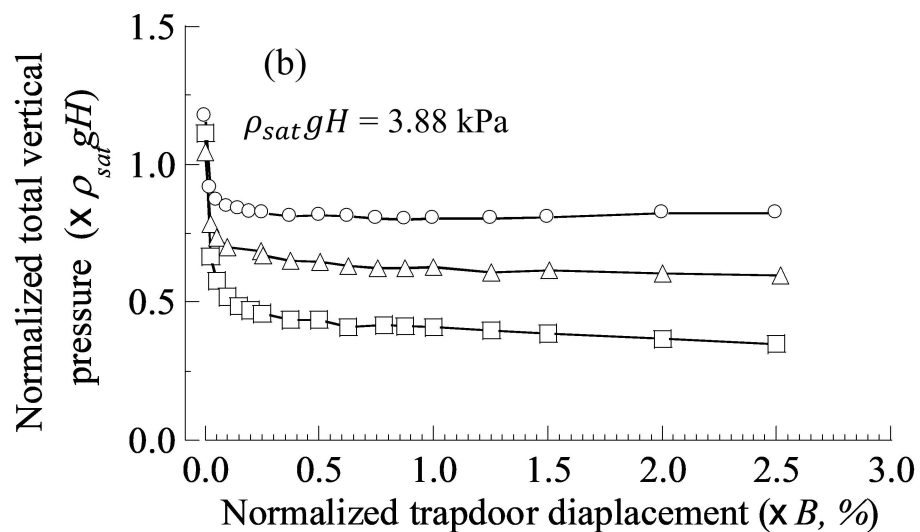
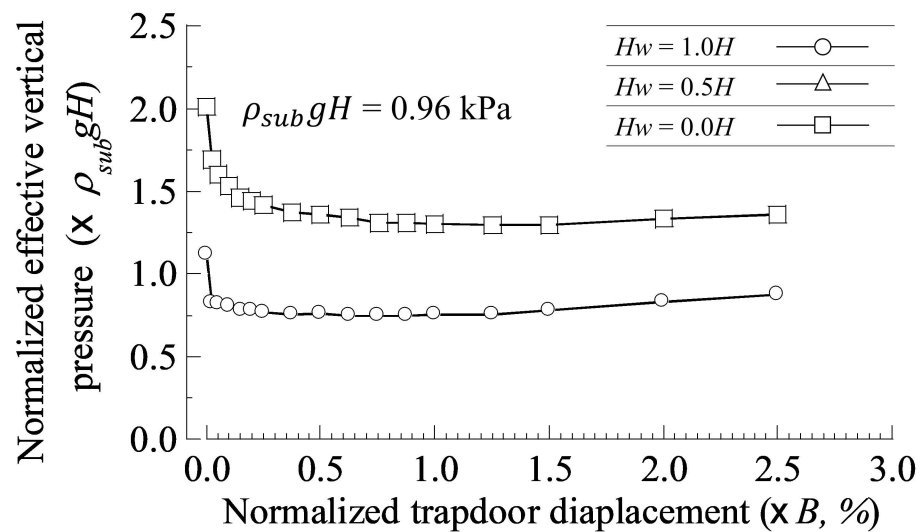
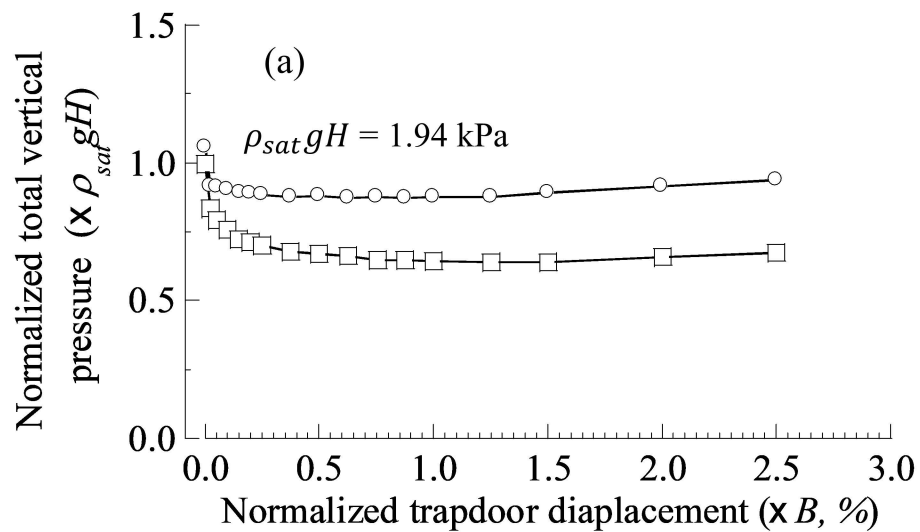


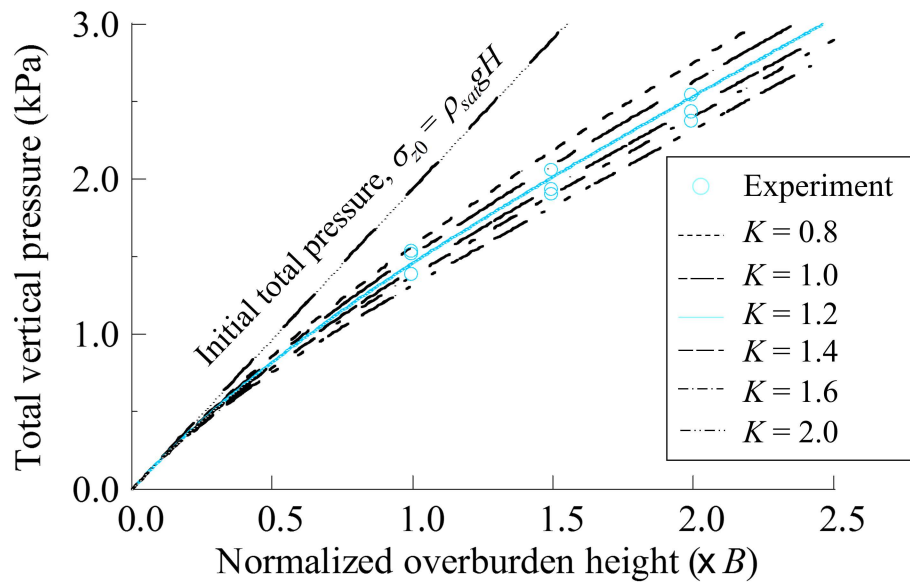
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