Modelling of horizontal arching on retaining walls

Modélisation de la pression des terres horizontales contre les murs de soutènement

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ABSTRACT

The horizontal arching mechanism transfers horizontal earth pressures acting on flexible retaining wall panels to neighbouring elements via soil shear stresses. In this research, the horizontal arching mechanism and lateral displacements of fixed cantilever walls are investigated using finite element tests. A 300mm high, L-shaped model basement comprising separate but contiguous wall panels of different widths and stiffnesses was built to accommodate this purpose. A series of six tests was carried out at 45 grad, where the panel widths and thicknesses around the model basement were varied, so that the effects of panel geometry and stiffness on horizontal arching could be studied. It is shown that panel restraint displacements and base bending moments of the most flexible, narrow panels can be an order of magnitude smaller than conventional active earth pressure calculations would allow.

RÉSUMÉ

Par effet de voûte horizontal, la pression des terres agissant sur un parement de mur de soutènement peut être transférée aux éléments voisins par l'intermédiaire de la résistance au cisaillement du sol. Le mécanisme de cet effet de voûte ainsi que les déformations latérales des murs de soutènement ont été étudiés dans des essais en centripètes. Un modèle ad hoc de mur de soutènement de 300 mm de haut et comportant des parements de différents largueurs et épaisseurs a été construit. Cinq essais ont été effectués à une inclinaison de 45° où ont été effectués. L'épaisseur et le largeur des parements du modèle de mur de soutènement ont été variés pour étudier l'influence de leur géométrie et de leur rigidité sur l'effet de voûte horizontal. Les résultats montrent que l'effet de voûte horizontal diminue lorsque la largeur du parement augmente alors que la rigidité du parement n'influence pas cet effet de voûte.

1 INTRODUCTION

It is widely acknowledged that the earth pressure distribution on retaining walls in a three-dimensional soil-structure interaction problem. Previous research has established the influence of wall installation effects, wall stiffness and support conditions, and wall friction, on earth pressure distributions. The horizontal and vertical arching mechanisms, and their effect on pressure distribution on retaining walls, have since been identified to be of similar importance. While this has been the subject of much discussion, it has not yet led to practical guidance for designers.

The focus of this paper will be on the horizontal arching mechanism, a phenomenon where wall elements in their plane view will carry disproportionate amounts of earth thrust depending on their relative deflection. Current earth-pressure theories are based on walls of infinite width,-defining in-plane strain. The neglect of arching may lead to unnecessary concern about the failure of flexible retaining systems that are supported by stiff but intermittent supports.

A study is made of the distribution of horizontal earth pressures on a cantilever retaining wall system, investigating the effect of panel geometry. Previous researchers (Fang and Ibschick, 1986; Bolton and Pavlic, 1987; Pets and Ricou, 1996) have usually focussed on the plane strain problem. Here, six parametric tests were carried out with a retaining wall system simulating a 1:12.7m deep basement excavation at prototype scale, with six various panel widths and bending stiffnesses. Excavation was simulated by the incremental removal of a heavy fluid load inside the model basement. The horizontal displacement of the wall crests, and bending moments at their fixed bases, were measured as excavation was carried out. It will be shown that horizontal arching around flexible panels can be inferred to reduce by an order of magnitude the lateral pressures acting on them.

2 MODEL RETAINING SYSTEM

The retaining system designed for this research was an L-shaped, 300mm high model basement. The model basements comprised separate but contiguous panels of different widths and thicknesses. A plan view of the model basement indicating the layout of the different panels is shown in Figure 1. The flexible basements panels are numbered 1 to 5, with widths of 25mm, 80mm, 160mm, 550mm and 200mm respectively. This translates to widths of 1.8m, 6m, 2.7m, 8.7m and 9m at prototype scale, respectively. Thin panels were 47mm (0.18") thick, medium-stiff panels were 65mm (0.25") thick, and stiff panels were 95mm (0.37") thick. These panels were bolted to the base, with the tension of their being secured. A laboratory test was carried out to investigate the validity of this assumption. The resulting load-deflection curves were found to be within 10% of theoretical values. The surrounding "rigid" panels were 127mm (0.5") thick and had additional bolts on their vertical sides, further limiting their lateral displacements.

Figure 1: Plan view of model basement
The entire model basement was made of aluminum alloy with a Young's modulus of 70 GPa. The difference panel thicknesses can be correlated to different thicknesses of concrete walls, sand, and concrete. It is observed that the 5% panels are clearly much thinner than conventional earth pressure would allow for such deep containment walls. The relative bending stiffness of the walls, proportional to their thickness cubed, see 1:2:4:8.

