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3-D finite element modelling of slurry trenching

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ABSTRACT: The movement due to trenching for the construction of diaphragm wall has to be considered when there are nearby structures. Such trenches are often constructed in panels of length 3m to 6m with width ranging from 0.6m to 1.2m. The problem is 3-dimensional and a 2-dimensional plane strain analysis will yield grossly conservative results. Axisymmetric analysis has been used to simulate the trenching process, but this may still be inadequate. In this paper, 3-dimensional finite element analyses were conducted to analyse the trenching process. The results were calibrated against a reported field study at a site which contained a thick marine clay layer. Data including lateral deflection, pore pressure and surface settlement allow a careful evaluation of the movement in the ground adjacent to the trench. The results suggest that 3-dimensional analysis can capture the reported data reasonably well. The results from 3-dimensional analyses will also be compared with that from axisymmetric analyses.

1 INTRODUCTION

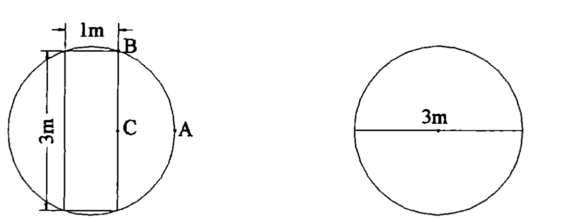
The movement caused during the excavation of a trench for the construction of a panel of diaphragm wall is often an overlooked issue. One reason for this is that the movement is not amenable to two-dimensional analysis, which will produce unacceptably conservative results. In Singapore, increasingly, such construction is required very near to old buildings marked for preservation. Many of these buildings are masonry structures founded on footings. The relevant authorities often imposed requirements that allow for very small movement. The effect of movement caused during the construction of the diaphragm wall is therefore an important issue as the relevant authority is concerned with the total movement, and any movement during the diaphragm wall construction will mean a smaller allowable movement during excavation of the basement. This can raise the cost of construction substantially.

The construction of diaphragm wall is often constructed in panels. To avoid excessive movement, usually, the panel is constructed one at a time when near to structures which cannot tolerate large movement. The panel for such construction usually has a length of 3m or 6m and a width of 600mm to 1m. The behaviour of the soil around this rectangular opening clearly will not be two-dimensional. Axisymmetric analysis has been used to investigate the stability of circular trench such as that for the construction of bored piles (Britto & Kusakabe, 1983). The question of whether an axisymmetric approximation can be used to simulate the soil behaviour during the construction of a rectangular trench has to be examined. However, two issues need to be addressed if an axisymmetric analysis is to be used as a simplification of the real problem. First is the accuracy of this simplification. Secondly, when there is a concentrated load next to the opening, this cannot be correctly simulated by an axisymmetric analysis. It is therefore important to conduct three-dimensional (3-D) finite element analysis to evaluate the movements during the construction of a panel of diaphragm wall.

In this paper, the difference between using an axisymmetric and a 3-D finite element analysis is first investigated. Such a comparison will help to produce a better understanding of the behaviour during trenching. It will also help to establish whether an axisymmetric simplification is adequate for analysing the movement around a rectangular trench. To further help establish the reliability of the 3-D analysis, a field case, where a single trench was excavated for testing purpose, will be evaluated. The predictions from 3-D finite element analysis are then compared to the field measurements. This will lead to a better understanding of the adequacy of such 3-D finite element analysis and points to the direction for further research.

