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SESSION / SÉANCE 4b

Displacements and soil-structure interaction: Earth retaining structures and deep excavations

Underground retaining structures and deep excavations

Déplacements et interaction sol-structure: Structures de soutènement et excavations profondes

Fouilles et structures en souterrain

G. LOMBARDI (Chairman) / B. SIMPSON (Discussion Leader) / T. ROTONDA (Technical Secretary)

G. LOMBARDI: This discussion concerns underground retaining structures and deep excavations. However, we have not so many underground structures in the Proceedings, but maybe at the end of the meeting some words can be spent about them. Let me introduce to you the panel members. We have with us first of all Miss Tatiana Rotonda from the University of Rome. Then, we have asked three gentlemen to help with the discussion: Dr. P. Vermeer from Delft University of Technology, Delft, Netherlands; Dr. M. Stocker, director of the Bauer Spezialtiefbau GmBH, in Germany; and then Dr. I. Symons from Transport and Road Research Laboratory of Burks, United Kingdom. Our discussion leader is Dr. Brian Simpson. You know him very well. He is the director of Ove Arup & Partners, he is a visiting professor at the City University of London and is also a member of the EC7 drafting panel. As for myself, my name is Lombardi, I am not a professor and I am generally dealing with hard rocks and not with soft soils. Unfortunately, our time is tight, since we have to close this session in time for us to attend the Closing Session. Now I give the floor to Dr. Simpson for his introductory remarks.

B. SIMPSON: Although this session is one of the final technical events of the conference, its subject is sufficiently popular to draw a large number of participants. The themes for discussion were selected from the papers.

In designing retaining wall, attention is usually concentrated on horizontal earth pressures and equilibrium. Several of the papers illustrate the fact that failure to consider vertical forces can have disastrous consequences, particularly for retaining systems which do not form continuous vertical structures. In the contributions to discussion, Stocker provides a practical reminder that the vertical components of forces from ground anchors must be carried by the base of the wall. Clayton shows how vertical forces and movement are important to consideration of wall friction, which affects horizontal equilibrium, and Simpson shows that they affect horizontal ground movements, even in "elastic" materials.

Design of retaining walls requires an understanding of ground movements. Vermeer discusses the engineering use of finite element methods, emphasising that the methods should be no more sophisticated than the soils data available, whilst Candler comments on the computing requirements of a practicing engineer. Measurement of ground movements has been essential to the development of understanding and theory, and Steiner points out that when adequate design calculations cannot be performed, construction can sometimes proceed successfully with the support of monitoring. The construction process itself may significantly affect the performance of a wall, as discussed by Symons (sheet piling) and Klein (effects of grouting).

Recently developed means of earth support, including reinforced earth and soil nailing, are assuming great commercial importance. Stocker presents a comparison between measured movements of soil nailed excavations and other means of support, showing good results for the soil nails. Holtz and Shlosser present information on the strains experienced by geotextiles whilst Bastick presents data from a major instrumented experimental abutment. Brady discusses the difficulty of predicting displacements in service, in relation to the use of factors of safety. The title of the session includes "Underground retaining structures", and Calabresi presents a discussion on measurement and calculation of movements around a tunnel in stiff clay which made use of soil nailing.

Several papers in Session 4b mention the important subject of vertical forces on retaining walls. In design, attention is often concentrated on horizontal equilibrium, and in some cases insufficient consideration of vertical equilibrium has led to failures. In considering the displacements of retaining walls, vertical forces are often neglected, especially if a subgrade reaction model is adopted. I want to suggest that vertical shear forces between the wall and soil may have a significant effect on horizontal displacements.

Fig. 1a shows a basic subgrade reaction model in which the soil is represented by a series of disconnected horizontal springs. An improved model, developed by Arup Geotechnics in the program FREW (Pappin et al (1986), Ford et al(1991)), is shown in Fig. 1b. In this, the disconnected springs are replaced by blocks of elastic material which can have any specified variation of stiffness with depth. The stiffness coefficients have been derived from finite element analyses. Earth pressures are also restricted to remain within active and passive limits, with some allowance for redistribution of stresses for flexible walls (Pappin et al (1986)).