### 3 MODELLING THE EXCAVATION SEQUENCE

Fraction e: sand was poured outside the basement to relative densities of 63% (test HYC2), 78% (HYC6), 69% (HYC3), 54% (HYC6) and 53% (HYC7) respectively, in the five tests that will be analyzed here. These panels (stiffness 0.57 x 10^6 Nm/ m at prototype scale) were used in tests HYC2 and HYC5; medium-thick panels (stiffness 1.4 x 10^6 Nm/m) in test HYC6; and thin panels (stiffness 4.6 x 10^6 Nm/m) in tests HYC4 and HYC7.

Medium Predominant (SPT 3) with a density of 1500 kg/m³, retained inside a rubber bag, was used to generate stress levels corresponding to K=1 conditions inside the basement. The sand outside the model basement would have created an earth pressure coefficient K_e = 1.5 - 1.8 due to the absence of wall movement, which would have generated lower stress levels. However, as demonstrated by Postie et al. (1996), in-situ walls do bring the earth pressures to K_e = 1 during construction. Equilibrium conditions within and outside the model wall are acheived by small outward deflections during the initial acceleration of the model.

Draining the level of fluid then simulates excavation inside the model basement. The level of fluid was exposed by a laser tracking ball floating within an external standpipe connecting with the fluid in the model basement. Following the achievement of equilibrium at 45s, the heavy fluid was dropped by 20mm to simulate an excavation of 0.05m prefix prototype scale. Panel cross-displacements are reported at each stage, together with bending moments 20mm (0.06m prototype) above the base in test HYC7.

### 4 RESULTS

Figure 2 shows the displacements of all the panels of different stiffnesses and widths, from all the tests, but reported as prototype scale. Panel creep displacements are plotted against the depth of excavation, see 7. Recorded data from panels 3 and 4 is not shown because of their positioning on the model basement, leading to other three-dimensional effects (Du et al., 1996). The data show a wide spread. In general, the thinner panes have experienced larger displacements than the stiffer panels, as must be expected. On the other hand, these factors differences in displacements were much smaller in proportion than the differences in their bending stiffness. Clearly, thin panels were also receiving smaller lateral pressures.

Conventionally, wall displacements are normalized as a ratio of the wall height w/l, while the normalized system stiffness of a retaining wall can be expressed by the following: O'Rourke (1993), as \( w / t \) where \( t \) is the unit weight of the soil. A composite dimensionless group \( U = w / (fH^2) \) made therefore be useful. If soil were simply a heavy fluid, \( U \) would not vary with \( L \) since \( w / L \) would remain constant for an elastic cantilever, non, of course, would \( U \) vary with panel width. Figure 3 shows the data of Figure 2 normalized as \( U \) versus excavation ratio \( DH \).

The spread of \( U \) at a given \( DH \) is simply due to variations in the earth pressure coefficients mobilised behind the various panels at different stages. Figure 3 does assist the recognition that thin or narrow panels always deflect less than thick or wide panels, even having autoclaved for the effect of \( E1 \) in \( U \). Panel width \( B \) influences soil wall strain on horizontal planes, through the ratio \( w / B \), and flexibility that leads to increased \( w / B \) also leads to reduced earth pressures through arching.

### 5 DISCUSSION AND ANALYSIS

A theory for horizontal arching is outside the scope of this paper. One might imagine that earth pressure profiles may evolve to be different than the simple triangle derived for sand by Rankine. However, the data can best be understood in relation to current earth pressure theories if an equivalent triangular earth pressure diagram is assumed, whose gradient is associated with an equivalent earth pressure coefficient. A chart can then be made of predicted wall deflections, each calculated by assuming some constant earth pressure coefficient in the active side of the wall panel and, similarly, a hydrostatic fluid pressure distribution beneath the simulated excavation on the resisting
side. The recorded panel crest displacements during the process of excavation can be superimposed onto the same chart, so that a progression of equivalent earth pressure coefficients can be inferred.

Figure 4 shows the theoretical model of a fixed cantilever that was used in calculations. Varying earth pressure coefficients ($K_e$) values were used to derive different deflection values, while $K_{e,HL}$ is always unity.

Figure 4: Theoretical loading model of cantilever used in calculations

Figure 5 shows the outcome for thin panel displacements. All three panels (taper, medium, and wide) display paths that track quickly across K values from 1 down to the theoretical active value of 0.22 for a perfectly smooth wall and 0.199 for a wall with roughness $k = 0.20$. The soil's internal angle of friction was found to be $\phi = 40^\circ$, derived using the equation suggested by Bolton (1986), for triaxial stress conditions:

$$\phi_{\text{om}} - \phi_{\text{act}} = 3f_L - 1$$

where $\phi_{\text{om}} = 25^\circ$, $f_L = \text{relative density} = 0.60$, and $f_L = 0.71$.

These equivalent active earth pressures are mobilized after about 3 m of "excavation" when the overall wall rotation is $\omega = 3 \times 10^{-6}$. This is similar to the value predicted by Bolton (1989). The paths continue onward to indicate that earth pressure coefficients $K_{o,HL} = 0.1$, and in the case of the narrower panel, below 0.65.