2 THREE-DIMENSIONAL FINITE ELEMENT ANALYSIS

In this study, the time dependent behaviour of the excavation of a trench was investigated using the finite element program, CRISP90, which incorporates a fully coupled consolidation analysis based on Biot's formulation together with a number of constitutive models for soils. CRISP (CRItical State Program), which is based on the finite element method, was developed by the Cambridge University Engineering Department Soil Mechanics Group (Britto and Gunn, 1990). This program can simulate excavation including the effect of time needed for each activity. It can also simulate the removal of soil as in an excavation. CRISP has been widely used to study problems of excavation and earth retaining structures, particularly those involving time-dependent behaviours (Powrie & Li, 1991; Bolton, et al., 1989 and Lee et al., 1993, and Yong et al., 1996). In this study, CRISP is used to conduct both the 3-D and axisymmetric finite element analyses. An attempt was also made to conduct 2-D FEM analysis, but numerical instability was encountered after an excavation of less than 2m, mainly because the soil



a)Plan view of 3-D analysis b) Plan view of axisymmetric analysis

Figure 1. Plan view of 3-D & axisymmetric analyses

Depth (m)	Soil description
50	GWL(-3.5m) Marine clay γ_{bulk}= 18.15KN/m^3 C_u = 28KN/m^2 K_o = 0.64(0-50m)

Figure 2. Soil profile for 3-D & axisymmetric analyses

was yielding. In general, it can be concluded that the movement from a 2-D analysis is excessively conservative and thus no further attempt was made to conduct the 2-D analysis.

In Figure 1, the plan view for the 3-D and axisymmetric analysis is shown. The excavation is to a depth of 28.0m, and the trench has dimension of 3m by 1m. The soil properties assumed for this comparative study are given in Figure 2. The 3-D mesh used in the analysis has a dimension of 61m by 23m and a depth of 50m. For the axisymmetric analysis, the boundary is set to be 31.5mm away from the centre line of the trench. The circumscribing circle has a radius of 1.5m. A total of 1610 brick elements are used in the 3-D FEM analysis, each element containing 20 nodes. Only the 8 vertex nodes have pore pressure as unknowns. Thus altogether, each brick element has 68 degrees of freedom.

To simulate properly the trenching process, 12 incremental blocks were used to simulate the excavation process. For the first two blocks, a 1.5m Thick layer of soil was removed. In each of the subsequent blocks, a 2.5m thick layer of soil in the trench is removed. In each of the incremental block, when the soil is removed, forces will be applied to the nodes along the vertical trench reflecting the total stress that will be applied by the filling of bentonite slurry in the excavated hole. The density of the slurry is assumed to be 12.16 kN/m^3, this is considered a typical figure for such operation. The application of equivalent forces at the nodes is necessary because in CRISP90, application of a continuous pressure on an element side is not implemented for 3-D analysis. The nodal forces are calculated to give the same net effect at the pressure from the bentonite slurry. As can be visualised, this poses a small problem at the surface of the trench. In reality, the slurry pressure at the surface is zero. But in replacing with an equivalent nodal force, a small equivalent force is applied at the surface node. This can cause a small problem to the predicted lateral movement there, but was found to be not significant and does not affect the overall behaviour.

3 COMPARISON BETWEEN AXISYMMETRIC AND 3-D ANALYSIS

In Figure 3, the lateral movement profiles in the trench versus depth at 3 different points in the 3-D analysis, marked as A, B and C in Figure 1. are compared to the prediction using an axisymmetric analysis. In this case, as expected, the movement at

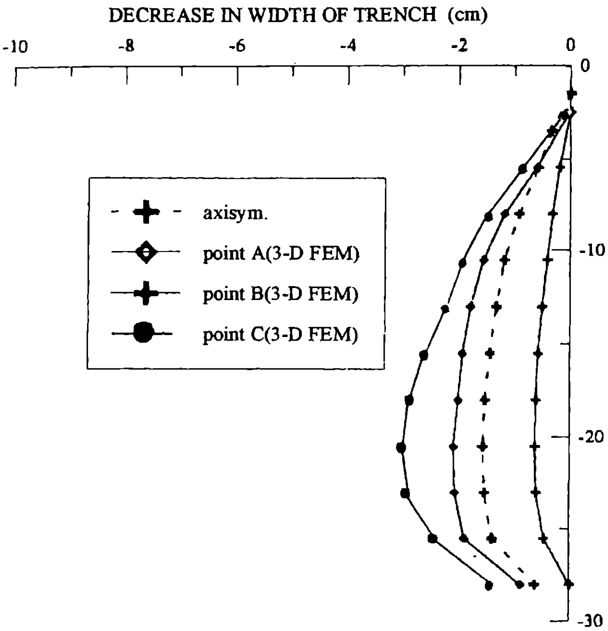


Figure 3. Change in width of the trench immediately after trench excavation and the input of bentonite slurry(comparison of axisymmetric and 3-D analyses result)

