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Modelling of horizontal arching on retaining walls

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

H.Y. Chua & M.D.Bolton
Schofield Centre, Department of Engineering, University of Cambridge, United Kingdom

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 centrifuge 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 gravities 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 crest 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 un effet de voûte horizontal, la pression des terres agissant sur un panneau 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 encastrés ont été étudiés dans des essais en centrifugeuse. Un model *ad hoc* de mur de soutènement, haut de 300mm et formé de panneaux de différentes largeures séparés mais contigües, a été construit. Cinqs essais à une pesanteur de 45g ont étés effectués. L'épaisseur et al largeure des panneaux du model de mur de soutènement ont été variés pour étudier l'influence de leur géometrie et de leur rigidité sur l'effet de voûte horizontal. Les résultats indiquent que l'effet de voûte horizontal diminue lorsque la largeure du panneau augmente alors que la rigidité du panneau n'influence pas cet effet de voûte.

1 INTRODUCTION

It is widely acknowledged that the earth pressure distribution on retaining walls is 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 distributions 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 plan view will carry disproportionate amounts of earth thrust depending on their relative deflection. Current earth pressure theories are based on walls of infinite width, deforming 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 Ishibashi, 1986, Bolton and Powrie, 1987, Potts and Fourie, 1996) have usually focussed on the plane strain problem. Here, six parametric tests were carried out with a retaining wall system simulating a 11.25m deep basement excavation at prototype scale, with various panel widths and bending stiffnesses. Excavation was simulated by the incremental removal of a heavy fluid from inside the model basement. The horizontal displacements of the wall crests, and bending moments near 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 basement 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 cantilever panels are numbered from 1 to 5, with widths of 40mm, 80mm, 60mm, 60mm and 200mm respectively. This translates to widths of 1.8m, 3.6m, 2.7m, 2.7m and 9m at prototype scale, respectively. Thin panels were 4.76mm (3/16") thick, medium-stiff panels were 6.35mm (1/4") thick, and stiff panels were 9.53mm (3/8") thick. These panels were bolted to the base, with the intention of their being encastré. 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 12.7mm (1/2") thick and had additional bolts on their vertical sides, further limiting their lateral displacements.

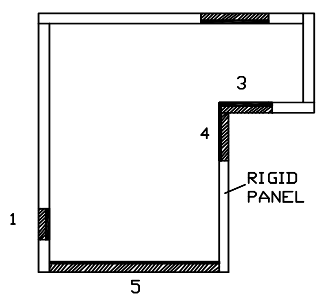

Figure 1: Plan view of model basement

The entire model basement was made of aluminium alloy with a Young's modulus E of 70GPa. The different panel thicknesses can be correlated to different thicknesses of concrete walls, being 302mm , 403mm, and 604mm at prototype scale. The thinnest panels are clearly much thinner than conventional earth pressures would allow for such deep cantilever walls. The relative bending stiffnesses of the walls, proportional to their thickness cubed, are 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% (HYC4), 60% (HYC5), 54% (HYC6) and 53% (HYC7) respectively, in the five tests that will be analysed here. Thin panels (stiffness 0.57 x 10^8kNm/m at prototype scale) were used in tests HYC2 and HYC5; medium thick panels (stiffness 1.4 x 10^8kNm/m) in test HYC6, and thick panels (stiffness 4.6 x 10^8kNm/m) in tests HYC4 and HYC7.

Sodium Polytungstate (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 $K_o \approx$ 1-sin ϕ' in the absence of wall movement, which would have generated lower stress levels. However, as demonstrated by Powrie et.al (1996), in-situ walls do bring the earth pressures to $K_o \approx 1$ during construction. Equilibrium conditions within and outside the model wall are achieved by small outward deflections during the initial acceleration of the model.

Dropping the level of fluid then simulates excavation inside the model basement. The level of fluid was monitored by a laser tracking a ball floating within an external standpipe connecting with the fluid in the model basement. Following the achievement of equilibrium at 45g, the heavy fluid was dropped by 20mm per excavation stage, simulating an excavation of 0.9m at prototype scale. Panel crest displacements are reported at each stage, together with bending moments 20mm (0.9m 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 at prototype scale. Panel crest displacements u are plotted against the depth of excavation, D. Recorded data from panels 3 and 4 is not shown because of their positioning on the model basement, leading to other three-dimensional effects (Ou et.al., 1996).