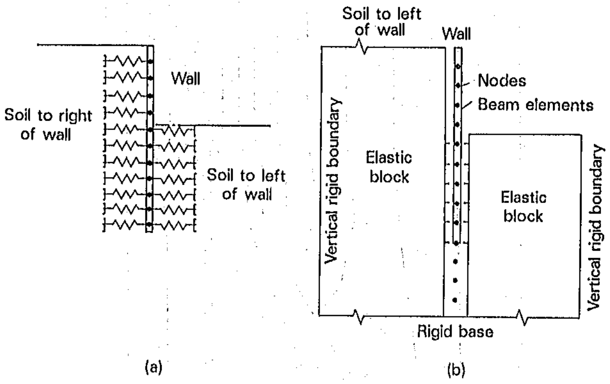

Figure 1. Numerical models of retaining walls; (a) subgrade reaction (b) FREW.

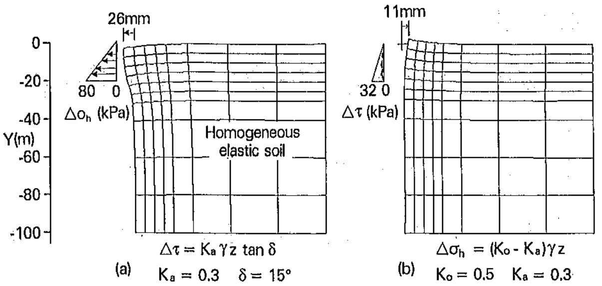

Figure 2. Horizontal displacement caused by changes of earth pressure: (a) lateral stress '(b) vertical shear.

Practical experience with FREW has suggested that this type of analysis leads to an overestimate of displacements measured in the early stages of excavation in which the wall is usually behaving as a cantilever. Three possible reasons for this have been advanced: (a) the ground exhibits high stiffness in the initial stages of its deformation and this has not been represented properly in the linear elastic stiffnesses used as data for the program; (b) the early stages of excavation are often in ground which is partially saturated and which may have its strength and stiffness enhanced by suction; (c) horizontal displacements may be reduced by the effects of vertical shear between the wall and the soil. Reasons (a) and (b) may well be valid, but comparisons between FREW and finite element analyses, using the same values of soil stiffness, suggest that (c) is also important, particularly when the initial coefficient of earth pressure, K_0, is fairly low.

Figure 2a shows a finite element representation of a block of uniform elastic material. A stress distribution has been applied which is equivalent to reduction of earth pressures to active values at the side of a 20m deep excavation. For this elastic block, the horizontal movement predicted at the top of the wall is 26mm. Figure 2b shows the same elastic block subjected to eh change of vertical shear stress which would occur between the wall and the soil as an angle of wall friction δ=15° is mobilised. The horizontal displacement computed as a result of this vertical shear is 11mm, in the opposite direction to displacement caused by reduction of horizontal earth pressure. If a larger value of δ had been used, this displacement would have been larger and could almost have cancelled the displacement caused by change of horizontal earth pressure.

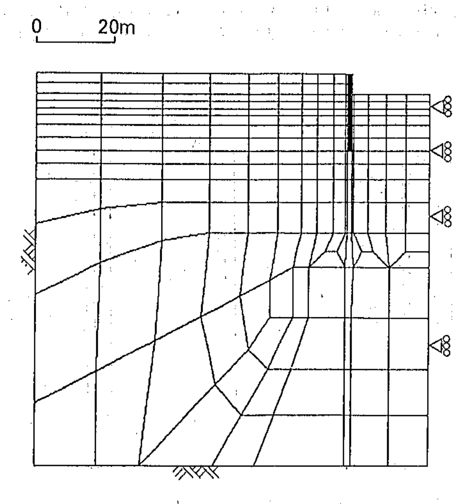

Figure 3. Finite element mesh used for analysis of 5.2m excavation.

