Centrifugal Testing of Model Tunnels in Soft Clay

Essais en Centrifugeuse sur Modèles des Tunnels

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SINOPSIS Analysis of a tunnel heading near to the ground surface is a complex three-dimensional problem, whereas a two-dimensional idealization can be much more easily analysed. Centrifuge tests on model tunnels in soft clay have been conducted to explore the relationship between the two-dimensional idealization and the more complex three-dimensional tunnel heading. Results from the two-dimensional model test series were in good agreement with stability solutions derived from plasticity theory. The three-dimensional test series revealed how tunnel stability is strongly influenced by the geometry characterizing the tunnel heading. On the basis of the test results, new stability criteria have been proposed to assist the designer in assessment of tunnel safety during construction.

INTRODUCTION

A basic engineering decision to be made in designing a tunnel in soft clay is whether or not the tunnel can be excavated without internal support. Risk of failure of a tunnel heading during construction must be assessed and the factor of safety estimated. Only a relatively limited amount of analytical or experimental work has been devoted to the assessment of overall stability in soft ground tunnelling. The criterion of the critical stability ratio (sometimes referred to as overload factor) being approximately 6, which was proposed by Broms and Bennermark (1967), is widely referred to by tunnelling engineers. In order to investigate further the factors affecting tunnel stability in soft clay, both analytical and experimental studies of tunnel behaviour have been undertaken at Cambridge University. Although other test series were conducted to investigate soil deformations and pore-pressures at working loads prior to collapse (Mair,1979), the particular series of centrifugal model tests described in this Paper were specifically concerned with overall stability.

TUNNEL IDEALIZATION

In order to investigate the influence of the more important parameters affecting tunnel stability, it has been necessary to make certain assumptions and formulate a simplified model of a tunnel under construction. In most instances of soft ground tunnelling, the unlined heading may be reasonably represented as shown in Fig. 1, where σ_T is the temporary tunnel support pressure (if any), C is the cover above the crown and D is the tunnel diameter; P is the distance from the tunnel face to the structural lining. In soft ground, temporary support is often achieved by the use of compressed air or pressurized slurry. The temporary support pressure, σ_T in Fig. 1, is therefore taken as being flexible. The interpretation of the dimension P depends upon the type of tunnel excavation technique adopted. If, for example, a tunnelling shield is employed and there is no overcutting edge (or bead), the representation of Fig. 1 reduces to the special case of P = 0. But this often may not be the case and it is the influence of the dimension P which has been a key factor in the studies of tunnel stability described in this Paper.

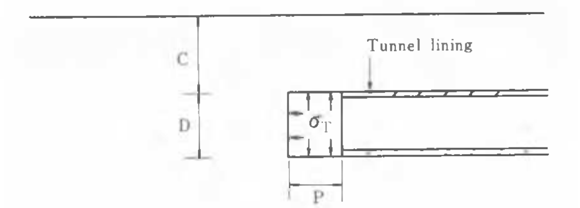

Fig. 1 Tunnel heading in soft ground

The basis of tunnel calculations is often the two-dimensional (plane strain) idealization shown in Fig. 2, which is much more readily analysed than the generalized case in Fig. 1 and corresponds to large values of P. The object of conducting the centrifuge model tests was two-fold: firstly to compare data from the two-dimensional tests with theoretical solutions, and secondly to investigate the influence of P and relate the two-dimensional idealization to the more realistic three-dimensional tunnel heading.

EXPERIMENTAL TECHNIQUE

The 4 metre working radius Cambridge Geotechnical

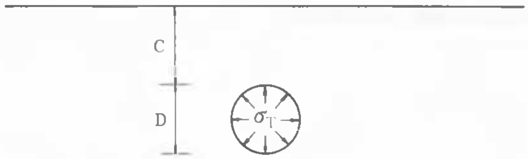

Fig. 2 Two-dimensional idealization of tunnel heading

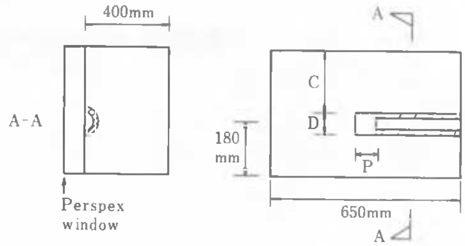

Fig. 4 Dimensions of 3D test series (tunnel headings)