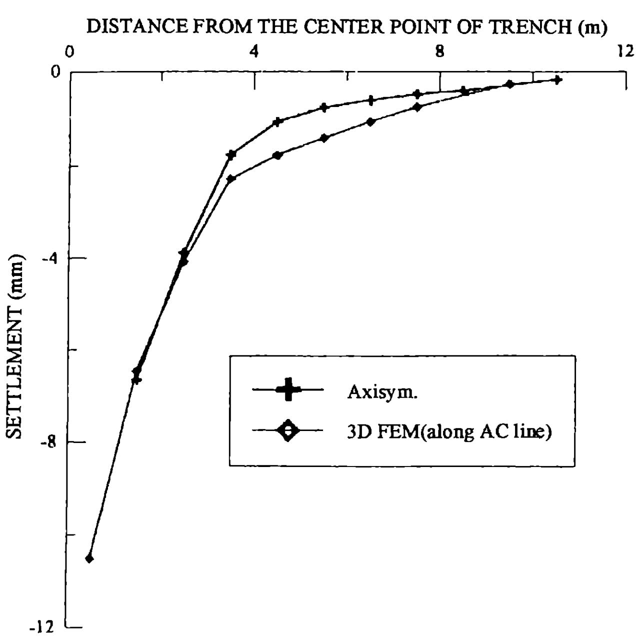


Figure 4. Settlement profiles after the trench excavation (comparison of axisymmetric and 3-D analysis)

a corner of the trench, Point B, is smaller than that predicted using an axisymmetric analysis. Clearly, the corner effect is present. In particular, at the bottom, the corner barely moves whereas there is a small movement in points A and C. However, the lateral movement predicted by the 3-D FEM analysis at the mid-point of the trench (Point C) and that at the circumscribed circular opening (Point A) both show more movement than the axisymmetric analysis. This was considered a little surprising. If the soil around the 3-D trench starts to yield, it would ultimately form an axisymmetric hole circumscribing the rectangular trench. Thus, it was initially thought that 3-D analysis would predict a movement smaller than that from an axisymmetric analysis based on a circle circumscribing the rectangular trench. However, the observed trend is the reverse of this.

In Figure 4, the settlement at the surface, along the centre line to the rectangular trench (AC in Figure 1.) and from the edge is shown. In this comparison, it could be observed that 3-D analysis produces a predicted settlement larger than that predicted by an axisymmetric analysis. Though the difference is not as pronounced as for the lateral movement, it nevertheless confirmed the trend observed that the axisymmetric analysis is stiffer than the 3-D analysis.

To understand this difference, it is important to examine the slightly different assumptions used in the two analyses. In both cases, it is assumed that the entire trench is filled with a slurry. Thus, for the 3-D analysis where the trench is rectangular in shape, at the equivalent points on the circumscribed circle, except for the four corners which touch the circle, the lateral stress acting on a vertical line is from the soil which has an initial K_0 of about 0.6. However, in the axisymmetric analysis, on a vertical line at the edge of the circular trench, it is in direct contact with the slurry, which has a K_0 of 1. Thus the lateral stress that has been mobilised to act along a vertical line on the same equivalent circle to support the stability of the trench may not be the same in the two cases. In fact, it could be smaller in the 3-D case than in the axisymmetric case as the soil is normally consolidated with a low K_0 value.