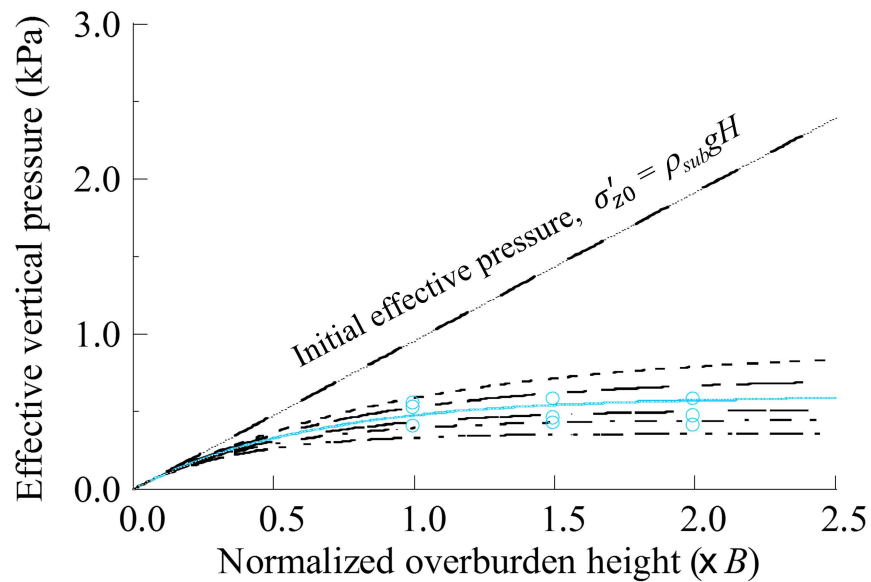
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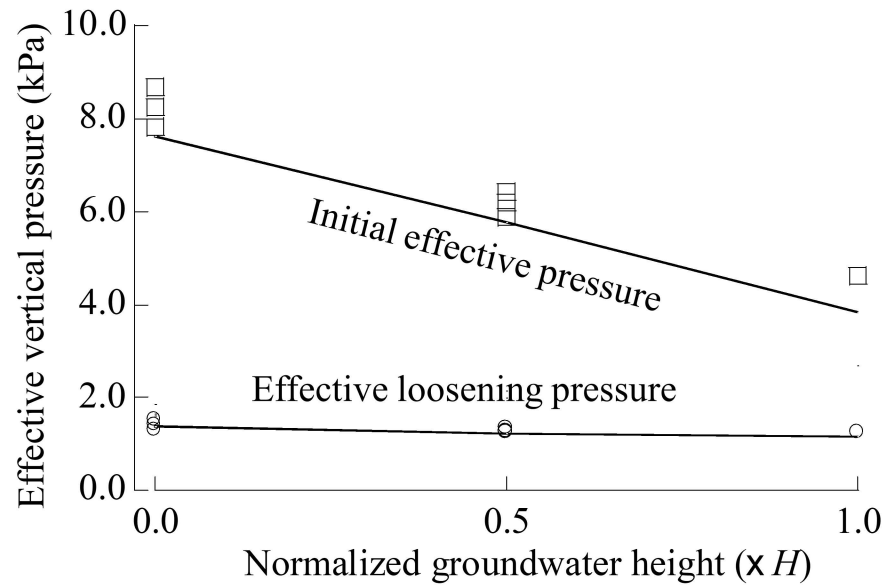
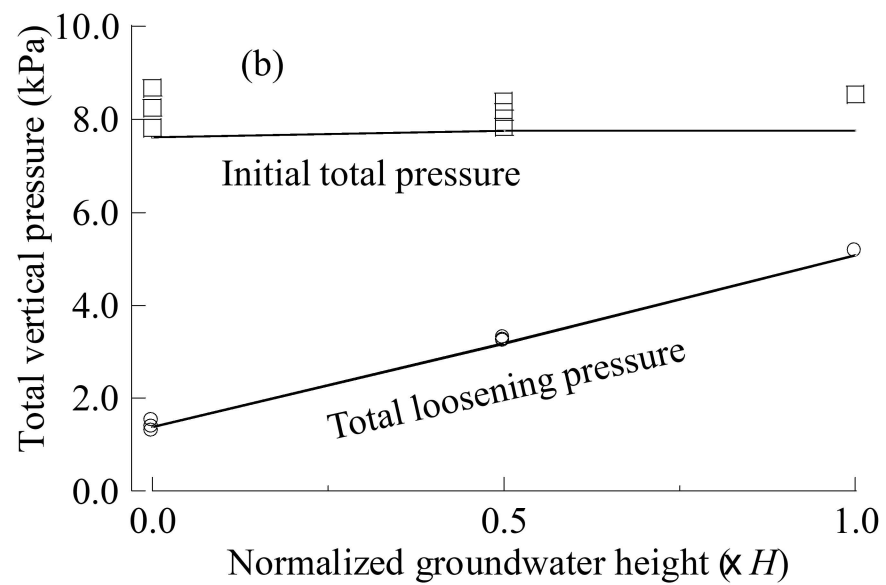
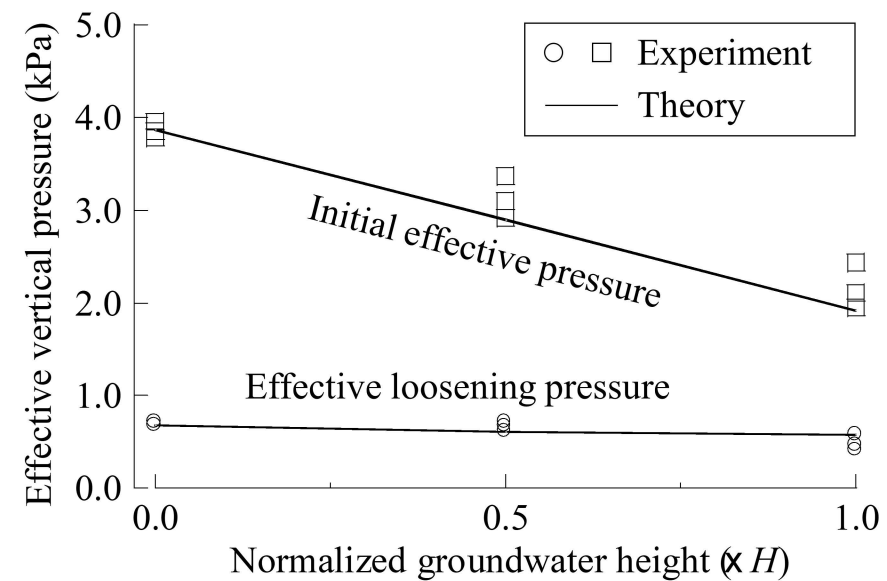
