Influence of sheet pile on stress distribution in non-invert tunnel: A centrifuge model study

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ABSTRACT

The interaction between sheet piles and existing non-invert tunnels is crucial in underground construction. This study investigates how sheet piles affect stress patterns in such tunnels, particularly their impact on the tunnel's reaction to surcharge load. The impact of sheet piles on a tunnel model's behaviour under surcharge load conditions was investigated through centrifuge model tests at a 1/40 scale. Image analysis during these tests offered insights into soil deformation and provides a comprehensive understanding of how soil responds to different stresses. The findings indicate that the presence of sheet piles in both sides of tunnel change the moment distribution in tunnel linings, leads to reversal of stress distribution in the crown elements, and increased moment values at the invert and spring elements. Additionally, the presence of sheet piles with a surcharge load not only intensified the deformed zones around the tunnel lining and the invert heave but also increased the vertical displacement above the tunnel.

Key words: *centrifuge model, tunnels, surcharge load, sheet pile, stress distribution*

1. Introduction

1.1. Study motivation

The Press-in Method, enhanced by augering techniques, has proven effective for pile installations in hard and stiff ground conditions, as demonstrated in the practical applications within the United Kingdom by Yamaguchi *et al.* (2018). While sheet piles provide essential support and protect against external pressures, they can also adversely affect existing tunnel linings. Okhovat *et al.* (2010) explored the effectiveness of sheet piles in mitigating uplift caused by liquefaction and managing damage in underground RC ducts during seismic events, emphasizing the importance of careful design to reduce the risk of increased shear damage. While researchers have primarily focused on full tunnel sections, there has been limited investigation into the impact of installing sheet piles near mountain tunnels that are subjected to surcharge loads. These tunnels are designed with both full and non-invert sections. For a visual reference, **Fig. 1** illustrates an example of a mountain tunnel subjected to a surcharge load in Nagasaki, Japan.

The potential for deformation, cracking, or even structural failure in tunnel linings, resulting from the installation of sheet piles, underscores the necessity of comprehensive investigation.

1.2. Objectives

This research investigates the interactions between sheet piles and non-invert tunnels concerning stress distribution and focusing on the influence of sheet piles on the tunnel's response to surcharge load. A centrifuge model test at a 1/40 scale was used to examine a tunnel model under two scenarios with and without a simulated sheet pile, both under surcharge load and without it. Furthermore, the study utilizes image analysis techniques, as outlined by Ueno *et al*. (2014), to monitor vertical displacement and soil deformation due to surcharge load.

Fig. 1 Mountain tunnel in Nagasaki, Japan

2. Methodology

2.1. Centrifuge modeling at Tokushima university

The centrifugal model experimental apparatus, developed at the University of Tokushima, features an effective radius of 1.55 m, and is designed to replicate specific stress conditions in model ground through rotation and the application of centrifugal force. It can achieve a maximum centrifugal acceleration of 100g and supports a capacity of up to 40 g·ton, allowing for the efficient simulation of various ground stress conditions, as shown in **Fig. 2.**

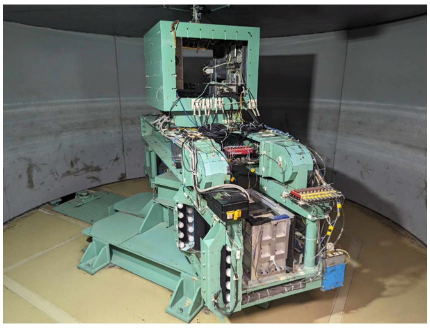


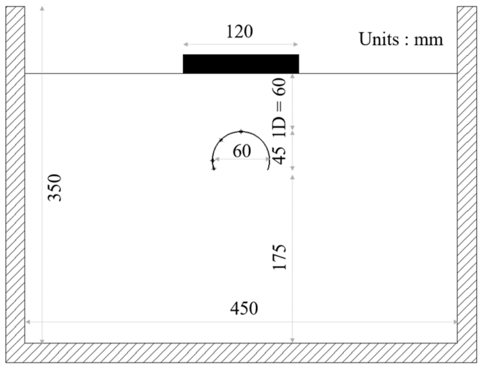
Fig. 2 Centrifuge apparatus of Tokushima university