To check this, the lateral total stresses acting at the same point, A, on the circumscribed circle in both cases are compared and shown in Figure 5. This figure shows that the total lateral stress from the axisymmetric case is slightly higher than that from the 3-D case at the same point on the circumscribed circle. This perhaps helps to explain the reason why the axisymmetric analysis produces a slightly smaller lateral movement and settlement than the 3-D analysis. As can also be observed from this figure, the replacement of the soil by a slurry does not produce back the same lateral stress acting on the vertical line just before the excavation. This is

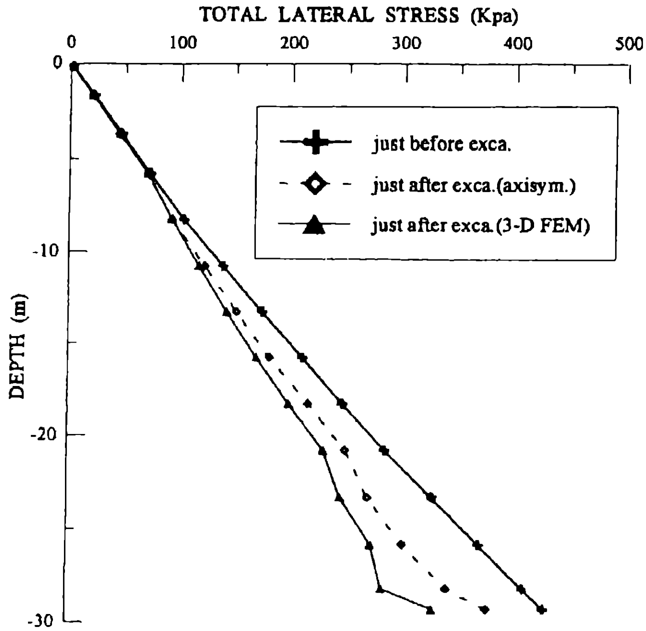


Figure 5. Total lateral stress change at the back of the trench wall before and after the trench excavation (comparison of axisymmetric and 3-D analysis)

Depth (m)	Soil description
10	Fill; Clay crust; GWL(-3.5m)
20	Marine clay; γ_{bulk}= 18.15KN/m³; C_u = 28KN/m²; OCR = 1.1; K_0 = 0.64(0-20m)
30	γ_{bulk}= 18.15KN/m³; C_u = 28KN/m²; K_0 = 0.64(20-31m)
	Rock

Figure 6. Soil profile of Norwegian case

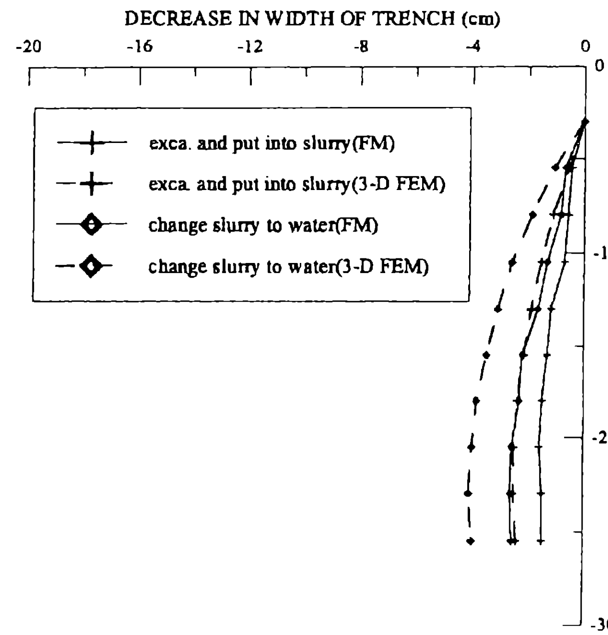


Figure 7. Change in width of the trench at two key stages of the trench excavation (Norwegian case)

expected as the density of the slurry is smaller than that of the soil, but is partly compensated by the fact that for a slurry, K_0 is larger than the in-situ value.

