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Research Paper

Modelling ground movements near a pressurised tunnel heading in drained granular soil

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ABSTRACT

Face pressurised tunnel boring machines usually engender a complex "expanding" displacement field near the tunnel heading, which has not been well studied. In this article, the ground movements near a pressurised tunnel heading in drained granular soil were first investigated by physical model tests, in which the catastrophic scenario of face collapse and the normal situation of shield advance were both reproduced. Then coupled Eulerian-Lagrangian analyses were performed to gain further insights into the ground movements near a pressurised tunnel front. The simulation results showed good agreements with the test data, and the ground response mechanism was finally made clear.

1. Introduction

Tunnelling inevitably perturbs surrounding soil. In urban areas, to ensure the safety of the existing nearby structures, it is important to assess tunnelling-induced ground movements.

Conventional empirical assessment of ground movements due to tunnelling is usually carried out using an assumption that resultant vectors of ground displacement are directed to a single focus, e.g. the tunnel axis [1–4]. Such an assumption could be made mainly because conventional empirical approaches were proposed largely based on case histories of open-face tunnelling, e.g. tunnelling with a non-pressurised shield or sprayed concrete lining, which ensured a consistent "contracting" field of ground displacement.

In comparison to the ground response resulting from open-face tunnelling, the ground displacement fields due to closed face tunnelling, e.g. tunnelling with earth-pressure-balance machines (EPBMs) or slurry-pressure-balance machines (SPBMs), can be very complex. Although the surface settlement profiles may be modelled as Gaussian curves, local "expanding" fields of ground displacement were often observed in the vicinity of the tunnel heading, which were usually considered as the result of excessive face pressure [5,6]. However, recent case histories [7,8] suggested that such expanding response could still be observed even with insufficient face pressures (face pressures are lower than the values of horizontal ground stresses at the tunnel axis). This counterintuitive observation implied that a complex kinematic mechanism, probably dependent on other factors in addition to face pressure, may take place within the subsurface ground. As little research exists with attempts made to detail the local response of ground near a pressurised tunnel heading, hitherto the complex mechanism remains unclear.

In this article, the ground movements near a pressurised tunnel heading were studied using both experimental and numerical approaches. Physical model tests were performed in dry sand to reproduce the main process of excavation with a pressurised front, e.g. the support at the tunnel face using the excavated material, the extraction of the spoils in the excavation chamber, and the advance of the tunnel boring machine (TBM). Following the principle from simple to complex, the scenario of tunnel face collapse (active failure) was first investigated. In these tests, the TBM did not move, and the soil mass beyond the tunnel face was deliberately brought to failure by excessive discharge of the spoils. Then the case of a tunnel dug with an advancing TBM was simulated, the face pressure in the tests was kept at a moderate level so that stable working conditions can be ensured. The internal displacements of the ground in front of the tunnel face were monitored in detail during the above two categories of tests so that a good understanding of the relationship between face support conditions and resulting ground movements can be achieved. Numerical modelling was carried out subsequently to replicate the complete process of the physical model tests. To well simulate the flow of the soil mass into the excavation chamber, the large deformation modelling technique, coupled Eulerian-Lagrangian (CEL) approach were adopted. The simulation was confirmed to be reasonable through a comparison with the experimental

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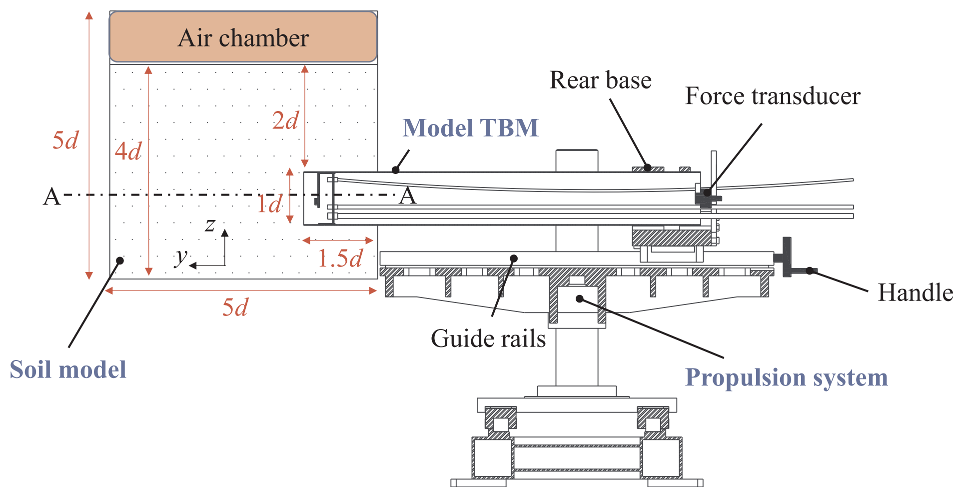

Fig. 1. Schematic of experimental setup (*d* is the diameter of the model TBM).

data, on the basis of which the underlying mechanism of the ground displacements observed in the tests was finally interpreted.

