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DEEP EXCAVATIONS AND TUNNELLING IN SOFT GROUND

EXCAVATIONS PROFONDES ET CONSTRUCTION DE TUNNELS EN TERRAINS DE FAIBLE RESISTANCE

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Introduction

The eleven papers in Session 4 contain much valuable information about the behavior of tunnels and open cuts. Several provide excellent examples of the reaction of different types of ground to various tunneling and cutting procedures. Hence, they serve admirably to supplement and exemplify the condensed presentation in the state-of-the-art report.

Tunnels

Vinel and Herman provide a most instructive example of shield tunneling in cohesionless soils. An experimental tunnel with a diameter of 9.9 m was driven for the Brussels Metro through sands of two formations. The upper, known as the Bruxelles sand, is loose but locally cemented with calcareous binder. The effective size is about 0.1 mm and the uniformity coefficient about 2.0. It is underlain at a depth of about 16 m by the much finer Yprésien sand which has an effective size occasionally as low as 0.002 mm and a uniformity coefficient ranging between 4 and 28. The tunnel was driven along the boundary between the two materials. The water table was generally near or below mid-height of the tunnel.

The shield contained 16 compartments to permit hand mining. The dry soil at the top tended to cave, whereas the wet soil at the bottom tended to flow in. Dewatering in the fine-grained Yprésien sand proved unsatisfactory, but tunneling conditions were improved substantially by the use of air pressure combined with water sprays in the upper part of the face. Attempts to inject chemicals and cement into the soil to prevent its caving into the annular space were generally not successful. Frequent collapses of the annulus caused difficulties in grouting; attempts to grout through jets on the shield were ineffective, but grouting through the concrete segments of the lining was more successful. Although occasional runs extended to the surface, the settlement over the tunnel was generally on the order of 15 cm. The settlement was preceded by a slight heave associated with the jacking pressures.

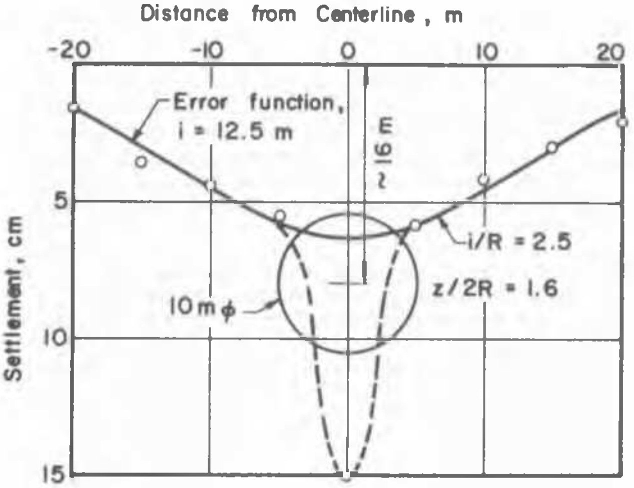

Fig. 1. Settlements over Bruxelles Tunnel in Slightly Cohesive Sand Showing Influence of Two Components of Lost Ground

The transverse settlement profile presented by Vinel and Herman is replotted in Fig. 1. A Gaussian error function fits the observed settlements very well except for the large subsidence over the centerline of the tunnel. It may be speculated that the subsidence profile consists of two components related to two different sources of lost ground. The wide portion may be associated with deep-seated ground losses caused by the inflow of wet soil at the sides and the bottom of the tunnel, whereas the central enlargement may have its origin in the ground losses concentrated over the crown. Because of the different widths and depths of the two sources of lost ground, the corresponding widths of the two components of the settlement troughs may differ appreciably.

The low modulus of the loose sands led the designers to the conclusion that the soil itself would not provide sufficient lateral support for the stability of the permanent lining. Consequently, tie rods were installed to control the deflections. It seems likely that the lateral support would actually have been greater than anticipated and that the tie rods might not have been necessary. It would be of interest to investigate this point more completely as further tunneling is carried out in the Brussels formations.