Centrifuge facility has been described by Schofield (1980). The experimental techniques developed for the centrifugal testing of model tunnels in clay are only briefly described in this Paper, the full details being presented elsewhere (Mair, 1979). The models were constructed by consolidating kaolin slurry in the laboratory and forming uniform samples of clay with an undrained shear strength of 26 kPa. The strength of the clay, together with its other engineering properties, was obtained from the considerable body of data obtained over the past two decades by research workers at Cambridge concerned with stress-strain behaviour of kaolin (e.g. Nadarajah, 1973). Since the model tests described in this Paper were designed specifically to investigate stability of tunnels in clay with a constant undrained shear strength profile, special precautions were taken to ensure that the moisture content of the clay remained unchanged during model preparation; the tunnel test was completed within a few minutes of starting the centrifuge. The dimensions of the models tested are given in Figs. 3 & 4. In the case of a tunnel heading of circular cross-section, a longitudinal vertical cut can be taken through its plane of symmetry (i.e. from crown to invert) and the view would be as shown in Fig. 1 and Fig. 4; the major feature in the design of the three-dimensional tunnel heading test series was the semi-circular tunnel with the plane of symmetry being the highly greased and almost frictionless interface between a Perspex window and the clay.

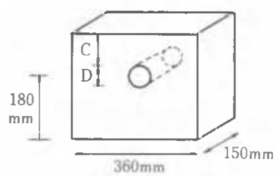

Fig. 3 Dimensions of 3D test series (plane-section tunnels)

Tunnels of 60mm diameter were cut in the clay models and tested at 75g and 125g. The models were therefore equivalent in terms of stability to 4.5 metre and 7.5 metre diameter prototype tunnels in soft clay of undrained shear strength 26 kPa. The cover-to-diameter ratio (C/D) was varied from 1.5 to 3. In the 3D test series a stiff semi-circular brass lining was placed in the tunnel for most of its length, so that only the heading of length P was unlined; the ratio P/D was varied from 0 to 3. As the centrifuge speed was increased to the predetermined level (corresponding to either 75g or 125g), tunnel stability was maintained by compressed air supplied to a flexible rubber bag within the tunnel. During the increase in speed the compressed air pressure was increased accordingly to always equal the total overburden pressure at the tunnel axis. When the centrifuge acceleration reached the predetermined value, the compressed air pressure was rapidly reduced until failure of the tunnel occurred. A grid of silvered Perspex balls pressed into the clay could be photographed through the Perspex window containing the model. Observations could therefore be made throughout the test of soil movements around the tunnel as it deformed under the self-weight of the surrounding ground when the temporary support within the tunnel was progressively reduced.

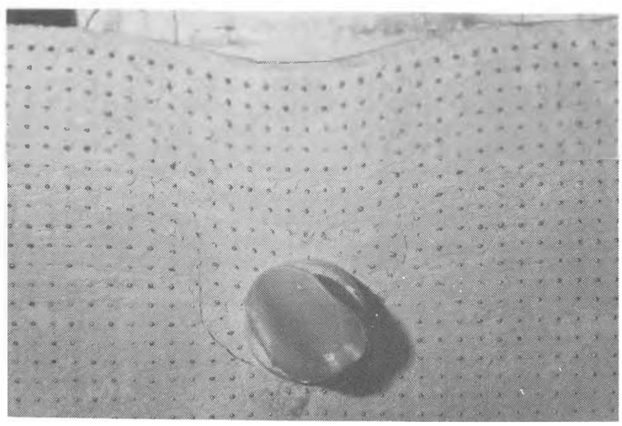

Fig. 5 View of a typical 2D model tunnel after failure (C/D = 1.8)

RESULTS OF 2D TESTS (PLANE-SECTION TUNNELS)

A view of a typical model from the 2D test series at the end of a test is shown in Fig. 5. Complete collapse of the tunnel has occurred causing it to fill with clay. The support pressure σ_T at which collapse occurred was obtained by plotting the support pressure throughout the test against both surface and tunnel deformations, and was found to be the same by either method. The observed variation of tunnel support pressure at collapse with cover-to-diameter ratio is given in Fig. 6. An envelope of the optimum upper bound solutions, together with a lower bound solution, have been derived from plasticity theory (Davis et al., 1979) and are shown on Fig. 6. The terms 'upper' and 'lower' bound solutions in the context of plasticity theory can be misleading when applied to tunnel support problems. Upper bound solutions derived from kinematically admissible mechanisms are always unsafe and therefore predict too low a tunnel support pressure capable of just preventing collapse; the reverse is the case for lower bound solutions. The results in Fig. 6 indicate good agreement between the model tests and the bound solutions.