The data show a wide spread. In general, the thinner panels experienced larger displacements than the stiffer panels, as must be expected. On the other hand, these factor 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 normalised as a ratio of the wall height u/H, while the normalised system stiffness of a retaining wall can be expressed, following O'Rourke (1993), as $EI/(\gamma H^4)$ where γ is the unit weight of the soil. A composite dimensionless group $U = uEI/(\gamma H^5)$ might therefore be useful. If soil were simply a heavy fluid, U would not vary with I since uEI would remain constant for an elastic cantilever; nor, of course, would U vary with panel width B. Figure 3 shows the data of Figure 2 normalised as U versus excavation ratio D/H. The spread of U at a given D/H 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 accounted for the effect of EI in U. Panel width B influences soil shear strains on horizontal planes, through the ratio u/B, and flexibility that leads to increased u/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 on the active side of the wall panel and, similarly, a hydrostatic fluid pressure distribution beneath the simulated excavation on the resisting

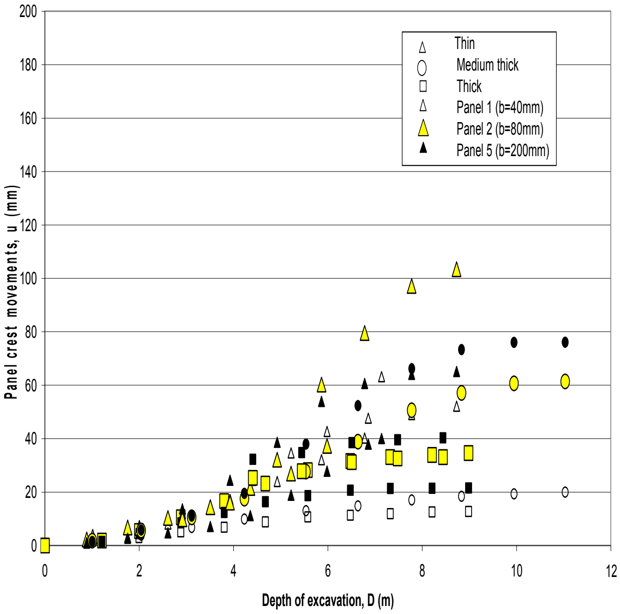

Figure 2: Panel deflections, u plotted against depth of excavation D, recorded from all tests

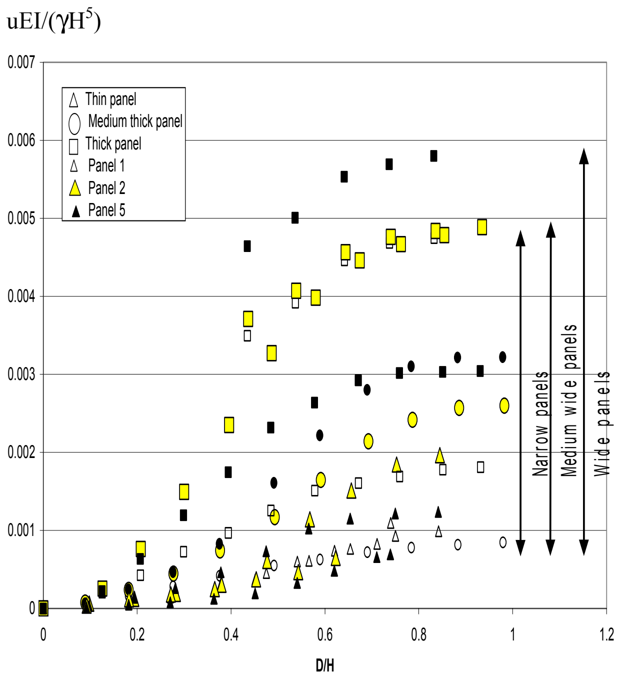

Figure 3: Replotting data from Figure 2 using the dimensionless group $uEI/(\gamma H^5)$ against D/H

side. The recorded panel crest displacements during the process of excavation can then 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) values were used to derive different deflection values, whilst K_{fluid} is always unity.