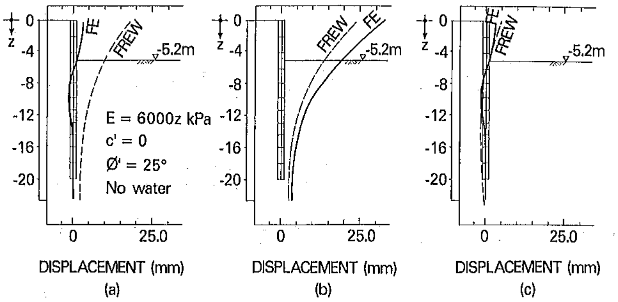

Figure 4. Computed wall displacements for 5.2m excavation.

Figure 3 shows the finite element mesh and other assumptions used to compute the displacement of a cantilever wall for an excavation depth of 5.2m. The computed horizontal displacements of the wall are shown in Fig. 4a, together with the result obtained for the same soil properties using FREW; the displacements computed by FREW greatly exceed the finite element results. In a second finite element computation, the elements adjacent to the wall and in the vertical plane beneath the wall were assigned negligible shear stiffness for vertical shearing. The results of this run, shown in Fig. 4b, indicate much larger horizontal displacements of the wall than for the finite element run in Fig. 4a; they even exceed the displacements computed by FREW, which are themselves increased because the coefficients of active and passive pressure have been adapted for δ=0.

The FREW program has recently been enhanced to include the effects of vertical shear on the wall and across the vertical plane beneath the wall. As a trial, the shear computed in the finite element run of Fig. 4a was specified to occur in FREW and the computed displacements are shown in Fig. 4c; much closer agreement with the finite element results is obtained by this method.

It is clear that vertical shear has a significant effect on horizontal movement. It is likely that this shear is mobilised mainly in the early stages of displacement and it has a proportionally larger effect when K_0 is low. Development of the program is continuing, allowing it to make a reasonable assessment of the shear likely to be mobilised between wall and soil, and beneath the wall, in response to the computed deformations and the requirement of vertical equilibrium.

REFERENCES

Ford, C.J., Candler, C.J., & Chartres, F.R.D. 1991. The monitoring and back analysis of a large retaining wall in Lias Clay. Proc X ECSMFE, 2, 707-710.

Pappin, J.W., Simpson, B., Felton, P.J. and Raison, C. 1986. Numerical analysis of flexible retaining walls. Proc Symp Computer Applications in Geo. Eng., Midland Geotechnical Society, UK

I will now call on our first speaker, Dr. Clayton.

Panel intervention

C.R. CLAYTON & A.V.D. BICA

Our presentation concerns small-scale one-g laboratory experiments on retaining walls. But first I would like to remind you of some classic work carried out in Germany, in the 1930s.

A free-embedded cantilever wall is unrestrained either horizontally or vertically. Therefore the vertical forces on the wall, which result from the shear stresses applied to it, are in equilibrium. In one of the earliest limit eqilibrium methods proposed for the analysis of this type of wall, Krey (1932) proposed that on the retained side, at the bottom of the wall, wall friction would act downwards on the wall, while above the point of rotation it would act upwards (Figure 1). He based these assumptions on observations of the movement of sand particles close to model walls. As a consequence, Krey considered that the passive pressure at the bottom of the wall would be quite small, and he proposed that it be calculated from the Rankine expression (implying that $\delta'=0$).