Two experimental tests were conducted to evaluate the impact of sheet piles on tunnel lining, both with and without the surcharge load. Each test adhered to a consistent procedure, where the acceleration was incrementally increased from 1 g to 5 g, 10 g, 20 g, 30 g, and ultimately 40 g, before being reduced back to 1g. Subsequently, a steel plate with mass 6.92 Kg was applied followed by a second cycle of acceleration increase from 1g up to 40 g, and then a decrease to 1 g. The detailed methodologies for both tests are presented in **Table 1**.

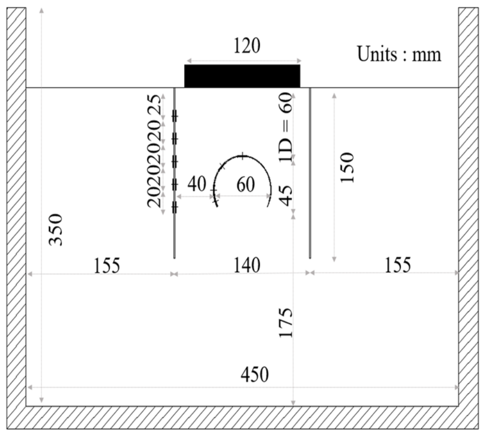
Table 1. Experiment procedures.

Steps	Experiment 1 without sheet pile	Experiment 2 with sheet pile
Step.1	Increase acceleration 5,10,20,30,40 (No Load)	Increase acceleration 5,10,20,30,40 (No Load)
Step.2	Return to 1 g	Return to 1 g
Step.3	Apply Load and Increase acceleration 5,10,20,30,40 g	Apply Load and Increase acceleration 5,10,20,30,40 g
Step.4	Return to 1 g	Return to 1 g

2.2. Model details, and material properties



(a) Experiment 1 without sheet pile



(b) Experiment 2 with sheet pile

Figs. 3(a, b) Model setup

The model setup and dimensions for both experiments are illustrated **in Figs. 3(a, b)**. The model was assembled inside a rigid container with internal dimensions of 450 mm wide, 350 mm high, and 200 mm deep. This container was designed to provide a stable and controlled environment for the experiment.

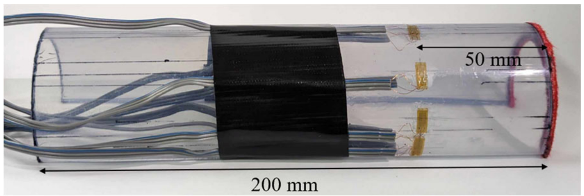
To simulate the soil environment in the centrifuge model test, dry silica sand (No. 6), known for its uniform grain size and physical properties, was used. Material properties are shown in **Table 2.** Sand was uniformly dispersed within the container using the air pluviation method, as described by Ueno (2000). The device was adjusted to regulate the pouring rate and the drop height of the sand. A drop height of 70 cm and 4 mm diameter holes for pouring were selected to reach a 50% relative density, essential for creating uniform soil conditions.

Table 2. Material properties of silica sand No.6

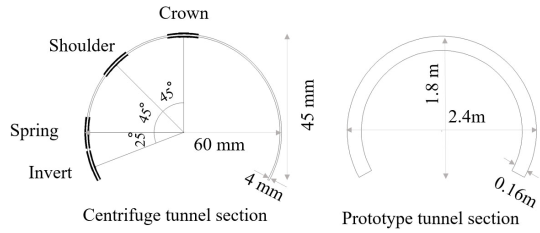
	Silica sand No. 6
Specific gravity: ρs (g/cm³)	2.644
Maximum dry density: $\rho dmax$ (g/cm³)	1.595
minimum dry density: $\rho dmin$ (g/cm³)	1.328
Maximum void ratio: e_{max}	0.991
Minimum void ratio: e_{min}	0.658
D_{10} (mm)	0.131
D_{30} (mm)	0.185
D_{60} (mm)	0.273

In our model, we aim to simulate a surcharge load that results in an approximate stress of 0.12 MPa on the tunnel lining. To achieve this, we utilized a steel plate measuring 12 cm in width, 19 cm in depth, and 4 cm in thickness, with a total mass of 6.92 kg. This configuration was specifically selected to ensure that, under the condition of 40 g of centrifuge acceleration, it would exert the desired stress level on the model.

