

A REVISIT TO NICOLL HIGHWAY EXCAVATION IN SINGAPORE

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ABSTRACT: This paper demonstrates the use of explicit finite difference program *FLAC* to numerically simulate staged braced excavation involving various stages of excavation and strutting. The short term undrained condition is considered in the analyses. A *FISH* script is developed, with automatic mesh generation capacity, to study the behavior of wall deformation and ground settlement during the stages of construction. The numerical model is developed using the case study of Nicoll Highway in Singapore. Both the geotechnical design and the causes of failure of the Nicoll Highway excavation are re-visited through extensive comparisons with existing published data. It is considered as a successful development with the main purpose in mind to develop a numerical model for the analysis of staged excavation in the construction of underground basements. The success of the development is to be used in assisting other design projects in the future.

Keywords: *FLAC, Untrained analysis, Nicoll Highway, Deep braced excavation.*

1. INTRODUCTION

Deep excavations are often carried out in congested urban areas, for example in underground transport systems, construction of basements and water distribution networks. They can induce unfavorable ground deformations that affect adjacent structures, particularly in soft ground. Numerical analysis of such a problem is a complex challenge. It consisted of stability analysis, dewatering system, stress analysis, and simplified and advanced method of preloading. Of interests in this analysis are wall displacement, ground settlement, the distribution of shear force and bending moment in the wall, the axial force in the struts, and the heave at the bottom of the excavation.

Researches have been carried out to study deep braced excavation problem both numerically and experimentally. Among the studies, finite element method (*FEM*) was widely used to estimate the behavior of wall deformation and ground settlement during the excavation process [1-3]. The *FEM* has also been used to study earth pressures, strut loads, bending moments, and horizontal deflection for a strutted sheet pile and ground settlement pattern process [4-6]. Hsiung [4] studied the effect of soil elasticity creep and soil-wall interface by numerical analysis and compared the results of the numerical model with a case study of excavation in sand.

This paper uses explicit finite difference program, *FLAC*, to numerically analyses staged braced excavation under undrained condition. Interface element is employed for better prediction of ground settlement. The computed values of wall

displacement from this study are then compared with those published for the Nicoll Highway study in Singapore.

2. STATEMENT OF THE PROBLEM (NICOLL HIGHWAY)

Nicoll highway project in Singapore was started to construct in 2001. The project consisted of construction of a new 33.6 km long underground highway. The first stage of construction was 5.4 km long which subdivided into two contracts: C824 and C825. The scope of the design and build contract C824 comprised of Nicoll highway and Boulevard Stations, 800m of bored tunnels and 1.6 km of cut and cover tunnels [7].

The braced excavation for the cut and cover tunnel were constructed for C824 of the project. The diaphragm wall 0.8 m width and about 40 m depth was braced by the steel struts with the help of walers and splays. Two layers of jet grout slabs, constructed using interlocking jet grout piles (*JGP*), were also installed after construction of the slurry walls to minimize deflection and ground movement during the excavation work [7]. The upper 1.5 m thick layer of *JGP* (to be removed before the 10th strut level installation) was placed at about 28 m below ground level. The lower (permanent) 3 m thick *JGP* layer was built 33.5 m below the ground level.

The excavation was kept open by a strutted system comprising of steel king posts (center posts), walers, and 10 levels of struts. The struts were spaced at 3.0 - 3.5 m vertically and 4.0 m horizontally. The width of the excavation was

about 20 m and it was about 33.5 m deep.

An extensive monitoring system was installed. It included more than 2000 monitoring instruments: settlement markers and inclinometers to measure soil and wall displacements; vibrating wire piezometers to measure pore water pressures; strain gages and load cells to measure the strut loads [8]. Figure 1 shows the cross section of the excavation.

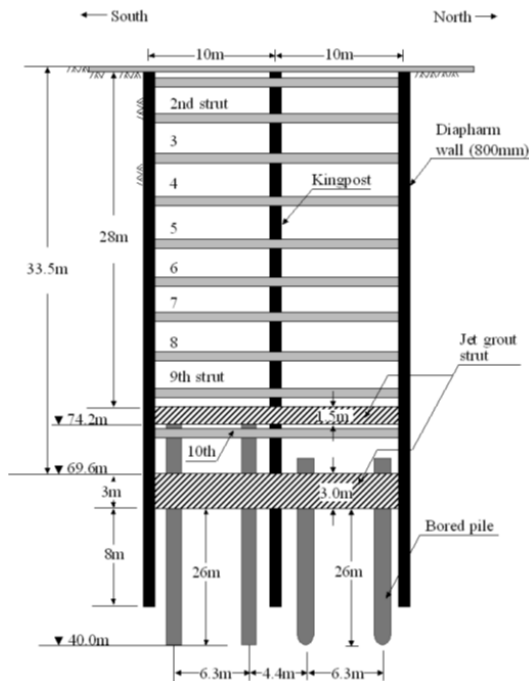


Fig.1 Cross section of the excavation [8]