We have recently completed a series of small-scale model wall experiments at the University of Surrey which aimed to investigate the stresses on the embedded length of a free embedded cantilever. Only the embedded length was modelled, with the other forces that would be applied to a full wall (active normal and shear forces) being applied externally. Figure 2 shows the distribution of normal stress and shear stress on an uncoated smooth steel wall close to failure. The soil was fine uniform Leighton Buzzard sand, which had a plane strain angle of friction of 47° at the density at which it was placed. Normal and shear stresses were measured using miniature boundary total stress cells. Two sets of data are shown. In the first (Case 1), the active length of the wall was assumed to be "smooth", that is δ' was taken as zero, and no external vertical downward force was applied to the embedded length to simulate the downward friction on the upper (absent) part of the wall. In the second experiment (Case 2) a downward force equivalent to an active angle of wall friction (δ_a') of 23.5° on the active length of the wall was applied. It can be seen that Krey's ideas concerning the direction of wall friction appear to be correct. But more than this, vertical loading of the wall (Case 2) has the effect of decreasing the vertical (downward) shear stress at the bottom of the wall on the retained side, and this produces an increase in the passive normal stress at this level.

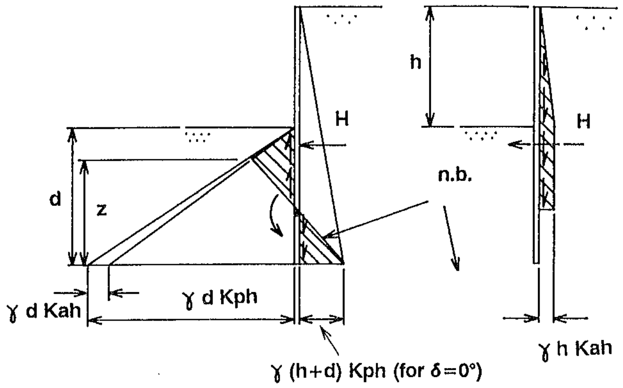

Figure 1. Design pressure distribution - free embedded cantilever wall (after Krey, 1932).

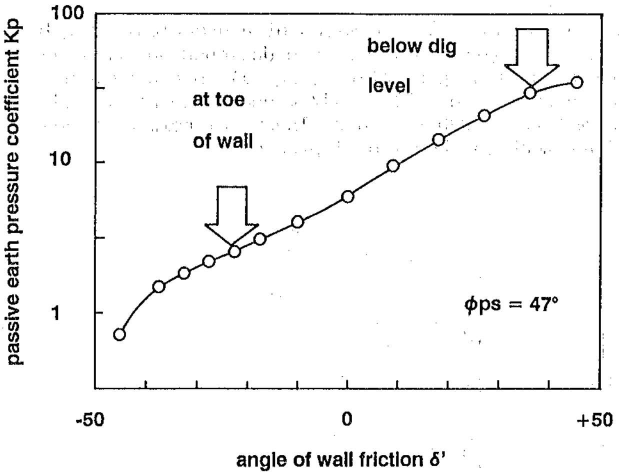

Figure 3. Influence of wall friction on Kp.

notes:

Kp for δ' +ve from Caquot and Kerisel (1948)

Kp for δ' -ve from Krey (1932)

see also Janbu (1972)