2. Physical modelling

2.1. Experimental setup and instrumentation

The experimental setup was composed of three key components: the propulsion system, the model TBM and the soil model. A schematic diagram of the setup can be seen in Fig. 1.

The propulsion system allowed precise forward and backward motion of a rear base along the guide rails to be controlled by a handle. The model TBM, attached to the rear base, was modelled by a stainless steel tube, which had a geometric scale of 1/60 relative to a 6 m diameter shield machine. A tension–compression force transducer was fixed between the rear base and the shield tail to measure the total thrust during the model TBM advance.

Traditionally, the EPBM is usually selected for fine-grained soils (e.g. clays, silts) and the SPBM for coarse-grained soils (e.g. sands, gravels). Since the model tests in this paper assume tunnelling through sand, the model TBM was designed to simulate the operations specific to the SPBMs.

Fig. 2 shows a typical SPBM and its working principles. A characteristic feature of the SPBM is that an excavation chamber is divided by a so-called submerged wall into a working chamber and a pressure chamber. The communication between the two chambers is enabled by an opening in the invert section of the submerged wall.

In this paper, a comparable excavation chamber, which reserves main components in the aforementioned SPBM, was used in the model TBM (Fig. 2). A major departure of the model TBM from a prototype SPBM may arise in the modelling of slurry circuit. Considering that the model TBM would operate in the environment of dry sand, the process of bentonite injection was omitted, and only the extraction of spoils was modelled. The sand in the pressure chamber was extracted from beneath the bulkhead using three PVC tubes linked to a vacuum pump. The vacuum pump system rested on an electronic scale so that the mass of extracted sand could be measured. In a prototype SPBM, the removal of the spoils is accomplished in the pressure chamber, and non-negative pressure should be ensured in the working chamber throughout the tunnelling process. However, in the presented model TBM, negative pressure may be generated around the PVC tube due to vacuum suction. Therefore, the PVC tubes installed on the bulkhead should be kept far enough from the opening of the submerged wall to avoid the occurrence of negative pressure in the working chamber. Trial tests on suction indicated that the soil within a distance of approximately 0.25*d* could be sucked into the PVC tubes. Therefore, the distance between the bulkhead and the submerged wall was set as 0.25*d*, which ensured that the soil in the working chamber naturally flows into the pressure chamber without any influence of suction. Meanwhile, one PVC tube in the upper section was exposed to the atmosphere, aiming to provide an environment of air circulation within the pressure chamber, which was found to be of great importance to keep the other three tubes free of blockage. A pressure gauge was placed at the centre of the submerged wall to measure the soil pressure, which could be controlled with the penetration rate of the model TBM.

All the model tests presented in this paper were carried out under 1*g* condition. In recognition of the fact that soil dilation may have an adverse influence on the observed deformation and failure mechanisms at low stress levels in a small-scale model [9], a uniform surcharge of 100 kPa was applied to the model surface by means of an air chamber on the top (Fig. 1), which could alleviate the influence from low confining pressure [10,11] and ensure mimicking more closely the field response (stress variations and ground movements).

A cover to diameter ratio of 2.0 was chosen for all the tests presented in this paper. The model TBM was initially positioned inside the soil model with a buried length of 1.5*d*, which maintained the geometry scale between the machine length and diameter in many Prototype SPBMs of around 6 m diameter [12–14]. The geometry of the soil model in the horizontal plane passing through the tunnel axis (section A-A in Fig. 1) is shown in Fig. 3. The overall width and length of the soil model were 10*d* and 5*d*, respectively, which were deemed to be sufficient to minimise the boundary effects according to experience [15,16].

In this paper, a cap-rod device was developed to measure the internal displacements of the ground. As shown in Fig. 3, the device was mainly composed of a stainless steel tube and an aluminium rod with caps at either end. The cap on the part of the rod laid inside the model was designed to capture the movement of the soil, while the other cap on the part of the rod extending out of the model container aimed to provide a measuring point, whereby the displacement data were picked up by a laser type displacement sensor with a repeatable accuracy of 0.01 mm. The rod was sleeved by the stainless steel tube which was fixed to the model container such that the rod could only slide in the tube with only one degree of freedom. To minimize friction effects, the rod passed through a PTFE plug smeared with silicone fluid.

In principle, both the vertical and horizontal displacement should be measured around the tunnel heading in the model tests. However, the air chamber congested the upper section of the model container, making it almost impossible to implement the vertical arrangement of the cap-rod devices. Therefore, all the cap-rod devices were laid horizontally with only the horizontal displacements comprehensively