4 COMPARISON WITH FIELD MEASUREMENT

A reported case of trenching (Dibiagio &Myrvoll, 1972) was used as the basis of this analysis. In this case, a trench to a depth of 28m was excavated. The trench length is 5m and the width is 1m. The soil profile was a thick marine clay layer of about thickness 28m underlain by a hard rock. The top 18m of this marine clay has a K_0 of 0.64 and the bottom 10m has a K_0 of 0.54. This suggests a normally consolidated soil overlain by a slightly overconsolidated soil. The top 2m is a fill. This soil profile is shown in Figure 6. In this case, only three-dimensional analysis is carried out.

In the test, an excavation over two days was carried out. The density of the slurry is initially 12.16 kN/m^3. 12 days later, this was reduced to 10.8 kN/m^3. Another 7 days later, this was replaced by water with a density of 9.81 kN/m^3. These details were faithfully simulated in the analysis.

The lateral movement at the vertical surface of the trench is shown in Figure 7. In this figure, it can be observed that the trend from the 3-D finite element analysis is the same as that measured in the field. However, consistently, the movements predicted using the finite element analysis are bigger than the measurements. The settlement away from the trench is also compared and shown in Figure 8.

Again, the settlement predicted is larger than that measured. Near to the edge of the trench, the difference is about 20%, but reduces with distance away from the trench. One aspect that clearly shows the importance of 3-dimensional analysis is the rate of reduction of settlement with distance away from the trench. In this case, the prediction agrees well with the field measurements. A 2-D analysis will usually predict a settlement that would tail much further than field measurement.

For further comparison of the overall behaviour, the measured change in width along a horizontal section at a depth of 15.5m is shown in Figure 9 with the associated numerical prediction. The observed pattern is again consistent with the observations made earlier. This shows that the numerical

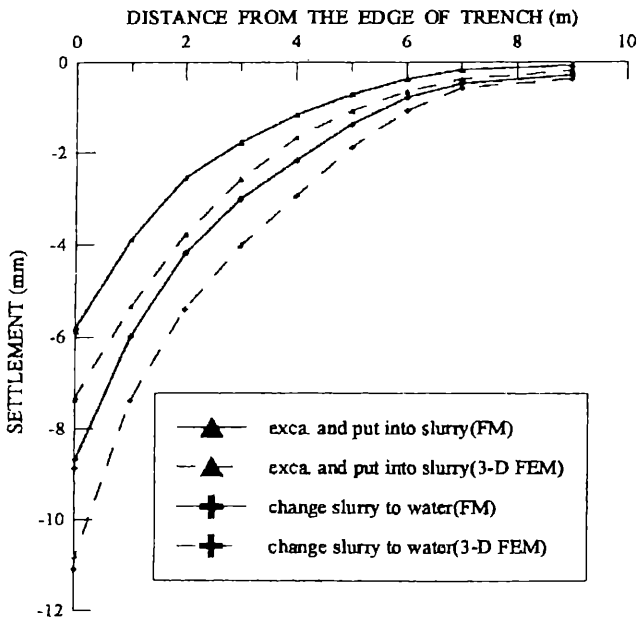


Figure 8. Settlement profiles at two key stages of the trench excavation (Norwegian case)

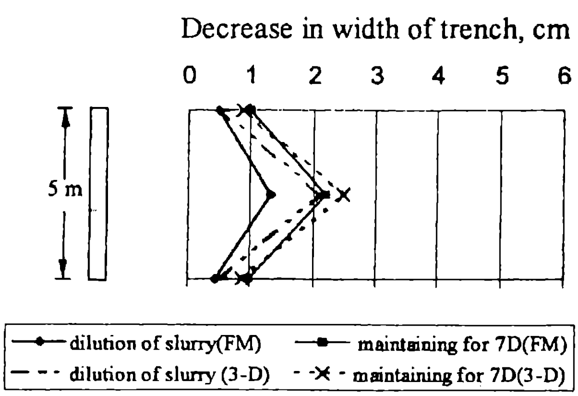


Figure 9. Change in width of the trench along a Horizontal section at a depth of 15.5m

prediction produces a movement larger than that measured; but the trend is very similar. As the movement increases, the prediction also agrees better with the field measurements.