Ruptures emanating from the tunnel haunches and forming the lower part of the collapse mechanism are visible in Fig. 5. Similar failure mechanism were evident in all of the tests and these led to the development of improved upper bound solutions, which have been presented in detail by Davis et al.(1979). Interpretation of the width of these mechanisms from simple plasticity theory was found to be consistent with the observed distance between the points of maximum slope on the surface settlement troughs(Mair, 1979), and in good agreement with the field data reported by Peck (1969) and Clough and Schmidt (1977).

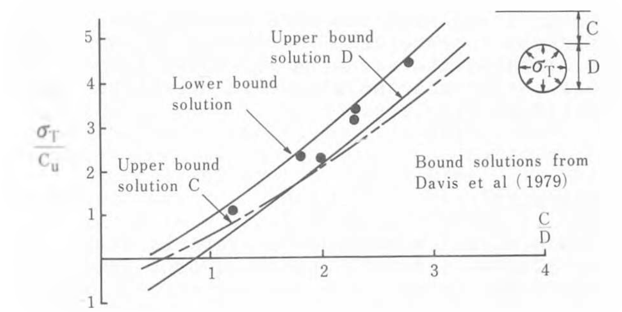

Fig. 6 Predicted and observed tunnel support pressures at collapse

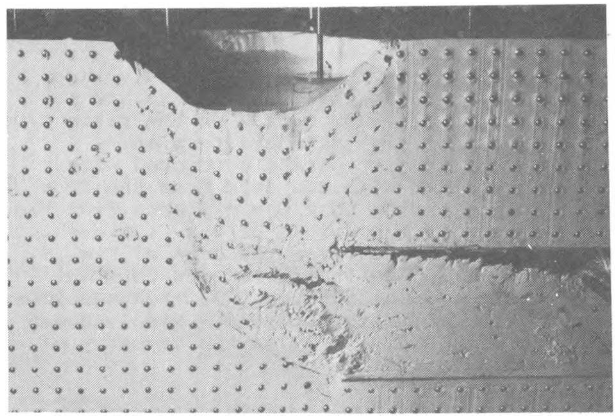

Fig. 7 Model tunnel heading after failure (C/D = 1.5, P/D = 0)

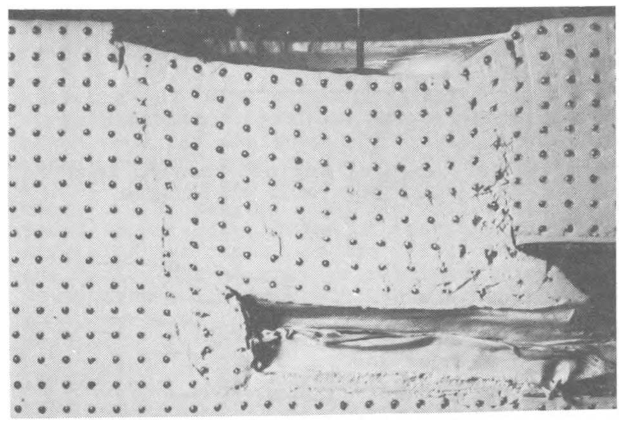

Fig. 8 Model tunnel heading after failure (C/D = 1.5, P/D = 2.0)

RESULTS OF 3D TESTS (TUNNEL HEADINGS)

A typical model from the 3D test series after failure is shown in Fig. 7; the cover-to-diameter ratio was 1.5 and the length of unlined heading, P, was zero (i.e.the heading was rigidly supported right up to the face). Displacement transducers for monitoring surface settlements can be seen in the photograph. Rupture lines are visible separating the body of clay entering the tunnel heading from the surrounding clay, and, within the moving body, evidence of intense shearing can be seen. In contrast, the model shown in Fig. 8 had a significant portion of the heading unlined (P/D = 2.0) and it exhibited a mechanism approaching perfectly two-dimensional behaviour, with the soil movements in the direction of the tunnel axis being small in comparison to the vertical movements. This transition from three-dimensional to two-dimensional behaviour was reflected by a marked decrease in stability, i.e. a significantly higher tunnel support pressure was required to prevent collapse.

