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Centrifuge modelling of tunnel face reinforcement using forepoling

A. Juneja[a,*], A. Hegde[a,1], F.H. Lee[b,2], C.H. Yeo[b,3]

[a] Department of Civil Engineering, Indian Institute of Technology Bombay, Powai, Mumbai 400 076, Maharashtra, India
[b] Department of Civil Engineering, National University of Singapore, 10, Kent Ridge Crescent, Singapore 119260, Singapore

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ABSTRACT

This paper investigates the effect of forepoles on stability of tunnel face and unsupported length during tunnel excavation in clay beds. Forepoles were modelled using 1 mm diameter brass rods. The tests were conducted using 65 mm diameter model tunnels with a flexible face at 100*g* centrifuge environment. The unsupported length of the tunnel varied between 1 and 1.5 times the tunnel diameter in different tests. The results seem to suggest that forepoles influence to reduce the length of settlement trough ahead of the tunnel face. However, width of the settlement trough remained unaffected. Excess negative pore pressures after collapse were noted to decrease with distance ahead of the tunnel face and increase with depth from the surface up to the tunnel axis. However, scatter in the measured data points suggest that the tunnel stability depends not only on the unsupported length of the tunnel but also on the length of forepoles. It is difficult to include these effects in the simple plasticity solution framework wherein the soil structure interaction is ignored.

1. Introduction

Forepoles are often used for supporting the ground ahead of the tunnel face during excavation. They also provide temporary support to unlined portion of tunnel (e.g. Pelizza and Peila, 1993). Forepoles are usually installed along the tunnel periphery in the longitudinal direction to form a supportive arch ahead of the tunnel face (Calvello and Taylor, 2000).

Jong et al. (2008) observed that forepoles behave as cantilever beams with free ends towards the tunnel face. Using 1 g model test results, they showed that maximum settlement occurred within one-diameter distance ahead of the tunnel face. Previous investigation using the centrifuge (e.g. Kamata and Mashimo, 2003) has shown that stiff forepoles prevent failure planes to reach the ground surface. Forepoles of length more than half of the tunnel diameter, were shown to improve the face stability.

Research by Hisatake and Ohno (2008) has shown that settlement ahead of the tunnel face can reduce when forepoles are installed in unsaturated sands. It is uncertain if these findings are applicable only to granular soils which can exhibit both volumetric and shear strains. On the other hand, undrained conditions are often maintained in tests using clay and hence volume of the settlement trough is usually equal to the volume loss in the tunnel (Casarin and Mair, 1981).

This paper investigates the effect of forepoles installed above the springline in model clay beds using centrifuge tests conducted at the National University of Singapore (NUS) geotechnical centrifuge (Lee et al., 1991). Surface settlement, and pore pressure changes in clay in front of the tunnel face are examined when support pressure in the tunnel is reduced to zero.

2. Experimental setup

Six model tests were conducted to investigate the effect of forepoling on face stability and deformation of unlined portion of tunnel during construction. The model tests were conducted at 100*g* centrifuge environment. Table 1 shows the variables using in this study. As can be seen, length of forepoles ahead of the tunnel face (L) and unsupported length of the tunnel (P) were the variables whilst tunnel cover (C) and the tunnel diameter (D) remained unchanged in the tests.

The tests were conducted using remoulded and reconsolidated commercially available kaolin clay. Table 2 shows properties of the clay used in this study. Model clay beds were prepared in strongbox of internal dimension 515 mm × 360 mm × 350 mm. The inside walls of the strong box were first coated with silicone grease and perforated flexible tubing placed over its base to facilitate drainage during consolidation. The tubing was then covered with a 5-mm thick sand layer. A sheet of propylene non-woven geotextile was also placed to provide a filter barrier in between

* Corresponding author. Tel.: +91 22 2576 7327; fax: +91 22 2576 7302.
E-mail addresses: ajuneja@iitb.ac.in (A. Juneja), amarnathhegde@gmail.com (A. Hegde), cveleefh@nus.edu.sg (F.H. Lee), g0500518@nus.edu.sg (C.H. Yeo).
[1] Tel.: +91 9967220904.
[2] Tel.: +65 6516 2274.
[3] Tel.: +65 81000256.

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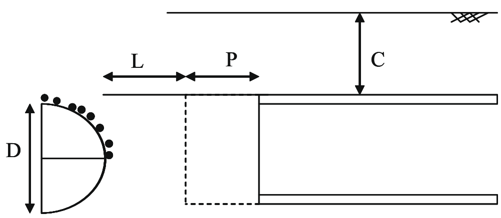
Table 1
Centrifuge testing programme.