To minimize boundary effects, the tunnel model was positioned more than three times its diameter away from the container's right, left, and bottom sides. The overburden depth above the tunnel was set equal to the tunnel's diameter. UPVC was selected instead of concrete, due to its flexibility and durability, to enhance accuracy and prevent breakage. The model, with a 6 cm diameter, 4.5 cm height, and 4 mm thickness, represented a prototype scale of 2.4 m diameter and 16 cm wall thickness at a 40g scale. Strain gauges at critical points crown, shoulder, spring, and invert recorded the strain response to provide insights into tunnel reactions to sheet piles and surcharge load. **Figs. 4(a, b)** illustrate the dimensions of both the model and the prototype tunnel section.



(a) UPVC Tunnel tube with strain gauges



(b) Centrifuge and prototype tunnel section

Figs. 4(a, b) Tunnel sections

Sheet piles were positioned 4 cm from the 6 cm diameter tunnel model on both sides to ensure clear separation for observing tunnel behavior under surcharge load. This setup, extending from the model's top to a depth of 15 cm as shown in **Fig. 3(b)**. Two stainless steel plates were used, each 20 cm wide, 15 cm high, and 1 mm thick, to simulate the sheet piles technique in the centrifuge model tests. With 40 g of centrifuge acceleration, these dimensions are equivalent to prototype sheet piles 6 m high and 4 cm thick. To analyze their behavior in detail, 10 strain gauges were installed on one of the sheet piles, as shown in **Fig. 5**. These gauges precisely measured the strain in the sheet piles under the influence of the surcharge load and tunnel location.

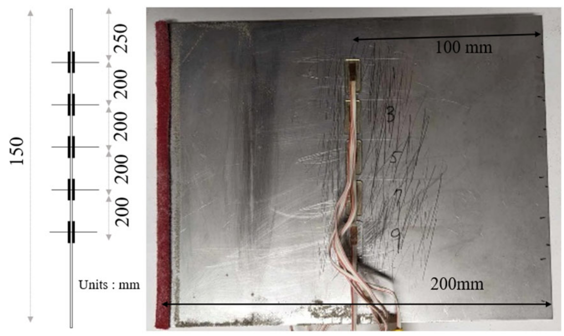


Fig. 5 Centrifuge model sheet pile

3. Experimental results

Utilizing the strain data from centrifuge model tests, the moment (*M*) and circumferential force (*F*) for the prototype were determined by **Eq. (1)** and **Eq. (2)**:

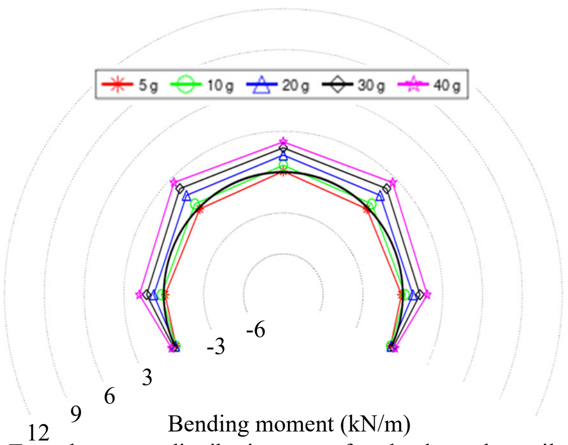
$$M = \frac{(\varepsilon_{outer} - \varepsilon_{inner})}{2} \times \frac{E \times I}{c} \quad (1)$$

$$F = \frac{(\varepsilon_{outer} + \varepsilon_{inner})}{2} \times E \times A \quad (2)$$