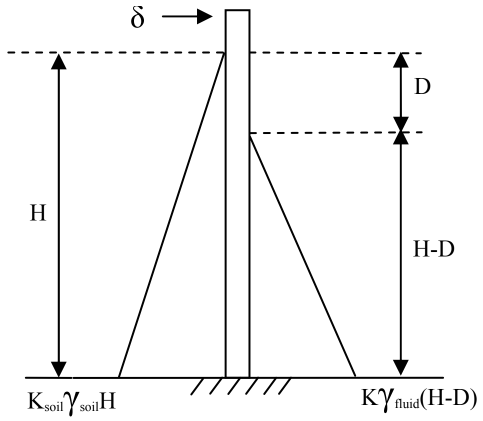

Figure 4: Theoretical loading model of cantilever used in calculations

Figure 5 shows the outcome for thin panel displacements. All three panels (narrow, medium and wide) display paths that track quickly across K values from 1 down to the theoretical active values of 0.22 for a perfectly smooth wall and 0.199 for a wall with roughness δ = 20º. The soil's internal angle of friction was found to be ϕ = 40º, derived using the equation suggested by Bolton (1986), for triaxial strain conditions:

$$\phi'_{\max} - \phi'_{crit} = 3I_D I_C - 1 \tag{1}$$

where ϕ'_{crit} = 32°, I_D = relative density = 0.60, and I_C =4.78.

These equivalent active earth pressures are mobilised after about 5m of "excavation" when the overall wall rotation u/H was about 3 x 10^{-3}. This is similar to the value predicted by Bolton (1989). The paths continue, coming eventually to indicate earth pressure coefficients below 0.1, and in the case of the narrowest panel, below 0.05.

Figure 6 shows a similar progression for the displacements of thick panels, where theoretical active values are 0.198 for a perfectly smooth wall and 0.182 for a perfectly rough wall, taking the angle of friction to be 42˚. The ultimate equivalent earth pressure coefficients are somewhat larger, but still end at values smaller that an engineer could otherwise have calculated with the same angle of internal friction.

In the test shown in Figure 5, the widest panel 5 seems to attract less earth pressure than the medium-width panel 2. This result also occurred in tests HYC2 and HYC4. Monitoring of 3 different locations on panel 5 also showed that 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 cross-walls to stiffen them, and the gap widths between the edges of panel 5 and these rigid panels might not have been adequate in some instances to maintain freedom of movement of panel 5 at 45g when the adjacent panels moved inwards slightly 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 arching 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 strain level). It was shown that:

$$\Delta p \propto \frac{Gu}{B} \tag{2}$$

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 pile spacing on the soil arching behaviour. They found that in the case of cohesionless soil, around 70% of the lateral earth pressure would be transferred to the drilled shafts (piles) if the shafts are 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 8d, they no longer found an arching effect.

This suggests that while horizontal arching should have been occurring to some extent on panels 1 and 2 (H/B = 6.2 and 3.1 respectively), panel 5 (with H/B = 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 advisability of analysing continuous box structures as genuine 3-dimensional problems (Lee et. al, 1998, Loh et. al, 1998).

Figure 7 shows an analogous state path for thick panels that had been provided with strain gauges 20mm above the base connection to measure bending moment (panels 1, 2 and 5 in test HYC7). Equilibrium was achieved at an initial earth pressure coefficient K 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 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 conformity with an active earth pressure coefficient, those for the narrow but thick panel 1 drop well below K = 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 Paik and Salgado (2003) to include elastic bending of cantilever panels of various height/width ratios is currently being developed.