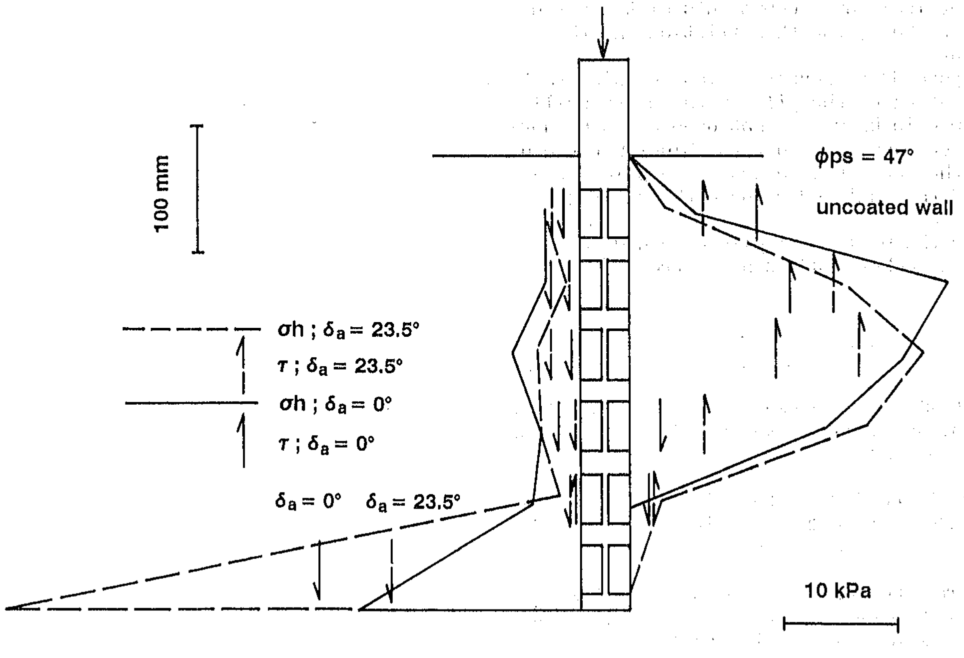

Figure 2. Distribution of normal and shear stress on embedded length.

Figure 3 shows how readily available earth-pressure coefficients predict that passive pressure will vary with depth, for an effective angle of friction of the soil of 47°. Immediately below the excavation level wall friction will act vertically upwards, and very large passive earth pressure coefficients (of the order of 40) are likely. Reversal of shear stresses near to the toe of the wall means that at this location the passive earth pressure coefficient can only rise to about 4. If the wall were subjected to external an upward force, then it could be expected that this (and the resistance of the wall to lateral loading) would further reduce. Thus the vertical forces applied to such a wall have a dircet influence on the horizontal passive pressures it can mobilize.

B. SIMPSON: I think Dr. Stocker has got some real sites to show us.

M. STOCKER: May I inform you of a practical example:
A secant pile wall had been designed and carried out as a slope protection (Fig. 1) in clayey and silty soil. The wall was 17 m deep. The piles had diameters of 900 mm. Three layers of permanent anchors took the horizontal pressure.

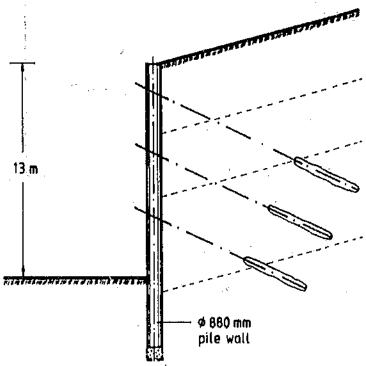

Figure 1. Vertical displacement of the pile wall due to lack of bearing capacity at the pile base.

After the wall had been finished and the anchors had been prestressed, the wall suddenly moved downward vertically by up to almost 150 mm in some places. The design seemed to be correct, it took care of the vertical force components of the earth pressure, the anchors, the skin friction and the bearing pressure.

What had happened? An investigation revealed that during installation of the piles with rotary drilling tools, the pile bases had not been cleaned thoroughly before casting the concrete. Slope water had collected in the loose soil beneath the pile footings, softened the soil and reduced the bearing pressure to zero.

To stabilize the wall, each pile base had to be grouted and the anchors had to be restressed.

Discussion

B. SIMPSON: I think we could afford two or three minutes for any questions to those speakers or other very relevant comments.

M. FERNANDES: I would like to ask Dr. Stocker if he measured the horizontal displacements of the wall.

M. STOCKER: The horizontal movement of the wall could not be determined, since a zero-measurement, i.e. a measurement before the failure, was not available.

I.F. SYMONS: The papers assigned to this session contain some valuable records of retaining wall and ground behaviour during construction from field measurements. However, in a number of cases lateral deformation profiles are given without the authors indicating whether these represent total movements or deflected shapes. To determine lateral movements using inclinometer or electro-level systems it is usually necessary to independently determine the movement of the top of the tubes from one or more remote stations located outside the influence of the construction activities. On congested sites this can prove difficult, although electronic distance measurement systems are now available which can provide high accuracy over large distances. It would assist if contributors to the session could give details of their measurement systems and indicate the likely accuracy.