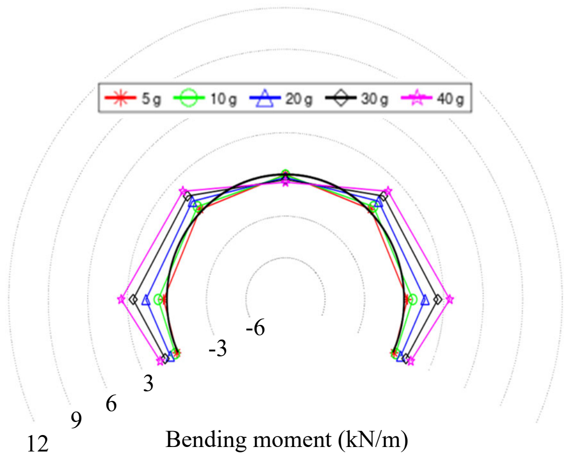
In these equations, ε_{outer} is Outer surface strain, ε_{inner} is inner surface strain, *E* is modulus of elasticity with value 3 MPa, *I* is moment of inertia, *c* is distance from the neutral axis to the outermost surface, and *A* is area of tunnel lining thickness over 1 m. These equations bridge between model scale observations and prototype structural behavior.

3.1. Tunnel lining moment and circumferential force

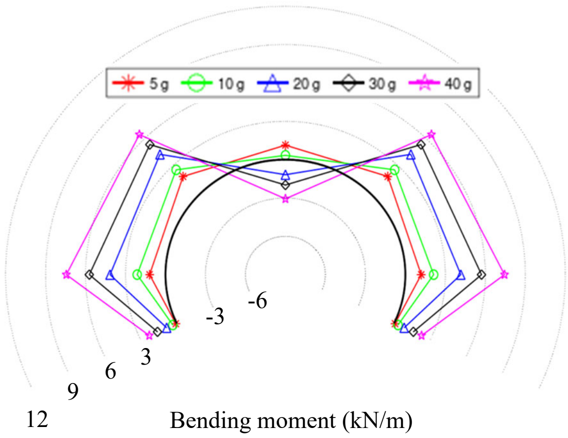
In our study, we assessed the impact sheet piles on tunnel behavior by measuring stresses at four critical points, the bottom invert, middle spring, side shoulder, and top crown. **Figs. 6(a, b)** illustrate the moment distribution in the tunnel lining both with and without sheet piles when no surcharge load is applied, while **Figs. 6(c, d)** illustrate the moment distribution for the same scenarios when a surcharge load is present. We noted that the presence of sheet piles on both sides of the tunnel concentrates pressures in the area above the tunnel, leading to increased bending moments at the invert and spring elements. Moreover, the crown elements experience a reversal in bending moment due to the sheet piles' influence. The addition of a surcharge load not only confirmed these effects but also intensified the measured values.



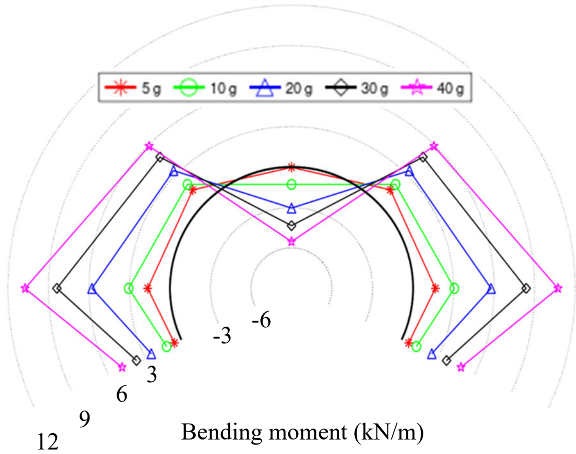
(a) Tunnel moment distribution case of no-load, no-sheet pile