3. NUMERICAL MODELLING OF STAGED EXCAVATION

In this paper the 2D *FLAC* program is used to conduct the numerical modelling. This program simulates the behavior of structures built of soil, rock or other materials that may undergo plastic flow when their yield limits are reached [9]. Materials are represented by elements, or zones, which form a grid that is adjusted by the user to fit the shape of the object to be modelled. Each element behaves according to a prescribed linear or nonlinear stress/strain law in response to the applied forces or boundary restraints. The material can yield and flow and the grid can deform (in large-strain mode) and move with the material that is represented.

3.1 Undrained Analysis (Short Term)

The analyses are conducted by using total stress formulation for undrained condition. All soil types are modelled by using Mohr-Coulomb models. For low-permeability soils, angle of friction was set to 0° and only the undrained shear

strength was used. More sophisticated soil models other than Mohr-Coulomb are not considered in this paper due to practical reasons and the lack of input parameters. Table 1 shows the soil properties used in the analysis, whilst Figure 2 shows the geometry for the undrained analysis of the Nicoll Highway excavation project.

Table 1 Undrained soil properties [7 and 10]

Soil type	ρ Kg/m ³	E kN/m ²	S_u kN/m ²
Fill	1600	10000	0
Estuarine (soft clay)	1600	6000	5
Upper marine clay, first half layer (<i>UMC1</i>)	1600	2000	10
Upper marine clay, second half layer (<i>UMC2</i>)	1600	4000	20
Fluvial soil (<i>F2</i>)	1900	14500	70
Lower marine clay, first half layer (<i>LMC1</i>)	1700	4000	20
Lower marine clay, second half layer (<i>LMC2</i>)	1700	7000	35
Fluvial soil (<i>F2</i>)	1900	14500	70
Old Alluvium ($N > 70$)	2000	100000	350
Jet-grouted soil	2000	90000	450

The friction angle of all layer is equal zero except of the fill layer which is 32 degree.

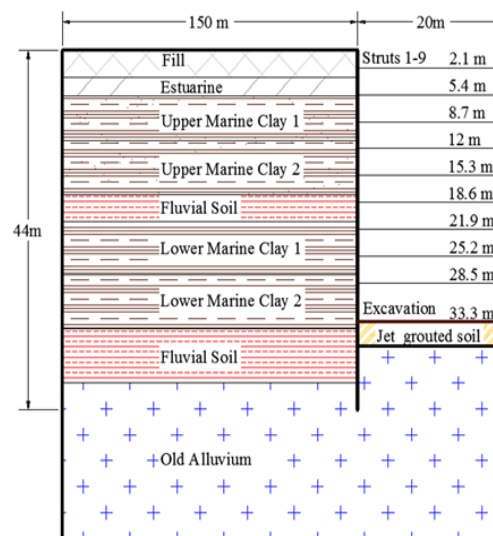


Fig.2 Geometry for the undrained analysis [7 and 10]

The material properties of the diaphragm wall and the struts are listed in Tables 2 and 3. The chosen Mohr-Coulomb model properties for analysis are adapted from Table 1.

Table 2 Properties of diaphragm wall [7 and 10]

Thickness (m)	ρ (kg/m ³)	E (GPa)	Poisson's ratio	I (m ⁴)
0.8	2400	19.2	0.2	0.04267

Table 3: Properties of the struts and preloads [7 and 10]

Strut number	Depth of strut below ground surface (m)	Cross- sectional area (m ² ×10 ⁻⁴)	Preload kN/m
1	2.1	218.7	568
2	5.4	218.7	1018
3	8.7	218.7	1816
4	12	218.7	1635
5	15.3	590.8	1458
6	18.6	590.8	1322
7	21.9	590.8	2130
8	25.2	590.8	2332
9	28.5	590.8	2173

The density of the material used for strutting system is 7850 kg/m³.