In Figure 10, the settlement with time at a point on the surface 3m away from the trench and along the centre line is shown. The overall trend is again consistent with the observations made earlier. However, one glaring difference comes at the 24th day. A change in the density was carried out, and the results of 3-dimensional analysis show this change. However, the measured value seems to indicate a much smoother transition. At this, stage, it is still not obvious what is the cause of this discrepancy in trend. However, for the change in slurry to water around the 32nd day, both the field

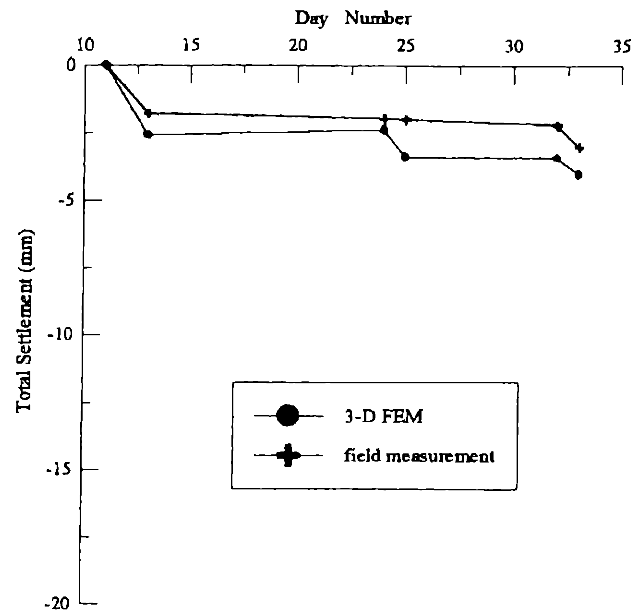


Figure 10. Time-settlement curves for reference point (3m away from the edge of the trench) (Norwegian case)

measurement and 3-dimensional analysis show a very similar increase in settlement.

In the above comparison, a proper 3-D finite element analysis has been conducted to simulate the field trial. Thus usual reasons to account for the differences between analysis and measurements, such as corner effects, cannot be used. The only factor to consider for this discrepancy is the properties of soil assumed. In this case, a guess was made of the soil properties. The values chosen for the soil parameters in the analysis are values estimated from experience based on conventional testing. Increasingly, there is recognition that when the movement is small, as is the case here, the mobilised strain is also very small and the actual mobilised stiffness can be higher. With our recent knowledge of small strain stiffness, this can partly account for the observation that the predicted movement and settlement is larger than the measured value. However, as the current CRISP90 version used in the analysis does not include this capability, no re-analysis were done to ensure a better prediction.

5 CONCLUSIONS

In a highly built up place like Singapore, movements caused by excavation of a trench during the construction of a panel of diaphragm wall cannot be overlooked. The principal reason for this is that the relevant authorities are concerned with the total movement and any movement during the trenching means less allowable movement during the actual excavation of the basement.

Analysis of the movement caused by such trenching is limited as the usual 2-D analysis will produce unacceptably conservative results. Thus only axisymmetric and 3-D analyses are able to produce more reasonable results. In the study reported here, the behaviours predicted using a 3-D and an axisymmetric finite element analyses are compared. These analyses were conducted using the well known soil program CRISP. The 3-D analysis is subsequently used to evaluate a reported case history used as the basis for a comparative study. The following conclusions can be drawn from this study.

a) If an axisymmetric analysis is to be used as an approximation to the trenching process, care must be taken in interpreting the results as there is some differences due to the way the slurry pressure is applied to the trench edge. In particular, for a case where K_0 is small, the prediction by the axisymmetric analysis is not conservative, that is, it predicts a smaller movement.

b) The study indicates that 3-dimensional analysis can capture the trend of the movements at the trench and away from the trench well. However, consistently, the analysis produces movements smaller than that observed.

c) This discrepancy, perhaps, can be attributed to non-linear elastic behaviour at small strain. However, such an analysis has not been carried out as such capability is not available on the CRISP program used.

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