(b) Tunnel moment distribution case of no-load, with sheet pile



(c) Tunnel moment distribution case of load, no-sheet pile

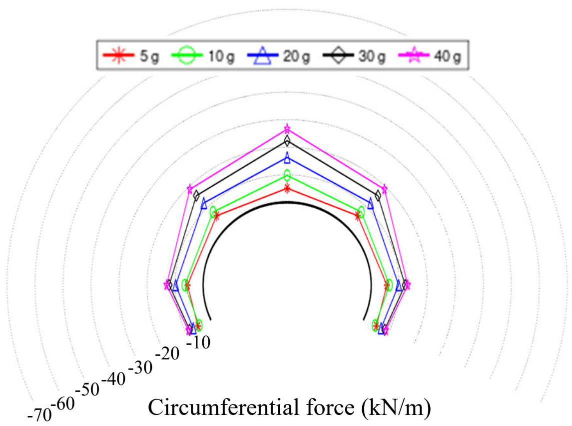


(d) Tunnel moment distribution case of load, with sheet pile

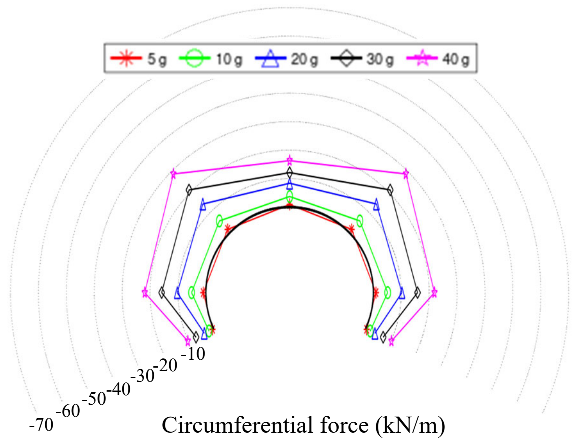
Figs. 6(a, b, c, d) Tunnel moment distribution (prototype scale)

The circumferential forces within the tunnel lining are affected by the presence of sheet piles. **Figs. 7(a, b)** show the circumferential forces in the tunnel lining with and without sheet piles, when no surcharge load is applied. In this scenario, an appreciable increase in compression forces is noted at the invert, spring, and shoulder positions, while a reduction is noted at the crown. Applying a surcharge load intensified the observed effects as shown in **Figs. 7(c, d)**. This variability in compression forces distribution underscores the need for careful consideration of tunnel lining design to ensure it can withstand uneven loading and maintain structural integrity under varied conditions.

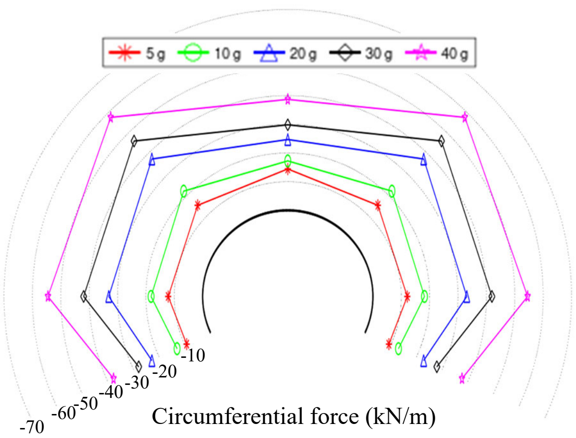
Consequently, the installation of sheet piles near non-invert tunnels has the potential to cause deformation, cracking, or even structural failure of the tunnel lining if not properly addressed. Therefore, it is evident that this installation can induce significant changes in circumferential forces and moment distribution. These changes manifest not only as increased values but also as reversals in bending moments, particularly under surcharge loads, thereby amplifying the issue.



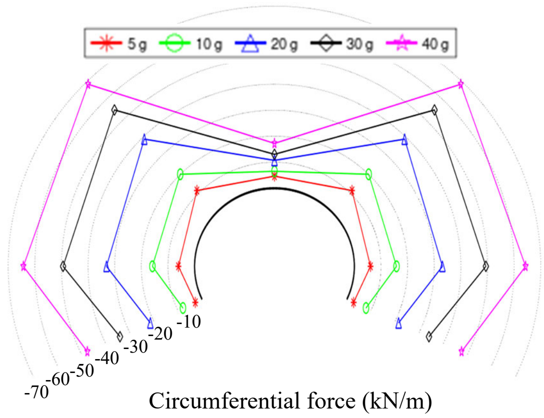
(a) Tunnel Circumferential force case of no-load, no-sheet pile