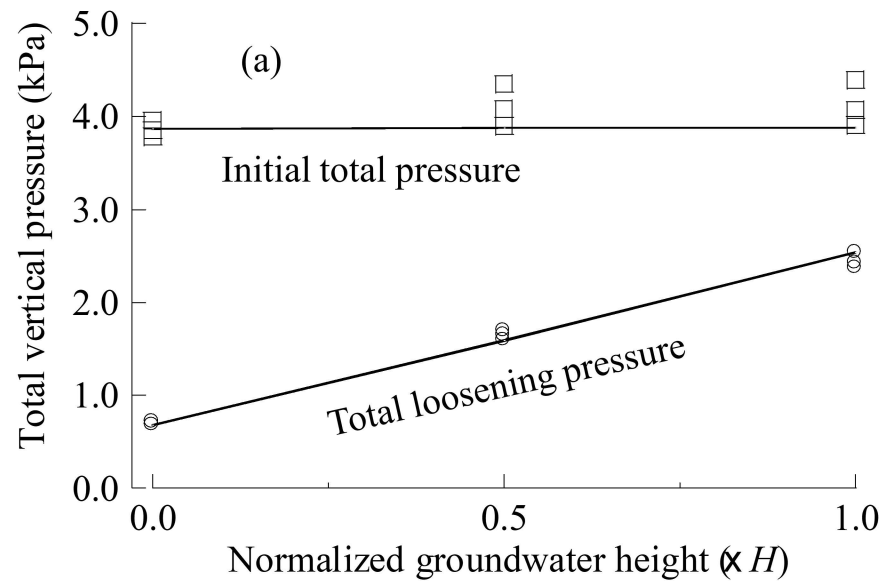


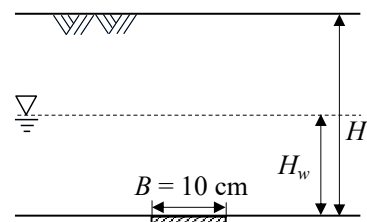
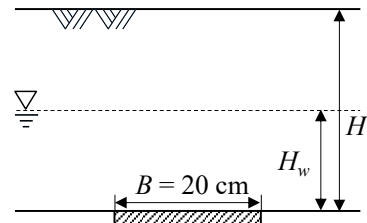


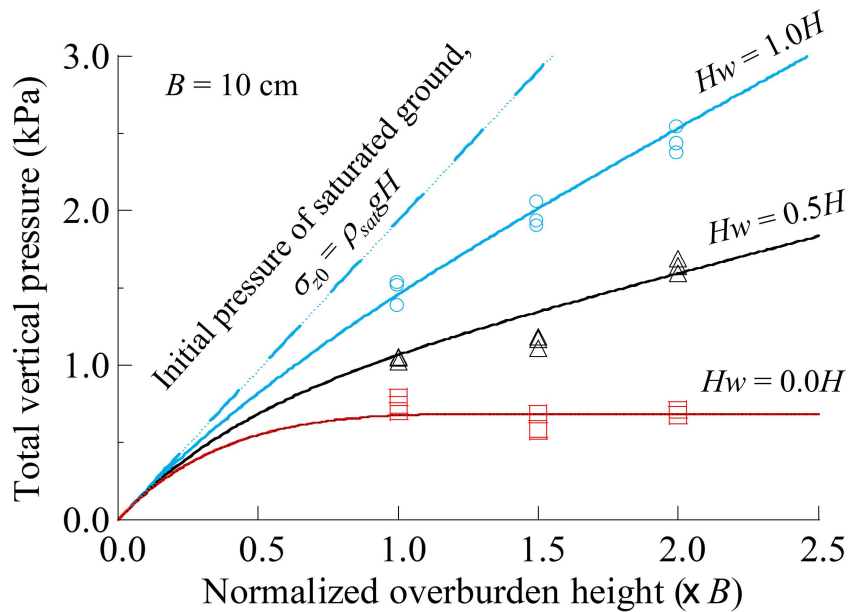
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