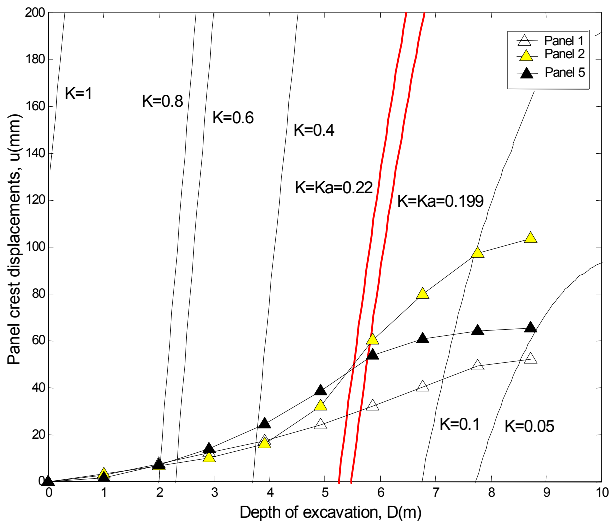

Figure 5: Superimposition of recorded thin panel displacements on predicted panel displacements (results from test HYC5)

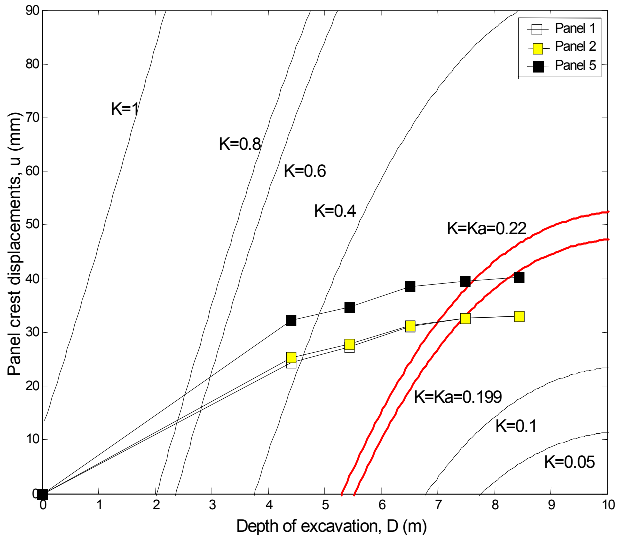

Figure 6: Superimposition of recorded thick panel displacements on predicted panel displacements (results from test HYC7)

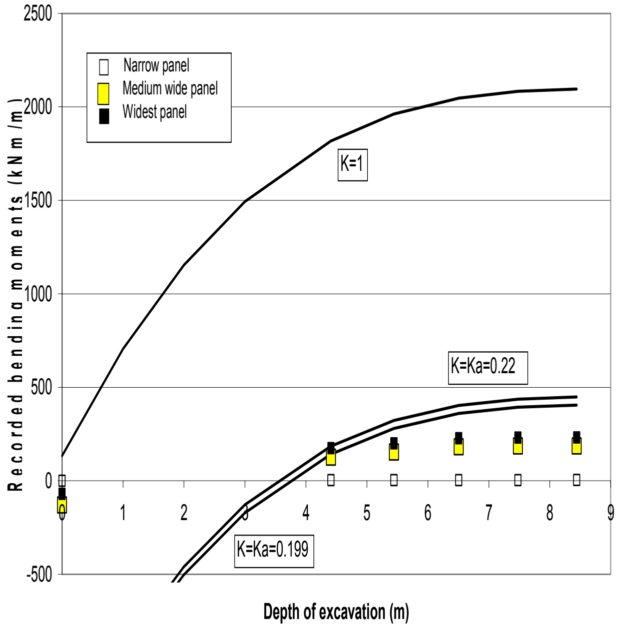

Figure 7: Superimposition of recorded thick panel bending moments on predicted panel bending moments (results from test HYC7)

6 CONCLUSIONS

The horizontal arching mechanism transfers horizontal earth pressures acting on a retaining wall panel to stiffer elements via the soil shear stress components. A model basement was 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 as 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 base bending moments also indicated that the magnitude of horizontal pressures on the panels was very small.

Although plotted panel displacements against excavation depth for panels of different widths and stiffnesses appeared to have a wide spread, this was a representation of different mobilised K values at different stages of excavation. Panel 5 which was a wide panel appeared to deflect less than panel 2, a narrower panel, in some tests. However this could be due to it getting stuck during excavation, because of inadequate gap widths separating it from the adjacent rigid panels which deflected individually as well.

Equivalent earth pressure coefficients K were obtained through the superimposition 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.

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