(b) Tunnel Circumferential force case of no-load, sheet pile



(c) Tunnel Circumferential force case of load, no-sheet pile



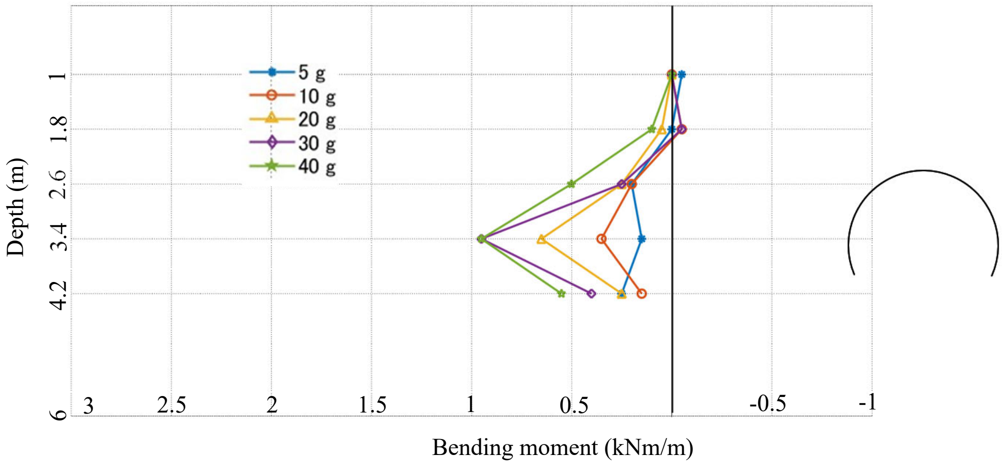
(d) Tunnel Circumferential force case of load, sheet pile

Figs. 7(a, b, c, d) Tunnel Circumferential force distribution (prototype scale)

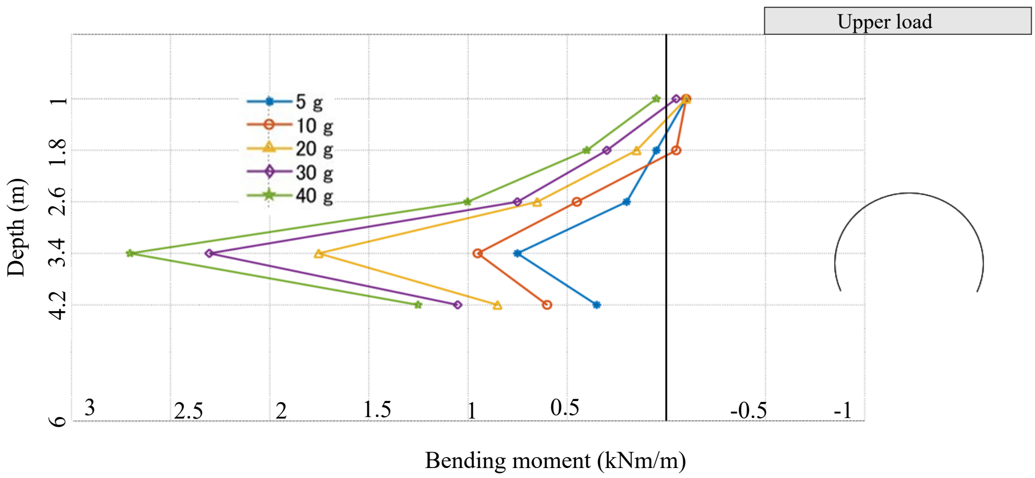
3.2. Sheet pile moment distribution

The moment distribution of the sheet pile was obtained using strain gauges attached to both sides of the sheet pile, as shown in **Fig. 5**. This distribution was calculated using **Eq. (1)**, where ε_{inner} represents the strain on the side facing the tunnel and ε_{outer} on the opposite side.

The distribution of bending moments along the sheet pile is significantly affected by the surcharge load, as shown in **Figs. 8(a, b).** Increasing the centrifuge acceleration from 5 g to 40 g notably increases moment distribution particularly in the area aligning the tunnel.