3.2 Modelling procedure

The procedure to simulate the deep braced excavation of the undrained condition within *FLAC* is illustrated by performing the analysis in several steps:

1. Generate the model grid, assign material models, material properties and boundary conditions for the physical system.
2. Determine the initial in-situ stress state of the ground prior to construction.
3. Determine the initial in-situ stress state of the ground with the diaphragm wall installed.
4. Excavate to a depth of 3.3 m.
5. Install the horizontal struts at the wall, at a level of 2.1 m below ground surface.
6. Obtaining results for the Stage 1.
7. Excavate to a depth of 3.3 m (Stage 2).
8. Install the horizontal struts at the wall, at a level of 1.2 m above excavation surface
9. Solve for Stage 2 results.

Steps 7 to 9 are repeated until the excavation of Stage ten is completed. The model was created using the command-driven mode and a user friendly *FISH* program was developed to facilitate

parametric studies.

4. RESULTS

After the numerical model has been developed, various results can be generated from the *FLAC* program. The most important result plots are wall displacement, ground settlement, and shear and bending moment diagrams.

4.1 Wall deflection

The deflections of the diaphragm wall at each excavation stage are indicated by the plot of x-displacement of the wall structure versus wall depth in Figure 3 for the preloaded struts. These plots are table plots generated using the *FISH* function called *wall_disp.fis*. The x-displacement and the y-position of each node along the wall are stored in ten tables corresponding to each excavation stage. The maximum deflection is approximately 195 mm at 23 m depth below ground surface. The maximum deformation occurred at the seventh stage of the excavation.

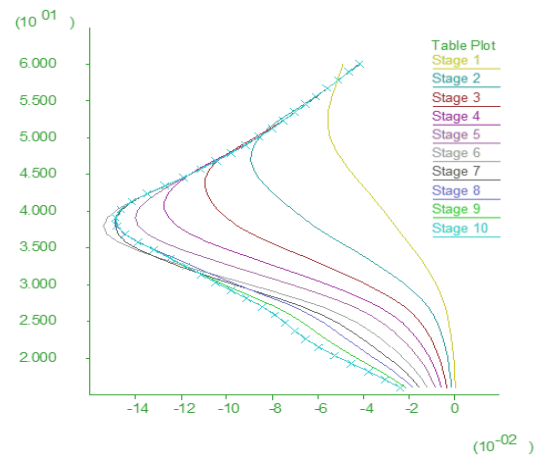


Fig.3 X-displacement of diaphragm wall at the end of each excavation stage

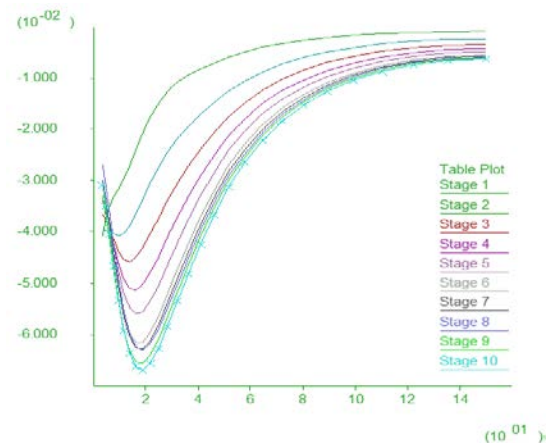


Fig.4 Surface settlement profiles at the end of each excavation stage

4.2 Settlement

Settlements behind the diaphragm wall at each excavation stage are plotted in Figure 4. The plot represents y-displacement of the soil versus horizontal distance from the diaphragm wall to 150 m. These plots are table plots generated using the *FISH* function *settle.fis*. The maximum settlement is approximately 140 mm and occurs at the tenth stage of excavation. All other stages' settlements

are shown in Figure 4 for the undrained analysis in this paper.

4.3 Bending Moment Diagram and Shear Force

The bending moment distribution in the wall is shown in Figure 5. The maximum value of the moment is 2173 kN.m that occurs approximately at the middle of the wall. This values is recorded at the final stage excavation.

