Earth pressure exerted on tunnels due to the subsidence of sandy ground

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ABSTRACT: In this paper, the change in the earth pressure acted on the tunnel lining and shear band formation of its surrounding soft sandy ground were investigated by the indoor tunnel heaving tests and F.E.M analyses. In the case of the rectangular tunnel model, the curved shear bands were developed from the edges of the tunnel roof toward to the ground surface and the earth pressure resulted in a dramatic increase just inside the edge of the roof. When circular tunnel model was lifted, the soil fractured at the points which leaned about 45 degrees from the crown and the vertical pressure increased on the both sides of the crown.

1 INTRODUCTION

If a ground displacement around a tunnel becomes excessive, this causes a shear band to develop in the ground as a result of the shear stress. In general, the investigation of the shape of the shear bands have contributed greatly in understanding the key for solving the various earth pressure mechanisms associated with tunnelling. Therefore, when estimating the changes in the earth pressure acting on a tunnel caused by some ground subsidence, care should be taken on how to develop the shear band in the ground.

Practically, the magnitude of earth pressure on the tunnel constructed in the consolidating ground was obtained by a method similar to the theory proposed by Spangler, as shown in Figure 1 (Spangler, 1948). Spangler's theory provides two vertical shear bands developing from the edges of a circular tunnel. The value of earth pressure acting on a tunnel was calculated to satisfy the stress equilibrium condition of the small element enclosed with shear bands. However, it was reported that the measured value of the earth pressure on the tunnel lining in the consolidating ground was much smaller than that of the earth pressure obtained from the Spangler's method (Tottori, 1978). And some experimental results have accounted for the difference in the shape of shear bands compared to Spangler's vertical one. (Akagi and Komiya, 1991, Nonogami and Konda 1984, Okochi et al. 1987)
In this study, tunnel heaving tests were carried out in the laboratory to investigate the changes in the earth pressure acting to tunnel due to the ground subsidence. The notable features of the change in the earth pressure acting to tunnel due to the ground subsidence were investigated by the model tests and F.E.M analyses. The changes in earth pressure and the deformation behaviour of soil were considered to be particularly dependent on the shape of tunnels, that is, the circular and rectangular tunnel models were used in this test. To simulate the shear band formation of soil due to the upheaval of tunnel, finite deformation F.E.M analyses were carried out and comparison results between the model tests and calculations can be observed.

2 LABORATORY INVESTIGATION

2.1 Test apparatus

To examine the deformations of sandy soil and the changes in earth pressure acting on a tunnel associated with ground subsidence, laboratory tests were carried out by heaving two types of tunnel models. The schematic diagram of the laboratory test apparatuses used are shown in Figure 2.

The physical properties of the tested sandy soil ground can be seen in Table 1. The dry Toyoura sand was flour put through a sieve from 500 mm above surface to make a sandy soil ground in 1500 mm wide and 300 mm in depth soil container. For the shear bands made visibly, the striped pattern was made in the ground by putting flour the coloured sand at intervals.

Two types of tunnel models were used for these experiments; (a) 300 mm wide horizontal plate, and (b) 300 mm diameter semicircular tunnel model. The horizontal plate corresponds to the rectangular tunnel. Before the sandy ground was placed into a soil container, the tunnel model was placed at the centre of the bottom of the container. Five pressure gauges were affixed to the horizontal plate at equal intervals, and another two pressure gauges were placed on the contiguous point on the bottom of the soil container, as shown in Figure 3. Two pressure gauges were placed on the both sides of bottom of container outside the plate, to measure the earth pressure around the tunnel. No pressure gauge was installed on the semicircular tunnel model because it was felt uneasy to keep the smooth curved external surface of the model. The tunnel model went up vertically at the velocity of 1.0 mm per a minute.

2.2 Test results

Typical cross-sectional views of the shear bands formations which were given by the upheaval to 20 mm of the horizontal plate are shown in Figures 4(a) and 4(b). Figure 4(a) is the case of 300 mm deep and
Figures 4 Shear band formation (Horizontal plate)

Figure 4(b) is 600 mm deep respectively. In the case of the horizontal plate, the curved shear bands were developed from the edges of the plate toward to the ground surface.

Figures 5(a) and 5(b) show the distribution of earth pressure measured on the horizontal plate of 300 mm and 600 mm deep, respectively. The earth pressure in these figures was displayed by the pressure ratio R', which is defined as the difference between measuring pressure and initial pressure divided by the initial pressure. The earth pressure resulted in a dramatic increase just inside the edge of the plate. The pressure ratio outside the plate became less than 1.0, that was, the earth pressure decreased outside the plate because the ground was lifted up by the upheaval of the plate. A point where it changes drastically in the earth pressure were adjacent to the shear bands.

On the other hand, in the case of using the semicircular tunnel model as shown in Figures 6(a) and 6(b), the position of the shear band formation was changed. Figure 6(a) shows the shear bands which were given by the test of 300 mm deep tunnel and Figure 6(b) was 600 mm deep. When semicircular tunnel model was lifted, the soil fractured at the point which leaned about 45 degrees from the crown.
3 Finite Element Simulation of Laboratory Experiments

3.1 Numerical Models

The Druker-Prager model was used to model the stress-strain behaviour of the sandy soil. The input parameters used in the analysis are listed up in Table 1. Most of the input parameters were determined from the results provided by standard geotechnical tests. The initial distribution of the pressure in the ground was obtained based on the results of a gravitational calculation with $K_0$ conditions. The horizontal plate and semicircular tunnel were modelled as a rigid element, introducing compulsive displacements vertically at the boundary nodes of finite element mesh under a spatially fixed tunnel model configuration.

It has been recognized that the shear band formation is affected by disturbance associated with the interface friction between the soil and tunnel. Therefore, contact elements were placed at the interface of the elements that represent the tunnel and the adjacent soil to investigate interface friction effects on the ground deformations.

Both the localizing of the deformation and the rigid rotation are supposed to influence the shear band formation around the tunnel, and their effects cannot possibly be analyzed using the small strain theory. Therefore, the finite deformation F.E.M. program was used to simulate the stress-strain behaviour which was obtained by the laboratory tests.

3.2 Numerical Results

The plain-strain views of the computed ground deformation and a contour line of the shear stress of the sandy ground at 20 mm upheaval of the horizontal plate are shown in Figures 7(a) and 7(b). Figure 7(a) shows the test results of 300 mm deep plate and Figure 7(b) shows one of the 600 mm deep. The computed shear stress resulted in dramatic increase at the narrow area bounded on the edge of the plate, and it was fitted by the shear bands which were observed during the laboratory tests.

Figures 8(a) and 8(b) shows the computed ground deformation and a contour line of the shear stress at a 20 mm upheaval of the semicircular tunnel model of 300 mm deep and 600 mm deep test, respectively. The shear stress increased at the point which learned about 45 degrees from the crown of the tunnel model, and that attended to give a better match to the location which the shear bands were produced by the laboratory tests.
Table 1  Physical properties of sandy soil.

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<table>
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4 CONCLUSIONS

In this study, the notable features of the change in the earth pressure acted on tunnels and the formation of the shear bands due to the ground subsidence were presented by the laboratory tests and F.E.M. analyses.

In the case of the horizontal plate, the curved shear bands were developed from the edges of the plate toward to the ground surface.
The earth pressure resulted in dramatic increase just inside the edge of the plate.
The ground outside the plate were in a condition of unloading due to the stress release as the plate upheaved.
When the semicircular tunnel model was lifted, the soil fractured at the point which leaned about 45 degrees from the crown, and the vertical pressure increased on the both sides of the crown.

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REFERENCES

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