Further interesting data concerning the driving of tunnels are given by Rossman in connection with full-scale experiments for the Warsaw subway. The author emphasizes that information necessary for design and construction can be obtained only by large-scale experimental tunneling. The soils consist of highly plastic clays at water contents somewhat below the plastic limit. The clays have been disturbed by glaciation and contain pervious inclusions in an erratic pattern.

An experimental tunnel of 18-ft diameter was driven by shield, and a junction chamber was excavated by hand. One portion of the tunnel was driven in free air after dewatering by wells. Because of the erratic and discontinuous character of the pervious inclusions, the ground-water lowering proved to be difficult and ineffective. Air pressure not only greatly reduced the difficulty, but appeared to prevent the otherwise excessive swelling of the stiff and fissured clays.

Observations indicated that the shield-tunnel lining, consisting of segments of cast iron, was subjected to a nearly equal all-around pressure. Moreover, in a branch tunnel of the same dimensions, it was noted that a 15-in. lining performed more satisfactorily than one having a thickness of 30 in.

The phenomena associated with the intense swelling of the clay, and particularly the reduction in swelling caused by an elevated air pressure on the order of one atmosphere, would be fruitful subjects for fundamental research.

The behavior of sand in the vicinity of an advancing shield is described by Smoltczyk and Holzmann. A tunneling machine having a diameter of 5.6 m was used successfully within a shield to tunnel through cohesionless sands in Hamburg. The maximum settlements were on the order of 2-3 cm. The paper deals theoretically with the earth pressures directly in front of the cutting machine and in the vicinity of the heading. The theory is rather elaborate and requires a knowledge of soil properties not easily evaluated.

Pfister, Norbert, Barbedette and Potevin describe the measures necessary to stabilize a zone of crushed dolomite encountered for 60 m within a rock tunnel in Switzerland. As the tunnel entered the zone, water under a head of 100 m flowed into the tunnel at a rate of 1 m^3/sec. The tunnel collapsed within 24 hours for a distance of 100 m and was filled with rubble for 300 m.

Injection by grouts or chemicals was considered impracticable; drainage had to be avoided because it would disturb the existing hydrologic conditions. Stabilization was accomplished by detouring the tunnel and freezing the crushed rock ahead of the detour tunnel. Valuable details are given concerning the procedures for coping with the extremely difficult problems. Tunneling is only partly completed at this time, but work is progressing satisfactorily.

A thorough discussion of the laboratory and in-situ properties of chalk is given by Dessenne, Comes, Duffaut and Gerard. The material has many of the characteristics of rock, but during tunneling is readily transformed into a soil-like medium. Several rock bursts were experienced in a tunnel having a diameter of 3.5 m at a depth of only 120 m. At this depth, however, the stress concentration at the tunnel wall exceeded the compressive strength of the rock. The bursting was easily limited by light steel ribs. In other portions of the tunnel, rock bolts anchored in resin, and a thin cover of pneumatically placed concrete, proved satisfactory for support.

Open Cuts

The excellent paper by Rodriquez and Flamand has already been discussed in the state-of-the-art report. It represents an outstanding example of the descriptive and observational data still urgently needed to improve our knowledge of the behavior of braced cuts in a wide variety of soils, and to extend the usefulness of semi-empirical methods of designing bracing systems. The project included a braced excavation to a total depth of 11.3 m in very soft Mexico City clay. A general excavation was carried to a depth of 2.3 m in the vicinity in order to decrease the tendency toward instability of the bottom; even so, the stability number $N = 4\ s_u/\gamma$ was on the order of 8. Measurements were made of strut loads, horizontal deformations of sheet-pile walls, and pore pressures in the surrounding clay. In addition to the results of the observations, the paper contains a useful account of the control of pore pressures by means of an electro-osmotic pumping system.

The data contained in this paper, along with information from several cuts in Oslo, provided the General Reporter with the key to a rational classification of open cuts with respect to their behavior during construction and the loads in their bracing systems.