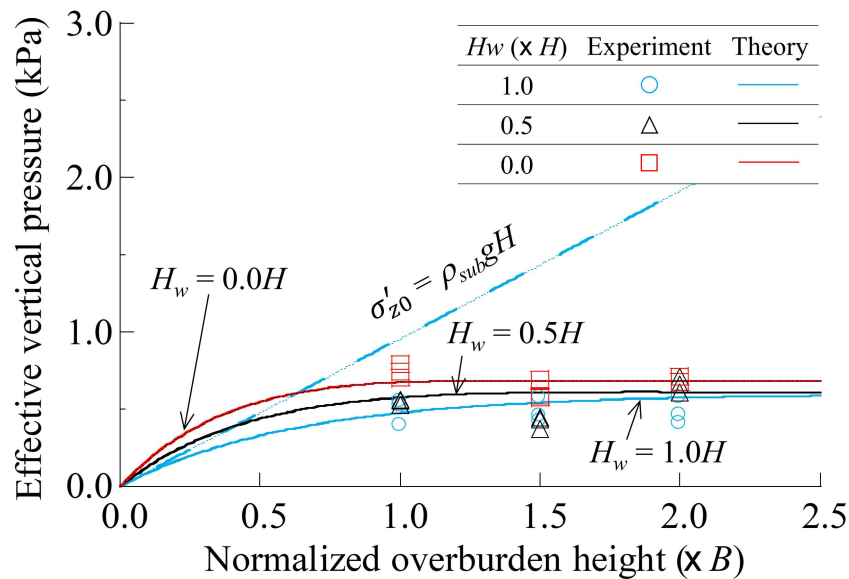
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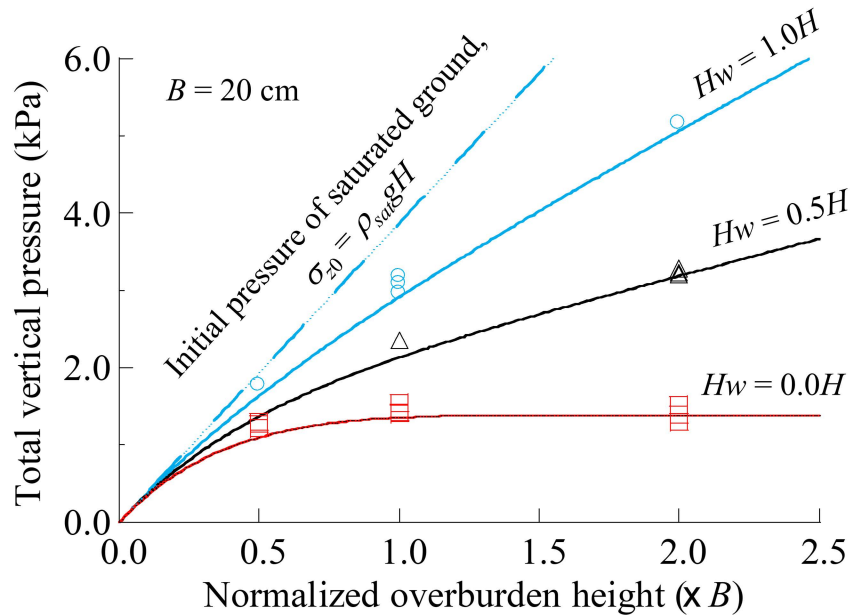
Schematic diagram	State of ground	B (cm)	H/B	H_w/H
	Saturated	10	1.0, 1.5, 2.0	1.0