Figure 6 shows a similar progression for the displacement of thick panels, where theoretical active values are 0.984 for a perfectly smooth wall and 1.182 for a perfectly rough wall, taking the angle of friction to be $42^\circ$. The ultimate equivalent earth pressure coefficients are somewhat larger, but still only at values smaller that an engineer could otherwise have contributed with the same angle of internal friction.

In the test shown in Figure 5, the wider panel 5 seems to attract less earth pressure than the medium- or narrow-panel 2. This result also occurred in tests HYC2 and HYC4. Monitoring of 3 different locations on panel 5 also showed that at a twist occurred, with one edge moving more than the other. Pure cantilever bending was possibly being hindered. Adjacent "rigid" panels beside panel 5 did not have cover-walls to stiffen them, and the gap between the edges of panel 5 and these rigid panels might not have been adequate to some instances to maintain freedom of movement of panel 5 at 45\% when the adjacent panels moved towards alignment during excavation.

Nonetheless, the fact that the narrowest test panels moved so little is quite striking. It is generally accepted that the magnitude of horizontal earth force is inversely proportional to the panel width and, as explored in Chua (2003), may be taken as being analogous to the contraction of a vertical cylindrical cavity in sand. The pressure reduction in the cavity is dependent on the proportional reduction in the radius of the cavity, and the soil stiffness (which will also be a function of the soil strains level). It was shown that:

$$\Delta p \sim \frac{Gu}{B}$$

where $G$ is the shear modulus of the soil, $u$ is the panel crest movement, and $B$ is the panel width.

Liang and Zeng (2002) modelled the effect of piezoeven on the soil squeezing behaviour. They found that in the case of unconsolidated soil, around 70% of the failed earth pressure would be transferred to the drilled shafts (piles) if the shafts were placed close in a row, with the pile spacing to diameter ratio ($s/d$) = 2. For a wide shaft spacing with $s/d = 5$, less than 20% of the lateral load was transferred to the shafts. Once the shaft spacing became larger than 8a, they no longer found an arching effect.

This suggests that with horizontal arching should have been occurring to some extent on panels 1 and 2 (HYC = 6.2 and 3.1 respectively), panel 5 (with HYC = 1.25), and between end-walls offering $s/d$ = 16 might have been expected to receive negligible lateral support. If occasional jamming of panel 5 did occur in some of these tests, this should bring to mind the unavailability of analysing continuous box structures at genuine 3-dimensional problems (Lee et al., 1998, Liao et al., 1998).

Figure 7 shows an analogous static push for thick panels that had been provided with strain gauge 20mm above the base construction to measure bending moment (panels 1, 2, and 5 in test HYC7). Equilibrium was achieved at an initial earth pressure coefficient $K_{o,HL}$ approximately equal to 0.8, because the initial fluid level was lower than that of the soil. If the fluid level had been higher, the initial $K_{o,HL}$ value would have been closer to 1.

Once again, a theoretical earth pressure coefficient has been calculated consistent with the bending moments registered as "excavation" took place. Whereas panel 2 and 5 bending moments for the thick wall panels come approximately into conformance with an active earth pressure coefficient, those for the narrow but thick panel 1 drop well below $K_{o,HL} = 0.1$. This is consistent with results obtained from the analysis of panel deflections, and reaffirms the fact that horizontal arching is influenced by panel width.

A theory for three-dimensional arching extending the work of Balk and Salgado (2003) to include elastic bending of multiple panels of various height/width ratios is currently being developed.
Although observed panel displacements against excavation depth for panels of different widths and stiffnesses appeared to have a wide spread, this was a representation of different models and values at different stages of excavation. Panel 5 which was a wide panel appeared to deflect less than Panel 2, a narrow panel, in some tests. However, this could be due to the gaging stock during excavation, because of inadequate slip widths separating it from the adjacent rigid panels which deflected individually as well.

Equivalent earth pressure coefficients K were obtained through the superposition of recorded displacements against predicted displacements, and it was found that K dropped to below active earth pressure values, even accounting for wall friction. This was found to be true for both thin and thick panels. This demonstrates that conventional design for narrow, flexible panels is over-conservative and that a horizontal arching mechanism may be employed to benefit retaining structure construction methods.

REFERENCES


6 CONCLUSIONS

The horizontal arching mechanism transfer horizontal earth pressures acting on retaining wall to stiffer elements via the soil shear stress component. A model has been built to investigate the influence of panel geometry on horizontal arching. The panels modelled were of different widths and bending stiffnesses.

An excavation sequence was simulated in the centrifuge, where it was found that the horizontal pressures on the flexible wall panels were reduced to very small pressures in the wall panels rotated about their bases. This was inferred from recorded panel displacements which were found to be much smaller compared to predicted displacements using conventional earth pressure theories. Recorded two bending moments also indicated that the magnitude of horizontal pressures on the panels was very small.