The results of the 3D test series are summarized in Fig. 9 in terms of the stability ratio at failure, N, defined by Broms and Bennermark (1967) as

$$N = \frac{\sigma_z - \sigma_T}{c_u} \tag{1}$$

where σ_z is the overburden pressure at the tunnel axis σ_T is the tunnel support pressure and c_u is the undrained shear strength of the clay. Also shown in Fig. 9 are the values of N determined from the two-dimensional studies, which in effect correspond to very large P/D ratios. It can be seen that small changes of P/D between 0 and 1 have a marked effect on tunnel stability and it is significant that most tunnelling cases fall within this range. Relatively small differences in stability ratio at failure can result in significant differences in temporary support required to maintain stability. The criterion of Broms and Bennermark (1967) is shown on Fig. 9 and, compared with the centrifuge test results, it appears to be somewhat conservative for P/D ratios less than 1. The results are plotted in an alternative form in Fig. 10 to illustrate the dependence of N on the ratio C/D; included in this plot are data from an additional pilot test series conducted with P/D = 0, together with the data from the 2D tests (corresponding to P/D = ∞) taken from Fig. 6. The lines for P/D values of 0.5, 1.0 and 2.0 have been constructed from the data of Fig. 9. The results indicate that N becomes constant for C/D values exceeding about 3. For shallow tunnels with C/D ratios between 1 and 3, N can vary from 3 to 9 depending on the geometry of the tunnel headings.

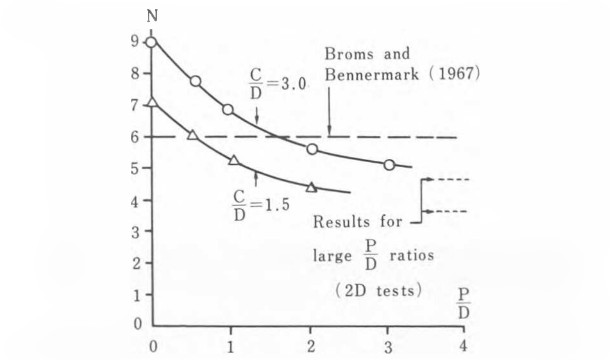

Fig. 9 Influence of unlined heading length on stability ratio at failure

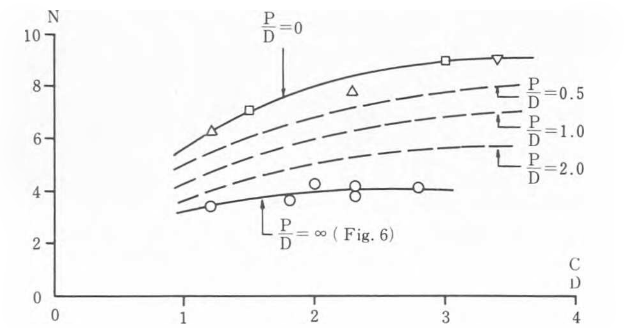

Fig. 10 Influence of heading geometry on stability ratio at failure

CONCLUSIONS

The results of centrifuge tests on two-dimensional (plane strain) model tunnels were in good agreement with theoretical stability solutions derived from plasticity theory. One of the roles fulfilled by the centrifuge tests was therefore the validation of numerical predictions. In addition the tests allowed observation of the mechanism of tunnel failure, which led to the development of improved upper bound stability solutions.

The centrifuge tests on model tunnel headings have related the two-dimensional idealization with three-dimensional headings and have indicated how tunnel stability is strongly influenced by the heading geometry. The stability ratios at failure obtained from the tests differed appreciably in detail from the stability criterion proposed by Broms and Bennermark (1967). In the light of the results, the stability of tunnels under construction in soft clay can be predicted with a greater degree of accuracy than was previously possible. An improved assessment can be made of the soil strength below which a tunnel heading would be unsafe without internal support.

In the case of a tunnel heading in soft ground, creation of a failure in the field would be both impractical and dangerous. The principal intention of this Paper has been to demonstrate how the technique of centrifugal modelling can provide the means of safety and repeatedly observing failures at model scale, thereby allowing detailed studies of the mechanics of tunnels deforming under the self-weight of the surrounding soil.

ACKNOWLEDGEMENTS

The research formed part of a wider investigation into the behaviour of tunnels in soft ground, which was supported by a research contract awarded to Cambridge University by the Transport and Road Research Laboratory. The authors are grateful to Professor A.N Schofield, who directed the research work, and to Mr. C. Collison for his assistance in operating the centrifuge facility.

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