	Unsaturated		1.0	0.0, 0.5
			1.5	0.0, 0.5
			2.0	0.0, 0.5
	Saturated	20	0.5, 1.0, 2.0	1.0
	Unsaturated		0.5	0.0
			1.0	0.0, 0.5
			2.0	0.0, 0.5



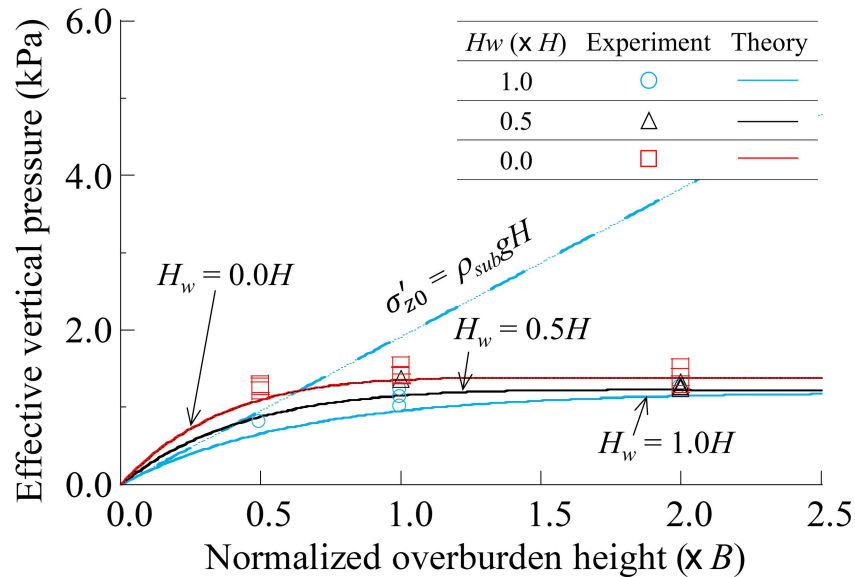
(a)



(b)



(a)



(b)