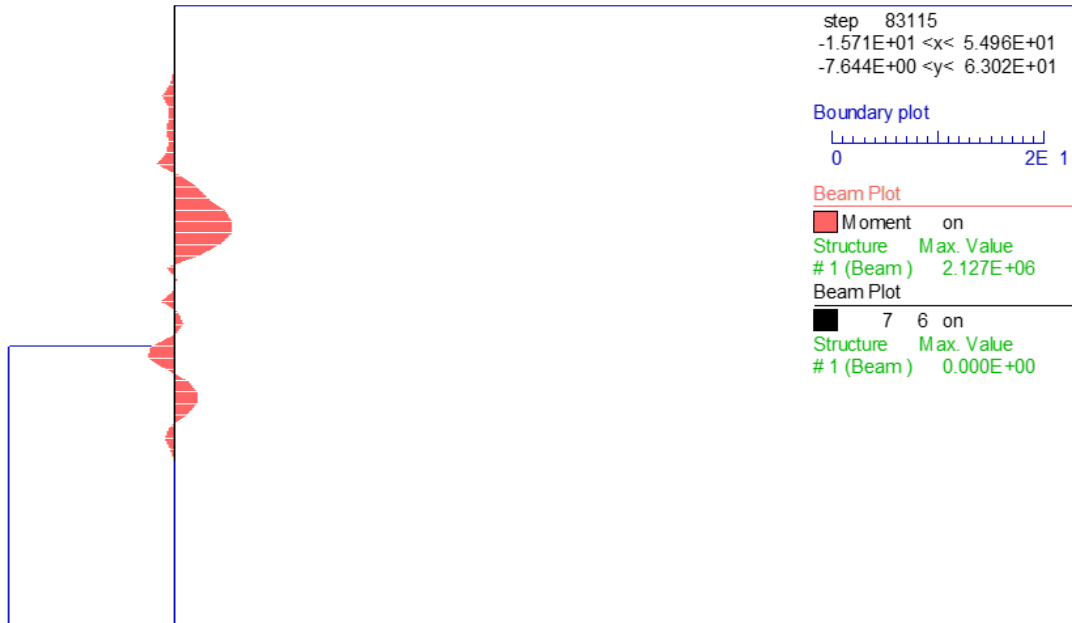


Fig.5 Computed bending moments (N-m) in the diaphragm wall at the final excavation stage

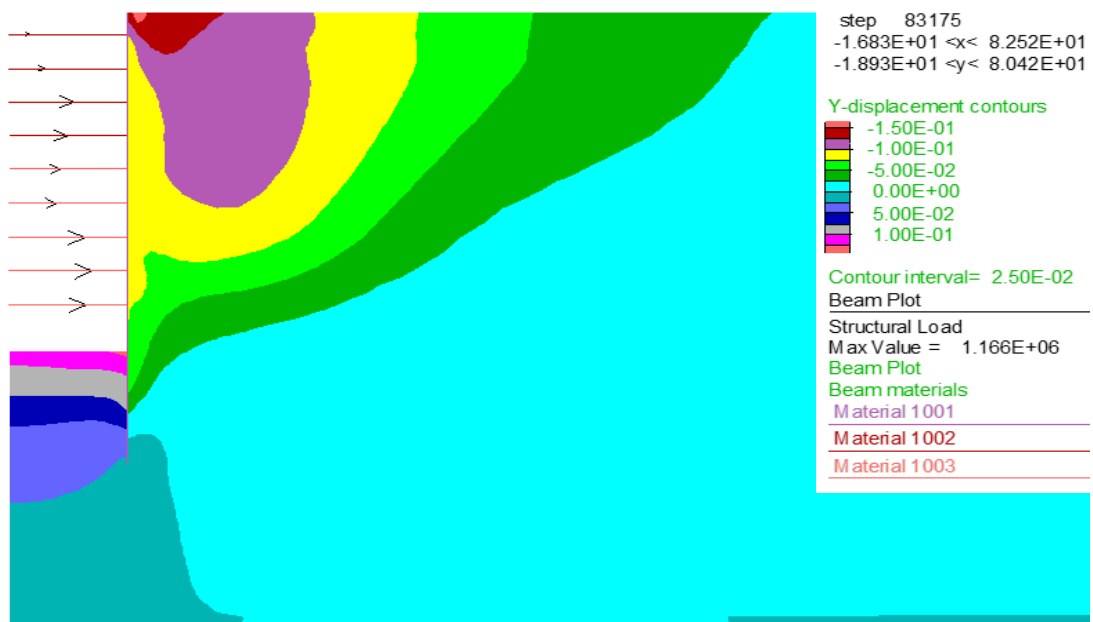


Fig.6 Computed y-displacement contours (m) in the grid and beams load (N) at the final excavation stage

4.4 Y-displacement contour and beams' load

Figure 6 shows the plot of the y-displacement contours and beams load at the final excavation stage. The maximum y-displacement is recorded at the bottom of the final stag excavation and the value is approximately 15 cm.