The state-of-the-art report dealt also with fundamental approaches to the reduction or prevention of excessive movements adjacent to braced cuts under different ground conditions. Three of the conference papers deal with various aspects of this problem. The paper by Boutsma and Horvat deals with the building of the Rotterdam Metro in soils consisting almost exclusively of soft compressible clay and peat, underlain at a depth of about 17 m by sand. The water table is very close to the ground surface.

Heavy sheet piles were driven about 0.5 m into the underlying sand along each side of the proposed trench which was to be 14 m wide. Excavation was then carried out to a depth of 4 m and a level of struts inserted at about street level. To avoid the necessity for additional struts while nevertheless keeping the ground movements small, the trench was then flooded and excavation carried out under water by means of a clamshell to the final depth of 10 m. In this fashion, an artificial canal was created. The soft underlying soil required that piles be driven into the sand for support of the prefabricated tunnel tubes which were floated into position through the canal. The piles were provided with adjustable heads to furnish uniform support for the tubes.

At another section, where the excavation was carried out in the dry, boils appeared when the depth reached 9 m. Failure was prevented by pumping from drainage wells, but lateral deflections of the sheeting reached 10-15 cm. The settlements associated with the dewatering indicated the superiority of construction by means of the water-filled trench. The paper presents observations regarding strut loads and piezometric levels as well as descriptions of the use and effects of well-point dewatering.

Huder describes the use of cutoff walls constructed in slurry trenches for supporting the sides of an excavation 17 m deep through lacustrine and morainic material with a high ground-water level. Bracing was provided by permanent floors installed as the excavation proceeded. Drains between and extending below the walls were used to lower the water level and to reduce the danger of piping during construction. Tension piles were needed to resist uplift. Inward deformations of the walls varied according to the soil type; they reached 37 mm near the bottom of the excavation in the lacustrine clays and ranged from 3 to 22 mm in the morainic materials. The settlement of adjacent structures was too small to be observed.

Properties of concrete cast in slurry trenches to form cutoff walls are discussed by Veder and Kienberger. The results of small-scale tests indicate, in accordance with general experience, that the quality of the concrete produced under these circumstances can be as satisfactory as that produced under normal working conditions.

Cellular Cofferdams

A valuable set of field observations on the behavior of a large circular sheet-pile cell in a cofferdam protecting an excavation is reported by Bailly, Bassal, Pilot and Schlosser. The cell had a total height of about 25 m, a diameter of about 19 m, and was driven into sand to a depth of about 10 m. It was filled with sand. One side was exposed to the sea at an average head of about 10 m, modified by tidal fluctuations of about 5 m; the other was exposed to the atmosphere after the enclosure was dewatered.

A complex pattern of deformation ensued upon dewatering. The sheet piles settled about 30 cm on the water side and a smaller amount on the land side. Yet the entire cell tilted toward the land. Moreover, the tilt on the water side, amounting to about 10°, was almost twice that on the land side; hence, the circular shape of the top of the cell was transformed into an ellipse with its shorter axis in the direction of the tilt. All the movements were progressive, possibly on account of the action of the tides, but the rate of movement decreased rapidly with time and became small after two to three months.

The sand fill settled with respect to the sheet piles. The corresponding transfer of load to the piles was reflected by a reduction in the measured vertical pressure in the fill as compared to the calculated weight of the fill. The distribution of pressures in the fill corresponded to that expected on the basis of the procedures used for the analysis of stresses in silos. Furthermore, the ring stresses in the sheet piles agreed reasonably well with those calculated from the measured pressures in the sand, although the sheet-pile stresses were found to differ greatly from pile to pile. The stresses in the piling due to driving were not measured.

The observations will serve as a fruitful source of data for those seeking a further understanding of the behavior of sheet-pile cells as retaining structures.

Buried Structures

The behavior of several types of buried structures and structural elements is considered from the point of view of elastic and elasto-plastic theory by Gorbunov-Possadov, Davydov, Ogranovich and Repnikov. The influence of the discontinuity introduced into the semi-infinite elastic half-space by such elements as sheet-pile walls or anchor plates is taken into account. The analysis of a deeply buried arched structure with rigid side walls is presented in some detail.

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