Test name	Ground cover C (mm)	Tunnel diameter D (mm)	Unlined portion P (mm)	Embedded length of forepole ahead of tunnel face L (mm)
AT-1	65	65	0	NA
AT-2	65	65	65	65
AT-3	65	65	65	130
AT-4	65	65	0	195
AT-5	65	65	0	65
AT-6	65	65	97.5	97.5



Caption with table

the sand layer and the clay slurry. De-aired clay slurry with water content of about 1.5 times the liquid limit was then slowly placed into the container, ensuring that no air was entrapped during the pouring. The slurry was allowed to consolidate on the laboratory floor first under its own self-weight and later under a surcharge of 205 kPa placed in steps over a period of 25 days on the clay surface.

After completion of 1 g consolidation, the front perspex window of the strongbox was removed to cut a 65 mm diameter semi-circular cylindrical cavity in the clay. The clear distance between the cavity and the top surface was 65 mm in all the tests. Forepoles were modelled using 1 mm diameter brass rods of flexural rigidity (EI) equal to 5.8×10^{-3} Nm^2. In this procedure, eight rods were pushed ahead of the cavity at equal spacing along the tunnel periphery. A stainless steel semi-circular lining was then inserted into the cavity. Length of the rigid lining was smaller than the length of the cavity in order to model the unsupported length of the tunnel. Furthermore, a pressurised rubber tube was also used to support the cavity during centrifuge spin-up and before the equilibrium was reached. The rubber tube was pressurised using zinc-chloride solution connected to a standpipe. Density of the solution was adjusted to be equal to the density of the clay. Fig. 1 shows the schematic diagram of the test setup.

Upon installation of the tunnel, holes were drilled from the sides of the clay bed ahead of the tunnel face at prescribed locations using drill bits. Fig. 2 shows the position of the pore pressure transducers (PPTs). Druck PDCR81 PPTs were inserted into these holes and the latter subsequently grouted up with kaolin clay slurry. Performance of these transducers is well documented (Konig et al., 1994) and is not repeated herein. The container sidewalls were refitted and the whole assembly was then subjected to self weight centrifuge consolidated at 100g until an average degree of consolidation of at least 95% was achieved. This typically required 8 h of centrifuge run. After reaching equilibrium, the zinc-chloride solution was gradually drained away from the rubber

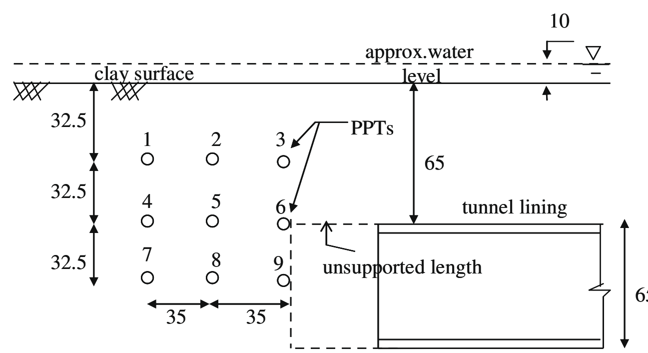


Fig. 2. Position of pore pressure transducers (PPTs).

Table 2
Properties of kolin clay.

Liquid limit (%)	Plastic limit (%)	Plasticity index	Specific gravity (Gs)	Effective friction angle (Φ^1)	Permeability at σ^1 = 100 kPa [k] (m/s)
79.8	35.1	36	2.60	25°	2×10^{-8}

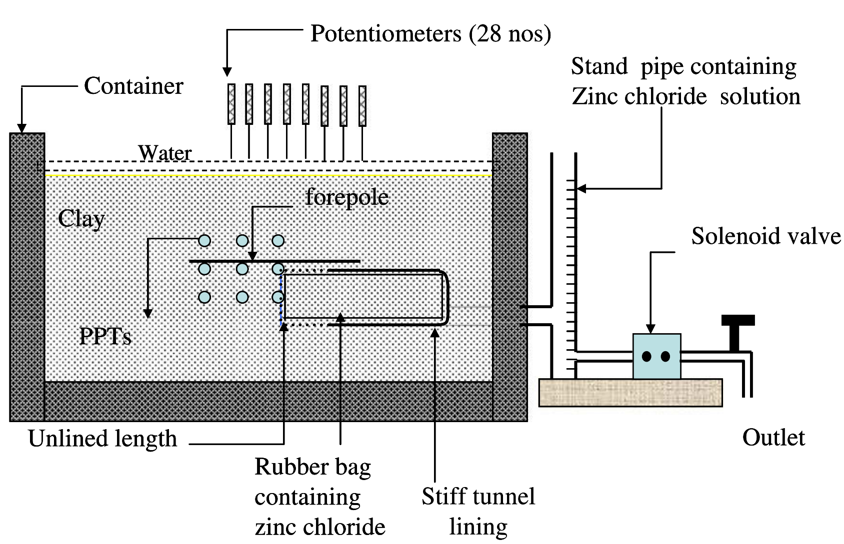


Fig. 1. Schematic setup of the tunnel model.