4.5 Axial Force and x-Displacement Contour

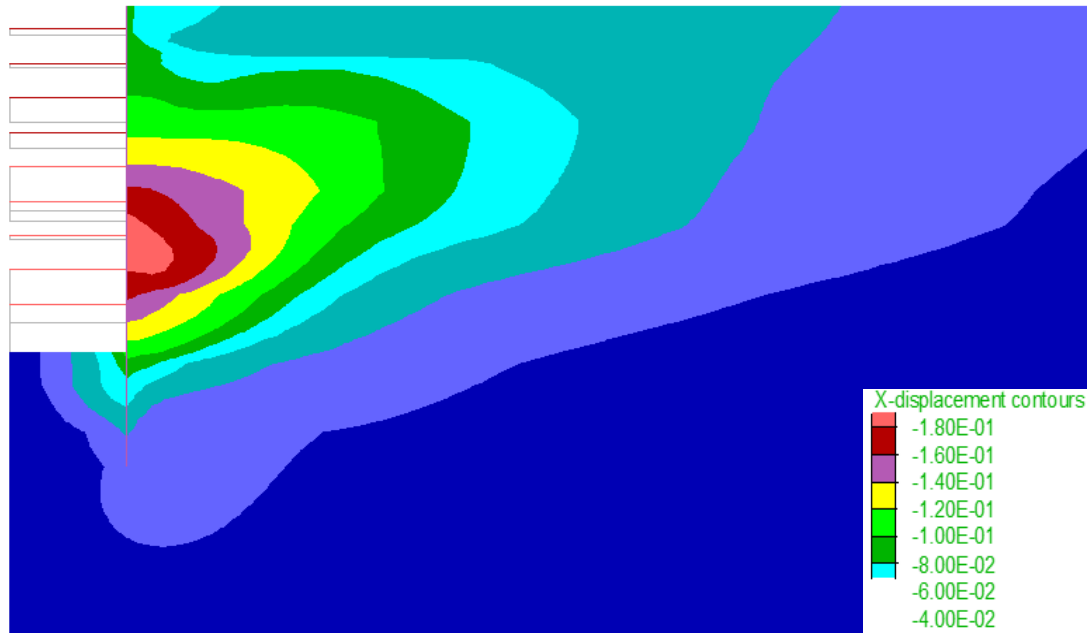


Fig.7 Computed x-displacement contours in the grid and axial forces in the struts at the final excavation stage

Figure 7 shows the plot of the x-displacement contours and axial forces in the struts after the final excavation stage. Note that actual values for the axial forces are plotted directly for these plots. The maximum axial force is recorded in strut number eight and the value is 1499 kN which corresponds to the location of maximum soil x-displacement.

5. COMPARISON WITH FIELD MEASUREMENTS AND PUBLISHED LITERATURE

The computed values of wall deflection from the numerical modelling based on the undrained analyses from this study are compared with the measured and predicted values of wall deflection as reported by Lee *et al.* [10] at the last stage of excavation shortly before the collapse. The measured wall deflection profiles were obtained from inclinometer I65 installed just behind the north wall within the collapsed zone. The computed, measured and predicted deflection profiles were in reasonable agreement, considering the uncertainties and complexities involved in the analysis.

The maximum value of wall deflection from the undrained analysis based on this study was approximately 19 cm which is very close to the measured value of wall deflection, 18 cm. The maximum value of wall deflection as reported by [10] was approximately 21 cm.

Figures 8 and 9 compare the wall deflection

profiles among this study, measured and reported by [10].

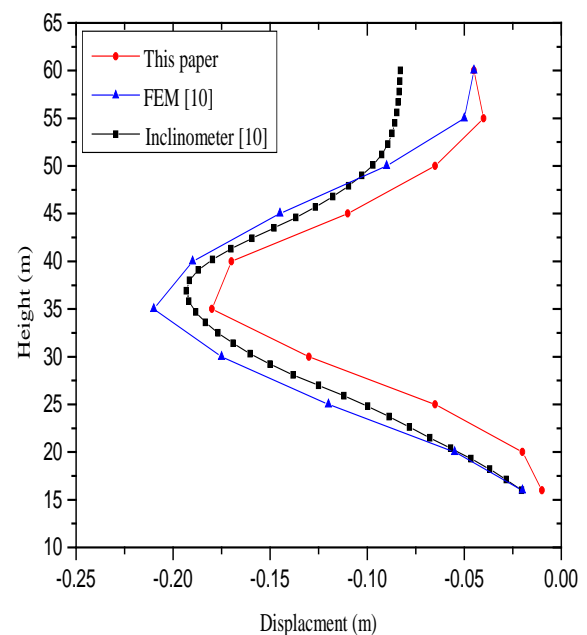


Fig.8 Comparison of computed, measured and predicted wall deflection [10]