(a) Sheet pile moment distribution in case of no-load



(b) Sheet pile moment distribution in case of load

Figs .8(a, b) Sheet pile moment distribution (prototype scale)

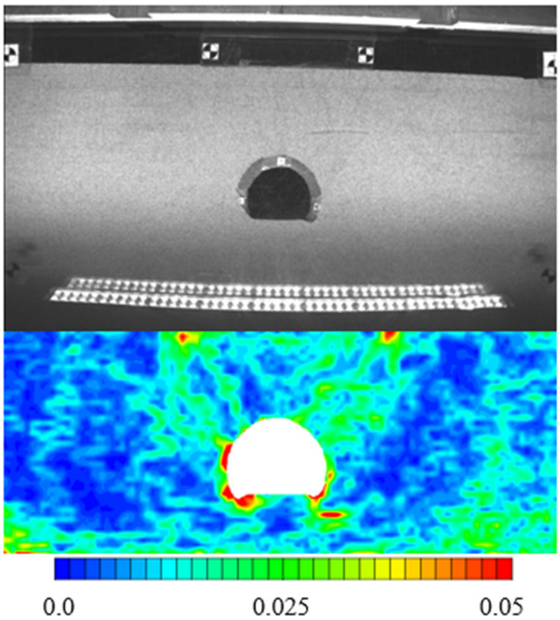
4. Image analysis

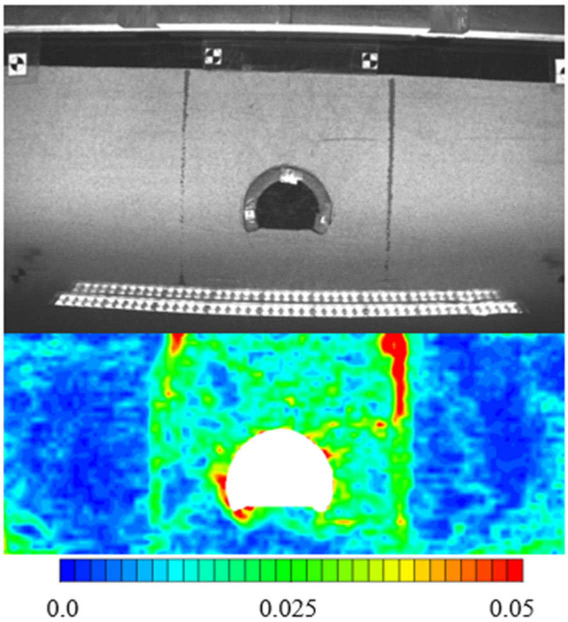
The image analysis technique utilized in this study employs a cross-correlation approach to measure soil deformation by comparing an original image to a deformed one. Developed initially by Ueno *et al*. (2014) and refined subsequently, this method involves analyzing brightness levels within specific pixel squares to accurately capture changes. During our analysis, we specifically examined the impact of the presence of sheet piles and surcharge load at an acceleration of 40g.

Defined in Mohr's Circle, the maximum shear strain is equal to the difference between the maximum and minimum principal strains. **Figs. 9(a, b)** show the distribution of maximum shear strain at 40g for both cases, with and without sheet piles, both cases with surcharge load. Our results indicated that the maximum shear strain is most pronounced at the area where sheet piles contact the ground. Furthermore, the presence of sheet piles on both sides around tunnel increases the maximum shear strain in the area between the sheet piles.

The presence of sheet piles on both sides of the tunnel concentrates vertical displacement directly above the tunnel, intensifying this effect. Conversely, without sheet piles, the surcharge load's impact is more broadly distributed, leading to reduced vertical displacement, as shown in **Figs.10(a, b)**. Moreover, vertical displacement of tunnel invert has been increased in case of present of sheet pile and surcharge load more than with the surcharge load only, as shown in **Fig. 11**.

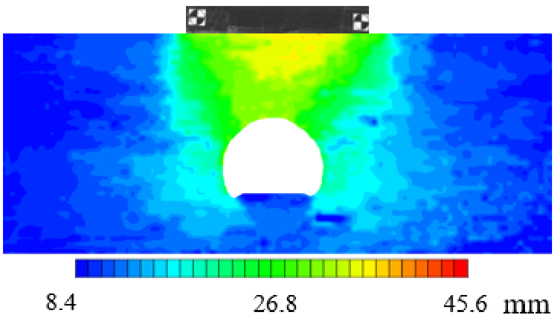
The preceding results indicate that the presence of sheet piles on both sides of the non-invert tunnel, particularly under surcharge loads, requires careful consideration. This installation has been found to lead to an increase in tunnel invert heave and vertical displacement in the area between the sheet piles.