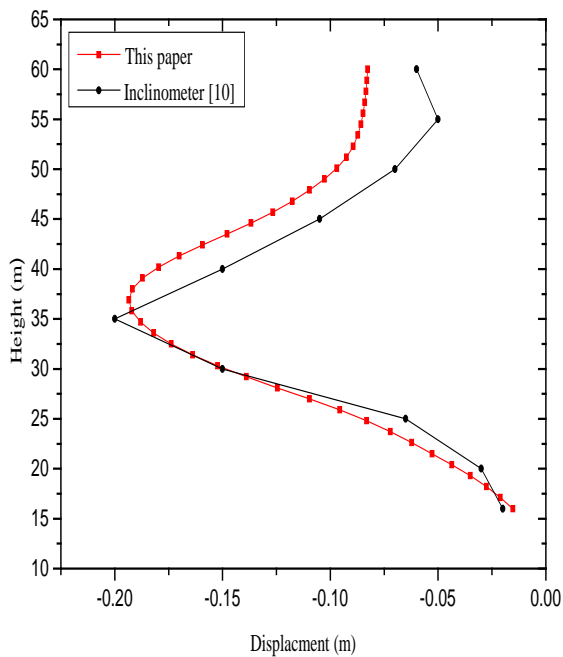


Fig.9 Comparison of computed and measured wall deflection [10]

6. INVESTIGATION AND DISCUSSION

Numerical modellings for the undrained analysis have been developed based on the Nicoll Highway excavation data. According to the geology of the site work, most of the layers of soil were soft clay and, due to presence of the groundwater table just below 2 m of the ground surface, the analyses were carried out for short term analysis of the clay. When the results were compared with the measured value and reported by some previous studies, the results from short term analysis have a more reasonable agreement because most of the excavation was undertaken in soft saturated marine clay which is likely to remain undrained during the four months excavation period.

In the short term analysis for clay, the analyses are conducted by using total stress formulation, rather than effective stress formulation. Because the analysis involved a collapsed excavation, it is important to ensure that the undrained shear strength of the soft clay was accurately reflected. The process of collapse is better simulated dynamically, where inertial effects can be invoked to equilibrate unbalanced forces that were generated during the collapse [10].

It is suspected that the main reasons for the difference of deformation values of the north and south walls were; firstly this may be because of the non-uniformity in the jet-grout layer, secondly some problems with the connection between the walers and the struts of the south side, and finally the construction of south side diaphragm wall with

curved sections.

According to [7], the wall deflection exceeded 500 mm for the south side walls, while the calculated design level was only 190 mm which was the same as computed from undrained analysis from this study. Therefore, the main reason for the collapse may be a structural design error of the bearing capacity of the walers, making them unable to take redistributed loads. Figure 10 shows buckling of a C channels waler.



Fig.10 Buckling of walers [7]

Different studies reported different reasons for the failure including an inappropriate method of analysis, under-design of the strut walers' connections, incorrect use of the geotechnical back analysis and inefficiency of the instrument and monitoring system. Based on the computed results from this study, it can be concluded that the main reason for the failure was the under-design of the strut walers' connections because the computed wall deformation was within the range of the designed value. The excavation length was about 1600 metres and the collapse occurred in the curved section, so it is credible that there were some problem in the strut walers' connections in the curved section.

7. CONCLUSIONS

A numerical model has been developed for analyses of deep braced excavation under short term undrained analysis. The developed model has successfully been validated by using the Nicoll Highway excavation example.

Various results have been presented and compared with published results among which are wall displacement, ground settlement, the heave at the bottom of the excavation, axial load in struts, and shear and bending moment distribution on the diaphragm wall. The computed, measured and predicted deflection profiles are in reasonable agreement, considering the uncertainties and complexities involved in the analysis.

The results of this research have revealed

future research topics for the development of three dimensional analyses. Further development of drained analysis model for deep braced excavation is also desirable.

8. REFERENCES

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