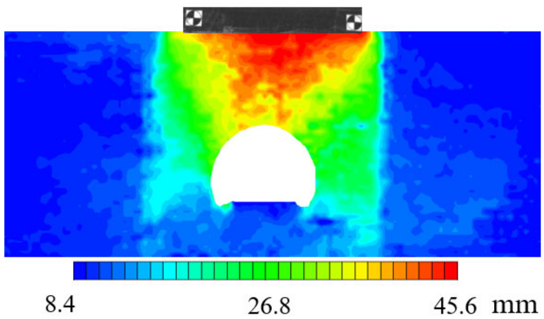




(a) Maximum shear strain at 40g acceleration, without sheet pile (b) Maximum shear strain at 40g acceleration, with sheet pile

Figs. 9(a, b) Distribution of Maximum shear strain





(a) Vertical displacement at 40g acceleration, without sheet pile (b) Vertical displacement at 40g acceleration, with sheet pile

Figs. 10(a, b) Distribution of vertical displacement (prototype scale)

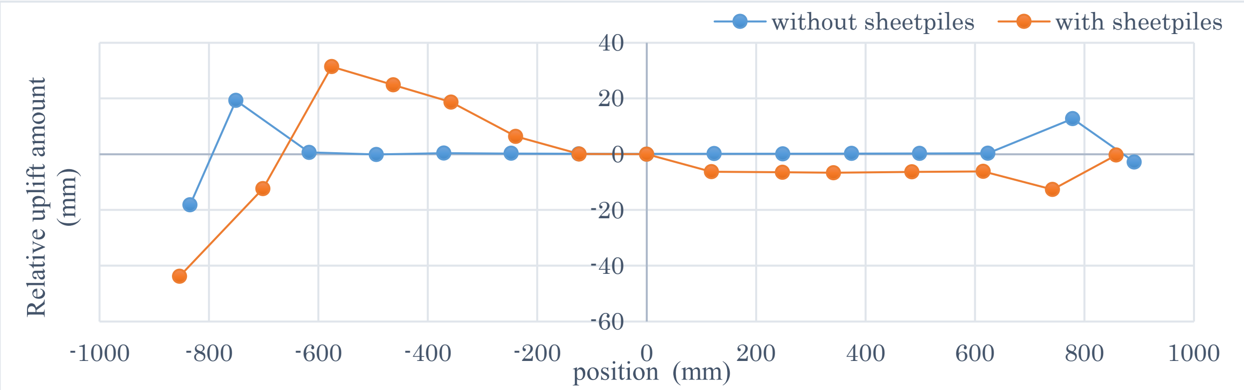


Fig. 11 Invert heave values (prototype scale)

5. Conclusion

In this study, we used a centrifuge model at a 1/40 scale to evaluate the effects of installing sheet piles near an existing tunnel, analyzing the tunnel model under two scenarios: with and without sheet piles, both under surcharge load and without it.

The presence of sheet piles makes the vertical stress increment distribution under surface load more uniform and constant with depth. In contrast, without using sheet piles, the vertical stress increment distribution tends to decrease with depth according to Bossinesq's theory. The increased vertical stress is transferred to the tunnel lining. Consequently, the tunnel lining experiences higher circumferential forces and bending moment values at the invert and spring elements, as well as a notable reversal in bending moments at the crown elements. These phenomena, which are exacerbated by surcharge loads, emphasize the potential for deformation, cracking, or even catastrophic failures if it is not appropriately managed. Furthermore, image analysis results indicate an increase in tunnel invert heave and vertical displacement in the area between the sheet piles.

In future research, the influence of tunnel shape on deformation will be investigated by comparing full tunnel sections with non-invert tunnels, considering both scenarios with sheet piles and surcharge load.

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